PROJECT REPORT

SUPPORTING AN ECOSHAPE PROJECT BY DEVELOPING AN ECO-DYNAMIC DESIGN OF ADDITIONAL LAND IN FRONT OF EAST COAST PARK, SINGAPORE

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PREFACE

This report is the result of a multidisciplinary project of 10 weeks as a part of the masters of hydraulic engineering at Delft University of Technology. The project is conducted for Ecoshape as a contribution to the “Building with nature” program. This project is used as a case to develop guidelines for an eco-dynamic design in tropical environments.

As this report has been written in the context of a masters of hydraulic engineering, it assumes some knowledge of the reader on coastal engineering and numerical modeling. Coastal engineering subjects are extensively elaborated on in chapters 2 to 4. Readers who are more interested in modeling are referred to the appendix.

We would like to thank our supervisors Claire Jeuken and Jeroen van den Bos for their persistent support to our team and Bas van Maren for his support with the modeling. We would like to thank Ecoshape for providing us with accommodation in Singapore. Furthermore, we would like to thank the National University of Singapore and the Singapore Delft Water Alliance for providing data, support and office space. At last we thank Boskalis Singapore for their hospitality and their support in accommodation and office space.

With a dot we end.

Robbert de Bruijn, Simon den Hengst, Robert Hasselaar and Andrzej Tusinski

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SUMMARY

East Coast Park (ECP), located at the southeast coast of Singapore, is reclaimed from 1965 to 1976 by the Housing and Development Board. From the east of the city centre up to Changi, about 1525 hectares of land were added. ECP is currently getting more and more crowded during weekends, which creates a demand for additional recreational space at this location. Contrary to this expanding need for space, the coastline at ECP is subject to erosion with an average erosion rate of approximately 1 m/y.

Analysis

Singapore, situated at 1° north of the equator, has an equatorial climate which is characterized by a constant high temperature (yearly average of 26.8 C), high humidity (yearly average of 84%) and heavy rainfall (yearly average of 2300 mm). The coast of Singapore is a marginal sea coast (tectonically stable) with a protected sea environment (protected from the open ocean). The coast in front of ECP consists of both mud and sand. The sea bottom at ECP is founded by the Kallang Formation (marine clay) and the Old Alluvium (mixture of sand, silt, clay and organic materials). The top layer of the reclaimed land is made of coarse-grained sand.

The coast at ECP is influenced by tides, monsoons and waves. The tide consists of a mainly diurnal tide from both the South China Sea and the Indonesian Sea and a semi-diurnal tide coming from the Indian Ocean. The mixing of these tides generates a considerable tidal asymmetry, mostly semi-diurnal water levels (mean spring tidal range of 2.64 m) and diurnal currents in the Singapore Strait. The wind wave climate is characterized by a low maximum significant wave height of 0.6 m nearshore. The northeast monsoon generates swell waves in the South China Sea which refract towards Singapore and approach ECP at an angle from the southeast. ECP is also subject to heavy ship traffic and the accompanying ship waves. Ship waves differ for ferries and cargo ships. High speed ferries produce long secondary waves ($H = 1$ m and $T = 15$ sec), while cargo vessels generate a very long primary wave ($H = 0.5$ m and $T = 70$ sec). These all reach the beach.

The tide and monsoons generate both eastward and westward currents. The combination of monsoons and the tide results in a residual current (yearly average discharge) to the west. These residual currents mainly transport fine sediments. The eastward sediment transport is induced by the tidal asymmetry (larger eastward velocities). The tidal asymmetry has more influence on coarse sediment than on fine sediments due to the difference in peak velocities.

The coast at ECP is eroding because the coarse-grained sediment is transported but there is no updrift supply of these coarse-grained sediments. Wave breaking induces a relatively small longshore current, which transports sediment within the breaker zone. Course-grained sediment is stirred up by wave breaking. The sediment is transported in cross-shore direction due to wave undertow, current induced turbulence created by the structures (groynes and breakwaters) and large scale eddies that develop during flow reversal. Further offshore the sediment is transported in longshore direction by currents.

The requirements that have to be met in order for the growth of the ecosystems to succeed are found in the habitat requirements of these systems. All habitat requirements however are highly dependent on the type of species and are very site specific. It is therefore difficult to distil one requirement that suits all these species.

Mangroves require a sheltered wave and current environment. A shallow mudflat in front of the forest provides both sheltering as well as accommodation space for accretion. The amount of possible accommodation space is determined by the tidal range in combination with the slope of the mudflat and the maximum tolerated inundation times of the different species. Patch sizes vary widely, but patches as small as 15 ha are found near Singapore.

Seagrasses require an environment that is sheltered from both waves and currents. Seagrasses are found to be able to grow up to depths of 25 m below MSL, but the high turbidity of the waters in Singapore limits the permissible depth to 8 m below MSL. There is no restriction on the minimum required patch size as patches of all sizes are found in nature. As there are seagrasses near ECP, there is a big chance that pollination will occur naturally when favorable conditions are created.

Corals grow on hard and bare substrata with either a horizontal or convex slope too prevent sediments from settling. Corals are very sensitive to the sedimentation regime as small sedimentation rates can already cause mortality. Corals only grow up to 6 m below MSL in Singapore due to the reduced light intrusion caused by the high turbidity of the waters. In general, encrusted and boulder shaped corals can withstand larger hydrodynamic energies than other species, but exact numbers are not known. Minimum patch sizes are also unknown.

The present situation at ECP does not include mangroves, seagrass or corals. This implies that the habitat requirements for these eco systems will have to be engineered. Large patches of seagrass are found to the east of ECP, situated behind an emerged seawall. Corals are found at the hard defenses near the Tanah Merah ferry terminal. Furthermore, corals have historically been present in abundance at ECP. Although mangrove forests are found in Singapore, they are not present and never have been present at ECP. There have been mangrove forests in the Marina Bay.

On the 30th of August 2011 a survey has been held among 96 visitors of ECP. It became clear that 77% of the participants do not swim in the waters due to the perception of a low water quality. If beaches disappear because of the design, they will have to be replaced by better quality beaches; i.e. less debris and cleaner waters. The most common reasons to visit ECP are leisure, sports and the view. The predominant preference of the waterfront view is the beach rather than nature. A common heard quote was: "If I want to see nature, I will visit neighboring islands such as Bintan or Batam or the Botanical garden in the city centre". Concluding, ECP is mainly considered as a recreational area.

Design

The goal of the project is to design additional land for recreational purposes with the inclusion and possibly the use of ecology (mangroves, seagrasses or corals). The design of the additional land with the inclusion of ecology was focused at the following principles:

1. Enlarge the area suitable for recreation (main purpose)
2. Improve biodiversity and ecology (main purpose)
3. Prevent and reduce erosion
4. Use nature for engineering purposes
5. Develop an constructible and economic design

These principles were followed by taking into account the navigational restrictions, the stakeholders and the habitat requirements.

The design process took into account design decisions such as the location, the type of additional land, the number of land masses, the height of additional land and the landfill material. Beside these decisions several considerations were made per design such as an extension or an island and protected or unprotected ecology. This process resulted in both top views and cross-sections of 11 preliminary designs.

Evaluation

The tools used during the evaluation were Delft3D (a numerical model to investigate hydrodynamics, sediment transport and morphology) and a multi-criteria analysis (MCA). The numerical model consisted of a nested model in the Singapore Regional Model (SRM). This nested model was especially developed for evaluating the effects of the design, such as checking if the habitat requirements were met.

The MCA of the different designs is based on six groups of criteria; utility, ecology, coastal protection, building with nature and overall costs. Starting with utility; mangroves do not directly increase the recreational value of an area as they replace the present beaches and block the view on the ocean. Coral reefs and seagrasses on the other can increase the recreational value.

Designs that create large areas of sheltering score high on ecology as both seagrasses and mangroves require sheltering from waves and currents. Corals on the other hand require reefs to establish, which are created in the form of hard and bare (submerged) revetments. Designs that implement ecology in such a way that it protects the coastline score high on the building with nature criterion.

The coastal protection of the designs is directly related to the coastline retreat at ECP. This retreat can be reduced by decreasing the wave action, currents or turbulence. A land extension or island can decrease the currents in cross-shore direction. Furthermore, the additional land can provide a large sheltered area along the coast, preventing erosion in this area. On the other hand, large land forms can also generate large scale eddies which in return increase erosion. By implementing an offshore coral reef, the ship and swell waves can be reduced. Other general options to counteract the coastal retreat are redesigning of the present breakwaters or the continuous nourishment of course materials, which are expensive in Singapore.

The length of hard and soft revetments and the amount of landfill materials needed are the main cost driving aspects of the different designs. As mangroves require a large shallow mudflat too grow on, designs incorporating mangroves contain the largest amounts of landfill. Furthermore, mangrove seedlings are very expensive, which increases the costs even further. Corals are relatively expensive as well, as they need a hard and bare substrate to grow on. Seagrasses on the other hand are very cheap; they grow in relatively deep water and the pollination will probably take place naturally.

All the designs have been implemented in the nested model from which the influence of these designs on the hydrodynamics and vice versa has been determined. Furthermore, the accretion of fine sediments has been investigated in the different simulations. Detached islands perpendicular to the coast induce flow velocities that exceed the allowed maxima for ecology and erosion, no matter how far the island is located from the coastline. Attaching one side of the island to the shore solves this problem as a basin is formed which is filled and emptied by the tides only. Although the basins create large sheltered areas, there is a possibility of stagnant water in these basins. The size of the opening and shape of the basin should prevent this phenomenon. Furthermore, the designs should be as streamlined as possible to minimize acceleration of the flow and to prevent the formation of large scale eddies on both sides of the design. The sedimentation rates on the mudflats in the sheltered areas of the designs all meet the required amounts as set forth by the habitat requirements.

After considering all the above mentioned criteria of the MCA and the results of the model runs, the “lagoon, unprotected corals” design has shown to score highest on the majority of the criteria. Although this design is expensive, it has such high ecological and utilitarian values that these high costs can be justified. The submerged breakwater poses an enormous possible breeding ground for corals. Furthermore, this design incorporates the building with nature philosophy extensively. Finally, by engineering coral reefs, the coastline can partly be returned to the historical coastline, where corals protected the shore from wave attack.

Conclusion

Tropical ecosystems can be incorporated in the design of additional land in front of ECP. All ecosystems are present in Singapore and some have even been present at and near ECP. If not already present, the habitat requirements of corals, seagrasses and mangroves can all be engineered.

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1 INTRODUCTION

The foundation Ecoshape is investigating how to implement the concept of “Building with nature” in engineering projects around the world since 2008. On the one hand, the program “Building with nature” has been created to gather applicable knowledge on the consequences of engineering projects on the environment. On the other hand, research is conducted on how to include nature in the design process and how to build with nature using the materials, forces and interactions present in nature (Waterman, 2008).

Coastal infrastructure works could benefit greatly from the ability to combine coastal protection and ecology. Recent coastal infrastructure designs show that hard or soft coastal defense systems are designed without incorporating ecology. However, many coastal ecosystems contribute significantly to the coastal protection. Tropical ecosystems such as mangroves, sea grasses and corals can help to achieve engineering targets (i.e. wave attenuation, prevention of erosion) and provide habitat by offering food, breeding and living grounds for various species. Furthermore, these ecosystems increase the attractiveness of an area. Finally, such an eco-dynamic approach has economical benefits, replacing expensive construction materials and methods with natural components.

Ecoshape is executing a project in Singapore called ‘Innovative bio-diverse coastal protection’. The project tries to develop guidelines and designs of an eco-dynamic coastal protection in a tropical environment. This design should ideally create a situation in which recreation, biodiversity as well as coastal protection are enhanced, without increasing the cost of construction. (Ecoshape, April 2011).

The collaboration between Ecoshape and the Singapore Delft Water Alliance (SDWA) led to a short course on eco-engineering on the 20th and 21st of January 2011 in Singapore. This course was held at the National University of Singapore and was attended by the Singapore Institution of Engineers. One of the main goals of this course was to teach the Eco-Dynamic Design (EDD) guidelines to the public attending the course. An artist impression of the results of this course is shown in Figure 1.1.

These EDD guidelines are described by a 5 step process (Ecoshape E.-E. C., January 2011):

1. Understand the system (physical, socio-economical and governance).
2. Identify realistic alternatives.
3. Valuate the qualities of alternatives and pre-select an integral solution.
4. Embed the solution in a project approach.
5. Prepare the solution for implementation in the next phase on the road to realization.

This report is the result of a project that has been undertaken to complete steps 1 through 3 of the EDD Guidelines for the Singapore case project location. The project is a study case. The project studies the feasibility of the realization of an eco-dynamic design in tropical environments.

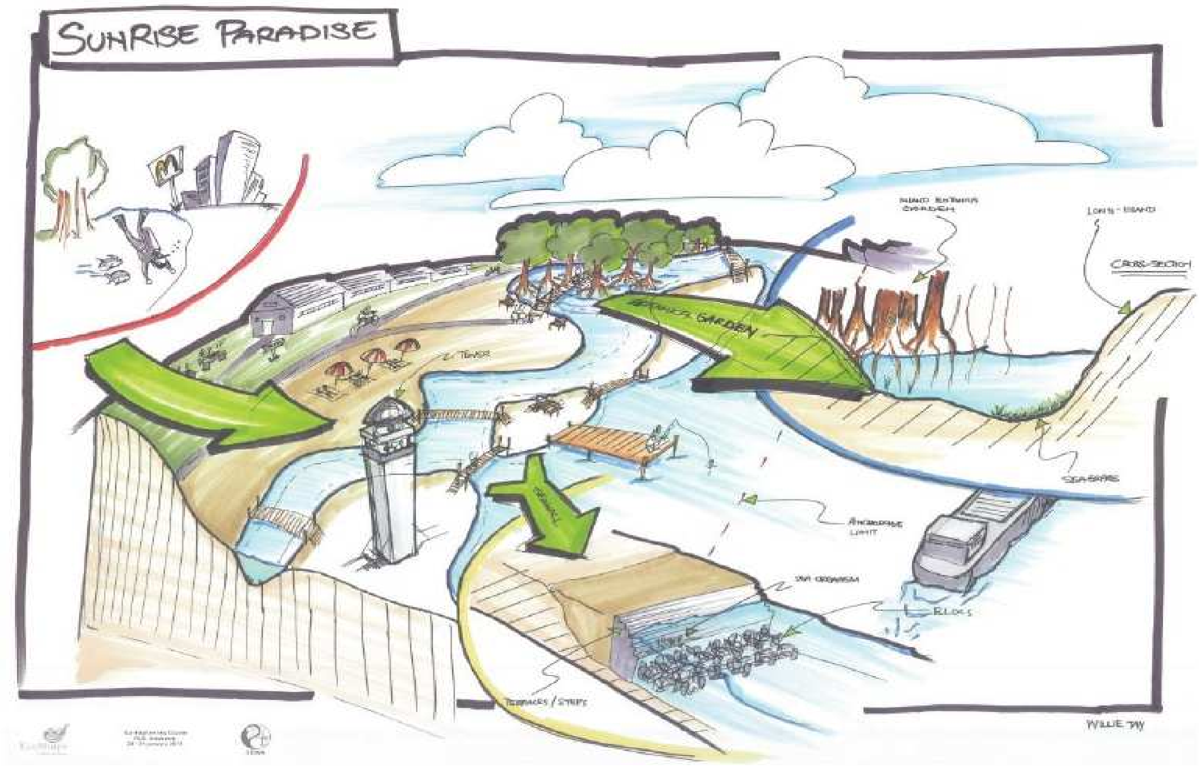


Figure 1.1 | An artist impression of the results of the first eco-design course

1.1 PROBLEM DEFINITION

Singapore is growing in terms of population and economy, which creates a demand for space for working, living and recreation. One of the options available for the Singaporean government is the construction of islands in front of East Coast Park (ECP). This plan originated from the "Concept Plan 2001" which has been released by the Urban Redevelopment Agency (URA). The concept plan maps out the long term (40 to 50 years) planning for land use and transportation in Singapore.

Besides this, there is on the one hand a change in the people's mindset about switching to a more sustainable way of living and constructing. On the other hand there is a necessity to construct more sustainable to use earth's resources and energy in a responsible manner. "Building with nature" presents an opportunity to achieve exactly this.

ECP is the longest park in Singapore and one of the few spots where people can sport and recreate in relative rest. ECP is getting more and more crowded during weekends, which creates a demand for additional recreational space at this location.
The location of ECP in Singapore is shown in Figure 1.2. The recreational surface area of ECP is 1.691.000 m^2.

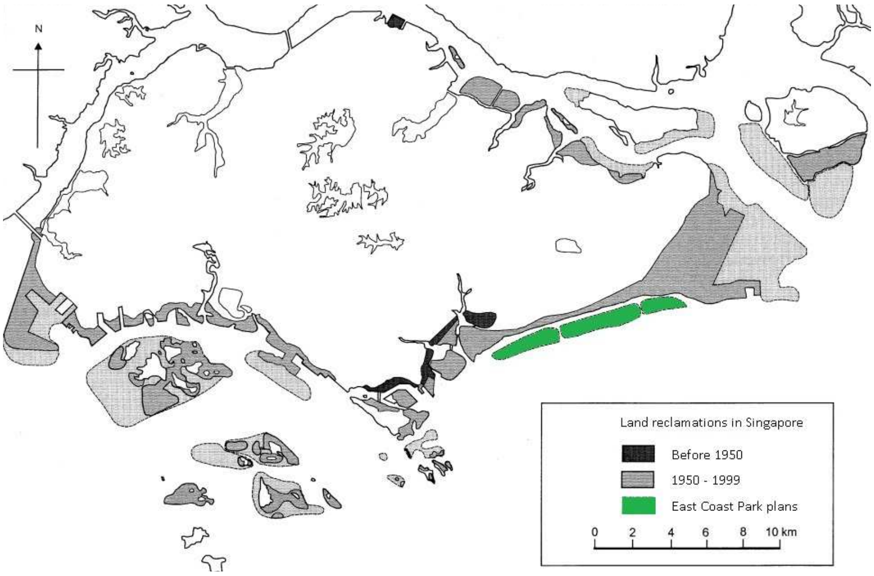


Figure 1.2 | Singapore with the East Coast Park Extension plans, after editing acquired from (Schwartz, 2005)

1.2 OBJECTIVE AND RESEARCH QUESTION

The objective of this project is to design and assess possible solutions for additional land in front of East Coast Park and to incorporate the implementation of ecological systems in these designs. At least one additional ecosystem component (mangroves, seagrasses or corals) will be included in these solutions, leading to so called eco-dynamic designs.

The objective of this project leads to the following research question:

How can tropical ecosystems such as mangroves, seagrasses and corals be incorporated in the design of additional land in front of East Coast Park in Singapore?

To answer the research question it is divided into two sub questions:
- Is the creation of additional land in front of East Coast Park (ECP) feasible in terms of available space, soil and hydraulic conditions?
- Is it possible to engineer the required habitat requirements for ecology at ECP?

1.3 PURPOSE OF THE RECLAMED LAND AND STARTING ASSUMPTIONS

The main purpose of the additional land is to provide space for recreation in front of ECP. Recreation is defined as all activities that take place in one's spare time with as goal leisure and relaxation; e.g. (water) sports, barbequing, nightlife and shopping.

The design should include at least 1 ecosystem (mangroves, seagrasses or corals). Furthermore, the "Building with nature" philosophy is preferably applied in the design. Finally, the current erosion is preferably reduced by the design.

1.4 STRUCTURE OF THE REPORT

The report is divided into five distinctive parts. The first part of the report is the system description. In the system description, the coast is classified and the environment (climate, tides, waves, currents, sediments, ecology and sediment transport) is described. The system description also includes a stakeholder analysis and a description of the results of the survey performed by the project group at ECP. The second part of the report is the design chapter. It describes the design process, the design requirements and restrictions and the design alternatives. The analysis of part 1 serves as a direct input for the development of the alternatives. The third part of the report is the evaluation, in which the design alternatives are compared. The fourth part of the report consists of a detailed elaboration of the chosen design alternative. It includes a detailed description of a location for ecology and the design of revetments. The fifth and last part contains the conclusion, limitations and recommendations.

2 SYSTEM DESCRIPTION

This chapter will describe the physical, ecological and socio-economic system of the project. The structure of this chapter is in accordance with the EDD guidelines.

2.1 PHYSICAL SYSTEM

2.1.1 COASTAL CLASSIFICATION OF THE EAST COAST PARK COASTLINE

Coastal systems can be classified based on:

1. Plate tectonic setting
2. The dominance of fluvial, wave or tidal processes
3. Relative sea level rise

This section deals with these classifications.

Tectonic-based classification

Singapore has a marginal sea coast, which is a tectonically stable coast and it is protected from the open ocean by islands.

Singapore is located at the Eurasian plate. The converging Java Trench along Sumatra is located at 700 km from Singapore. The city is located at 2200 km from the converging Manila Trench in the South China Sea.

Singapore is also located at the Sunda Shelf, which is a big (characteristic length of 3000 km) stable continental shelf. This shelf includes shallow seas with depths smaller than 100 m, like the South China Sea, the Gulf of Thailand and the Java Sea (Encyclopædia Britannica, 2011).
It follows that Singapore has a very little change of being affected by a tsunami.

Figure 2.1 | The shallow Sunda Shelf and the tectonic plate fault lines below Sumatra and near the Philippines, from (Google Earth, 2011)

Process-based classification

The process-based classification gives an impression of the relative influence of fluvial, wave and tidal processes in the formation of the coastal landforms. It depends on the supply of sediment by the rivers and the distribution of the sediment by tides and waves.

The coast of Singapore is a marginal sea coast (tectonically stable) with a protected sea environment (protected from the open ocean) according to the classification of Davies. Marginal sea coasts have wide continental shelves. They become low wave energy coasts due to the shallow waters, gentle slopes, sheltering by nearby islands and the limited fetch of the marginal seas (J. Bosboom and M.J.F. Stive, 2011).

The wave climate is characterized by a low maximum significant wave height of 0.6 m, which makes it a low wave energy coast (refer paragraph 0). The Iribarren number is an indication of wave behavior at the breaking zone (ratio between the slope steepness and the wave steepness). It has a magnitude of about 0.95, which corresponds to plunging waves. This implies that the waves are not completely dissipated, but they are definitely not reflected. Reflecting waves could negatively influence the navigational function of the Singapore Straits.

Singapore has a mixed semi-diurnal and diurnal regime with a mean spring tidal range of 2.64 m (meso-tidal regime, refer paragraph 0). The tidal currents are in the order of magnitude of 2-3 m/s in the middle of the Strait.

The combination of a low mean wave height and an average mean spring tidal range results in a tide-dominated environment (Masselink and Hughes, 2003). The relative tidal range (RTR), which is the mean spring tidal range (MSTR) divided by the wave height just before breaking, is equal to 6.6. These tide-dominated environments normally have a wide intertidal zone.

The east coast of Singapore used to be closely related to the Johor estuary east of Singapore. The Johor Estuary is mainly formed by the river and the tide. Due to the reclamations for Changi Airport the east coast became more separated from the estuary. The east coast is thus mainly shaped by the tide.

The current coastline is uninterrupted and straight, which suggests the influence of waves. The coast however is not exposed to high wave energy. Concluding, the characteristic land forms of a tide-dominated coast are not in accordance with the current coastline.

Relative sea level rise

The absolute or eustatic sea level rise (SLR) from 1990 to 2100 is estimated in a range from 18 cm to 88 centimeters according to the fourth assessment report from the Intergovernmental Panel on Climate Change (IPCC, 2007). Absolute eustatic mean sea level rise as an average of all green-house emission scenarios is predicted to be 32 cm.

Singapore is located in an area that is undergoing submergence due to eustatic sea-level rise. There may however be additional factors contributing to the submergence, like regional subsidence due to the compaction of sediments and the local withdrawal of groundwater at ECP. As a subsidence map for Singapore was not at our disposal, quantification was difficult (refer chapter 7 Limitations).

2.1.2 CLIMATE, TIDES, CURRENTS AND WAVES IN THE SINGAPORE STRAIT

The hydraulic conditions in the Singapore Strait are influenced by the monsoon climate but dominated by the tidal influences from the China Sea and the Indian Ocean.

Climate

Singapore, situated at 1° north of the equator, has an equatorial climate which is characterized by a constant high temperature (yearly average of 26.8 C), high humidity (yearly average of 84%) and heavy rainfall (yearly average of 2300 mm) (Singapore Biodiversity, 2011). The water temperature does not vary more than 1° with depth and varies around 30 and 31 degree at the surface (P. Tkalich). Salinity in the Singapore Strait varies between 26 and 33 ppt seasonally (Robinson R. , 1953). The difference in salinity is found in the difference in rainfall between the dry and wet seasons.

Singapore is located in the intertropical convergence zone between the two trade winds (at ±10° north and ±10° south). These winds subsequently lose their energy, which finally results in a lack of horizontal winds in this area and therefore a very moderate wind climate with average wind speeds of about 5 knots (refer Figure 0.15 in Appendix D). These same trade winds are creating the northeast Asian monsoon from December to February and the southwest Asian monsoon from June to September. A monsoon is a seasonally change in the prevailing wind direction.

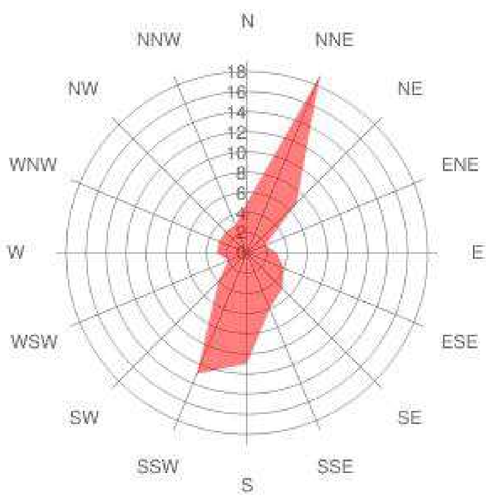


Figure 2.2 | Wind rose with wind speed in knots at Change Airport from daily observations in the period of 03/2006 - 06/2011 from 7 am till 7 pm (northeast of ECP) from (Windfinder, 2011)

Tides

This paragraph treats both the magnitude of the vertical tide (the tidal range) and the character of the tide (the importance of diurnal versus semi-diurnal components).

Tidal character

The Singapore Strait is influenced by an incoming mainly diurnal tide from the South China Sea and the Indonesian Sea and a semi-diurnal tide coming from the Indian Ocean as shown in

Figure 2.3. The mixing of these tides generates a considerable tidal asymmetry, mostly semi-diurnal water levels and diurnal currents in the Singapore Strait.

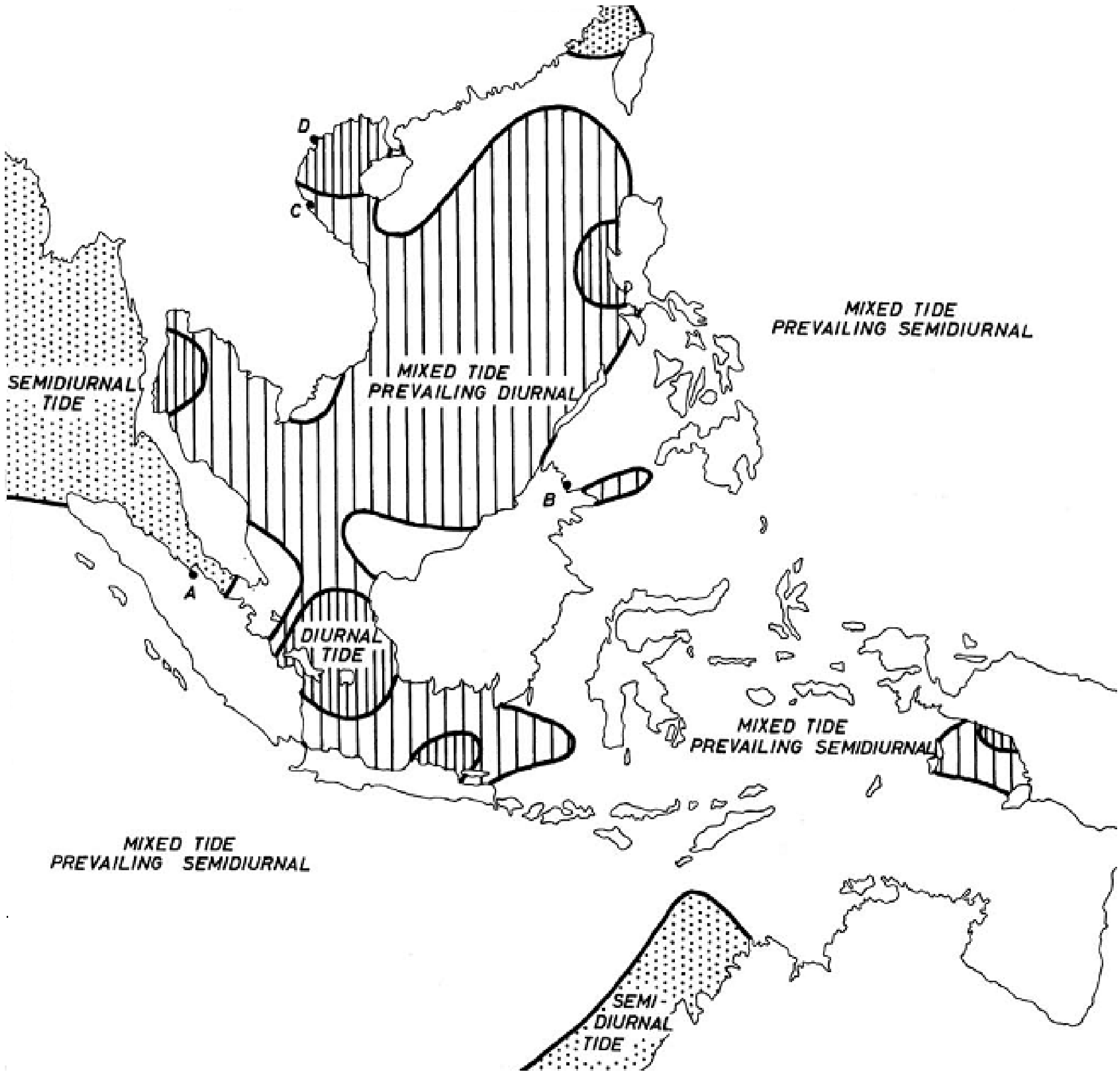


Figure 2.3 | Tidal regimes in Southeast Asia, from (Wyrtki, 1961).

Magnitude of the tide

Singapore has a meso-tidal regime, with a mean spring tidal range of 2.64 m. The maximum recorded tidal range at ECP is 3.49 m in February 1974 (S.Y. Chew, Beach Development Between Headland Breakwaters, 1974). The figure below shows the vertical tidal signal of the year 2004 at 2 locations; Tanah-Merah (east of ECP) and Pagar (west of ECP). This figure shows that there is no significant tidal difference along ECP. In Figure 2.5 the tide in 24 hours on a random date in 2004 is shown.

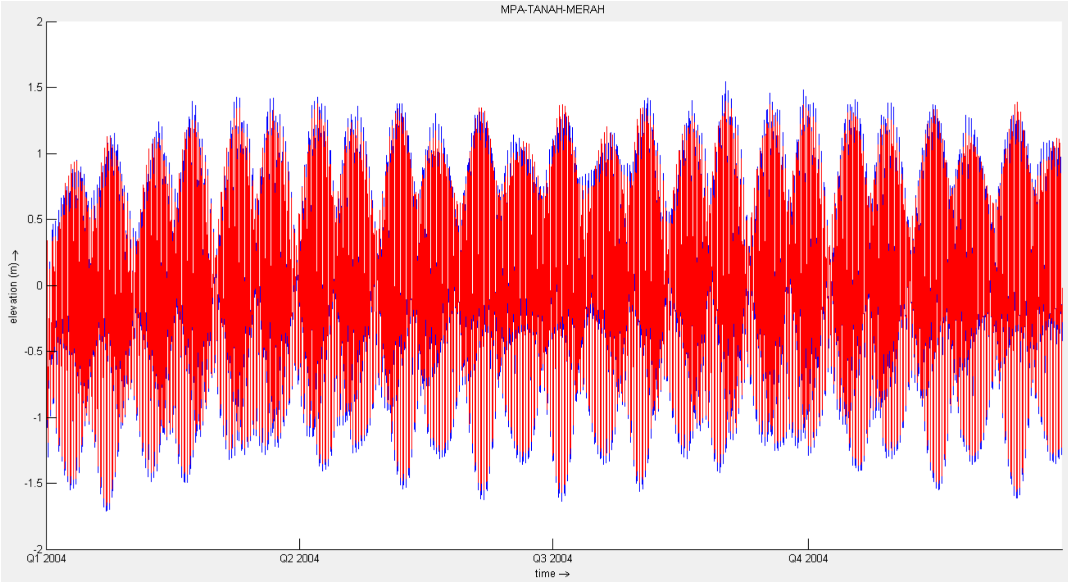


Figure 2.4 | Vertical tide for 2004 of the output stations Tanah-Merah northwest of ECP (in red) and Pagar southeast of ECP (in blue), from SRM Deltares/SDWA.

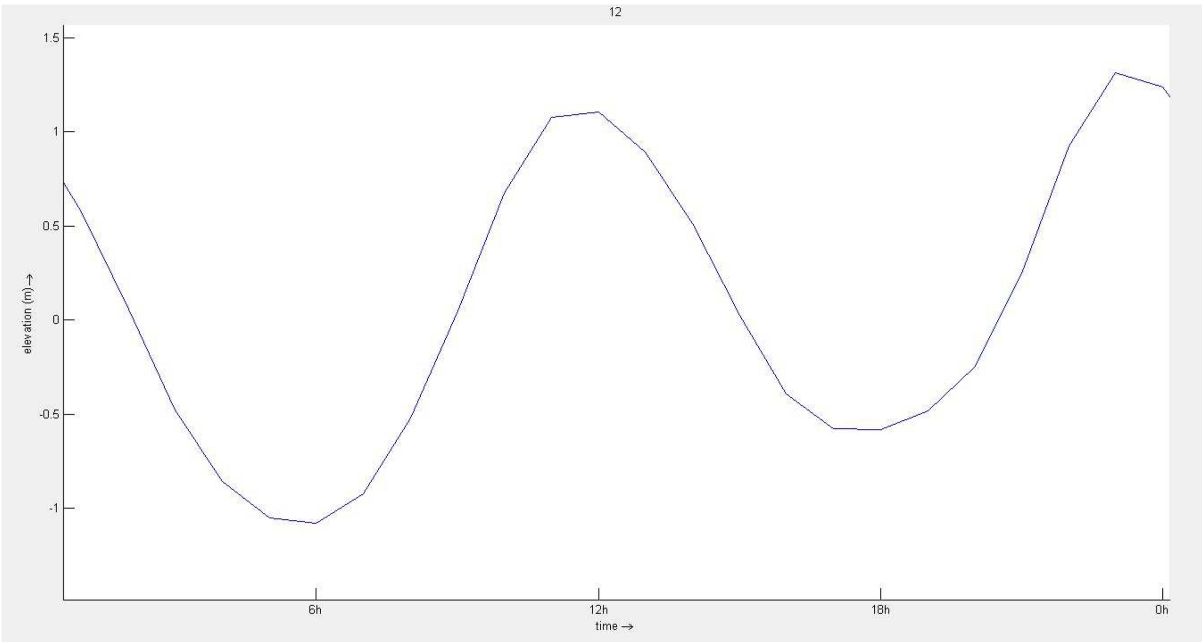


Figure 2.5 | 24 hours of the tidal cycle in front of ECP

Currents

The currents in the Singapore Strait are forced by the tidal asymmetry between the diurnal and semi-diurnal components of the tide and the monsoon induced residual currents. The diurnal tide is transformed producing both an increase in M2 amplitude and a strong tidal current through the strait (Maren, 2011).

These forces result in a current that is net westward during most of the year. The flow is net eastward during the peak of the Southwest monsoon during from June-September (Robinson R. A., 1953). In general, the flow velocities are highest south of Sentosa where the strait is narrow. The flow velocities can increase up to 3 m/s (Chen, 2005). The current velocities near the shore are on average below 0.2 m/s, increasing in strength towards the middle of the Strait up to 2 m/s (Burt, 2004). The monsoons generate wind driven currents that can be up to 0.15 m/s (Maren, Tides and residual flows, 2011).

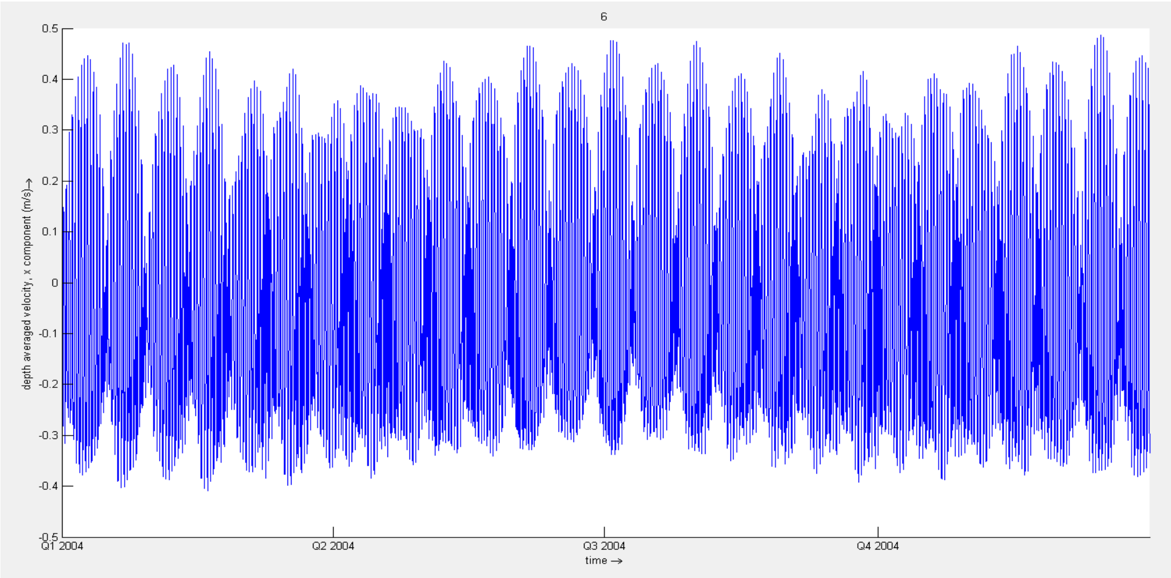


Figure 2.6 | Current velocities in the middle of ECP 700m of the coast, from SRM

In Figure 2.6, the computed east-west current velocities are shown. The influence of the monsoon is visible as the currents increase in strength from December to February. The maximum depth averaged velocities have been gathered from the SRM model and are shown in Figure 2.7. They increase very rapidly in the first kilometer offshore. From the figure it becomes clear that the maximum eastward velocities are stronger than the maximum westward velocities. The velocity depth profiles near the shore and in the middle of the strait are shown in Figure 2.8.

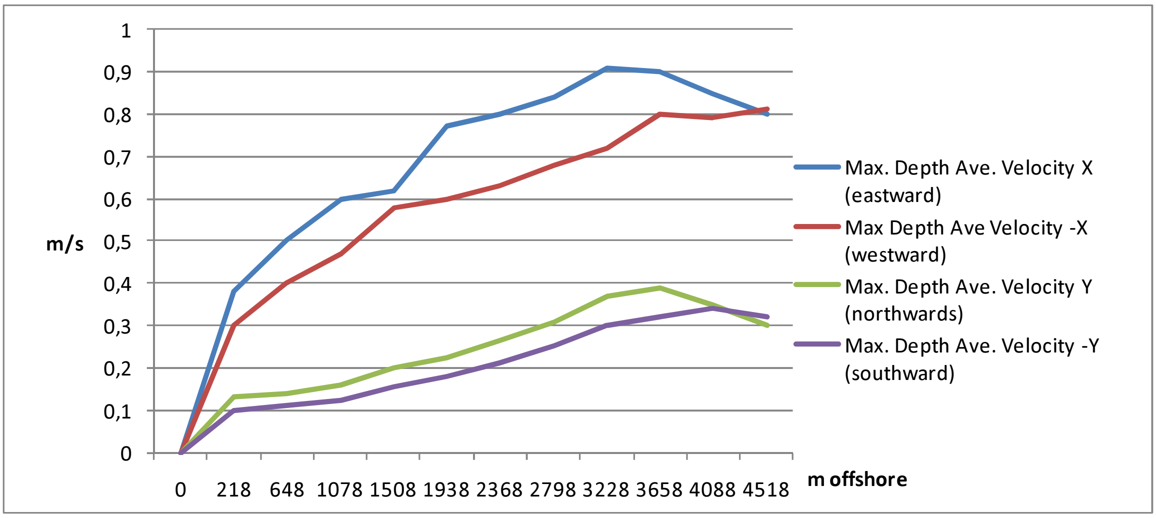


Figure 2.7 | Maximum depth average velocity from the coast into the strait of a one year tide (2004)

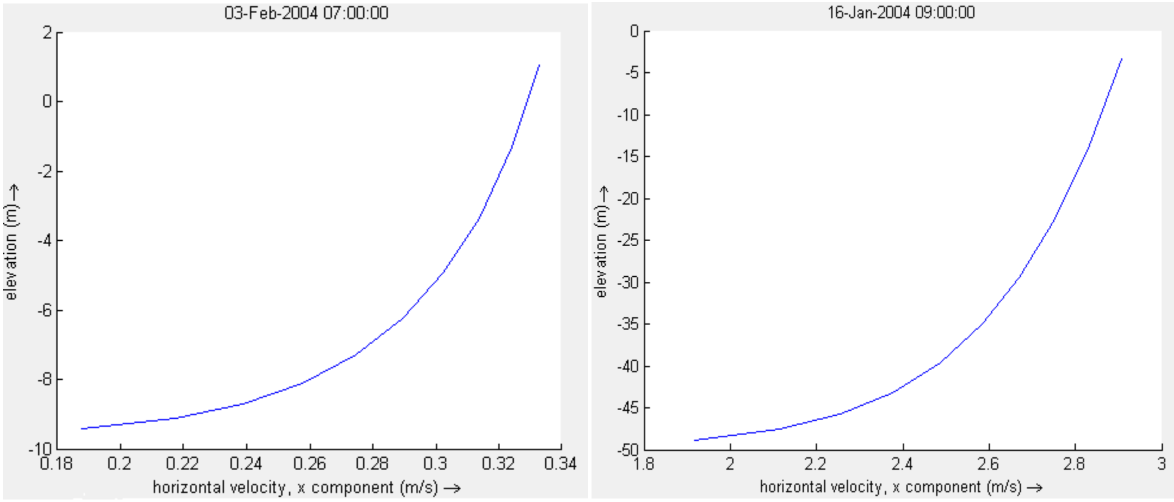


Figure 2.8 | Horizontal depth velocity profiles nearshore and in the middle of the Strait, from SRM.

The mean discharge in the strait (measured in both directions) is 2.52*10^5 m^3/s. This adds up to a total discharge of 7947 * 10^9 m^3 per year (going in both directions). The annual cumulative discharge to the west is 2500 * 10^9 m^3. This is roughly 31% of the total annual discharge which means that there is a net discharge of 31% directed westward.

Waves

ECP is exposed to four types of waves, namely wind, swell, ship and storm waves. Storm waves are induced by local typhoons.

<u>Wind and swell waves</u>
The southern coast is subjected to the impact of waves coming from the South China and Java Sea. The fetch of these waves however is limited by a number of Indonesian islands that reduce it up to 20-50 km. The maximum significant wave height at the east coast is 0.6 m nearshore (Burt, 2004). This is in accordance with the wave measurements carried out at ECP (refer Appendix C.3). A nearshore wave rose of ECP is shown in Figure 2.9. This figure includes both wind and Swell waves.

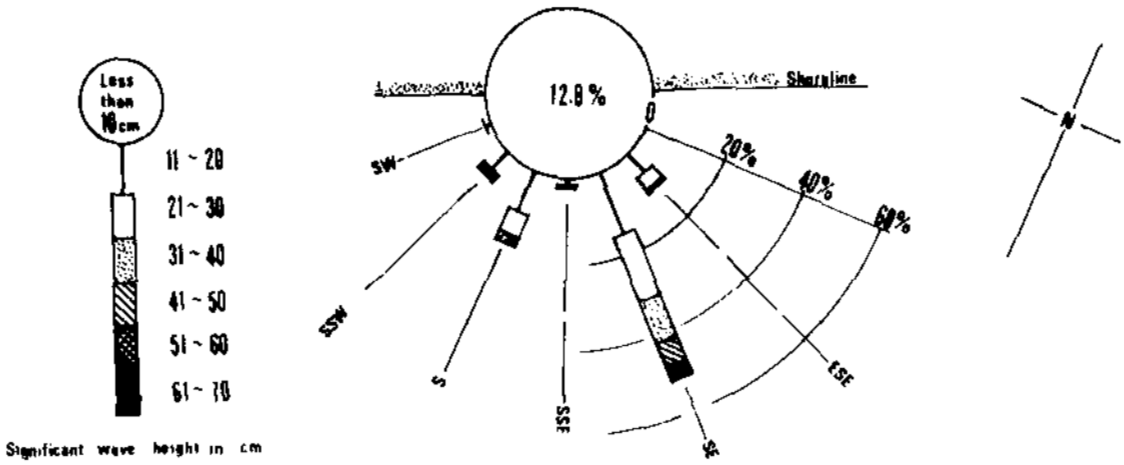


Figure 2.9 | Frequency of occurrence of various nearshore significant wave heights (Swell and Wind) at ECP, from (S.Y. Chew, Beach Development Between Headland Breakwaters, 1974).

Swell waves are generated by the northeast monsoon storms in the China Sea. These swell waves travel from the northeast to Singapore where they are refracted by the Malaysian peninsula, reaching the Singapore Strait from the east (Chew, 1974). Here they further refract and arrive at ECP from the southeast, see Figure 2.9. In Figure 2.9 the length of the bar represents the percentage of time the waves are from a certain direction and the shading corresponds to the different waveheights show on the left side of the figure.

Considering the data above and the low energy wind climate as described in paragraph 0, it can finally be concluded that wind waves reaching the southern coast of Singapore have a relatively small height and length and therefore have little influence on the coastal processes. Swell waves however do have influence, because they create the highest waves of about 1,1 m. The East coast is situated in a low energy wave environment and can therefore be classified as a protected sea environment (Davies, 1980)

<u>Ship waves</u>

About 133.000 vessels with a capacity exceeding 75 gross tons cross the Singapore Strait every year (Wolanski, 2006). Furthermore, about 90 ferries arrive and depart from Tanah Merah ferry terminal every day (Singapore Cruise Centre, 2011). Intense ship traffic can have a big influence on the local wave climate. This holds in particular for high-speed ferries as they can severely damage coastal environments (Kurennoy Dmitry, 2010).

Ship waves from ferries with average speeds of 14.1 m/s (27.5 knots) (which are present in the Strait) produce primary and secondary waves with mean wave heights of 0.8 m and a period of 10-15 seconds. The maximum wave height is 1.5 m (Kurennoy Dmitry, 2010). Large cargo vessels produce large primary waves up to 0.5 m with periods of about 69 seconds (M. Schroevers, 2010). These waves can travel over large distances and therefore easily cross the 7 km from the navigational channel to ECP. The ship waves could be included in model runs to check whether they contribute to the erosion of the designs and whether a sheltered wave environment is created behind the designs.

Table 1 | Highest ship waves (M. Schroevers, 2010), (Kurennoy Dmitry, 2010)

Waves at ECP	Ship wave heights	Periods
Cargo vessel	0.5 m	69 sec
High speed ferry	0.8-1.5 m	10-15 sec

Extreme conditions

Extreme events such as high storm surges, waves or tsunamis are rare in Singapore. This is mainly due to the sheltered location of Singapore, see 0. The winds at 1° north are mild and the shallow Sunda Shelf, with water depths ranging from 100 – 200 m, induces friction.

A tsunami of different causes can reach Singapore in some cases, but the wave height will be reduced. A tsunami due to an earthquake can definitely reach Singapore, but the wave height is very low. The closest fault line is located at the Sunda Arc in the Andaman Sea, which is 600 km from Singapore. The journey to Singapore reduces the wave height to 0.5 m due to spreading, friction and diffraction (Asia One News, 2011). An earthquake at the Manila Trench would result in a tsunami with a wave height of less than 0.4 m in the Singapore Strait (Ha et al., 2009). A tsunami due to a landslide, iceberg or meteorite can occur closer to Singapore, but the probabilities of occurrence are very low (Asia One News, 2011). A tsunami due to the collapse of an ice berg is not of importance in the tropical waters of Singapore. Neither is a tsunami due to a volcanic eruption. Not even the eruption of the Krakatau volcano in 1883 (the biggest bang in history), located at 850 km from Singapore, produced severe wave conditions near Singapore. This can be contributed to the sheltered location of Singapore (Choi et al., 2003).

A typhoon (tropical cyclones) can form near Singapore. In 2001, the tropical cyclone called Vamei formed and made landfall 60 km north of Singapore (Xin, 2010). It is approximated that a tropical cyclone near Singapore has a probability of occurrence of once in 100 to 400 years (Chang, 2003). The storm surge levels of the cyclone are in the same range as the tidal difference at ECP. In the worst case scenario of a cyclone near the Singapore coast, the surge levels are 1.6 m (Xin, 2010). Coinciding with high tide, the surge levels could range up to 2.8 m above mean sea level (Xin, 2010).

2.1.3 HUMAN INVERVENTIONS AROUND SINGAPORE AND EAST COAST PARK

Human intervention has a significant impact on the coastal environment of Singapore. This paragraph treats both the history of land reclamation in Singapore as well as the breakwaters which were constructed at ECP.

Only 3 km^2 of land were reclaimed in Singapore until 1959 (Engineers, 1986). Since 1965 Singapore has extensively been dredging and reclaiming land. In 2003, the area of reclaimed land was 93 km^2, which corresponds to 17% of the original area (538 km^2) of Singapore in 1965. Especially large areas of reclaimed land have been used for housing, air- and seaports, maritime and petroleum industries and recreational parks. Some large projects are the South-East Coast, Changi, Tuas, Jurong, Sentosa, Pulau Ubin, Pulau Tekong and the Pasir Panjang reclamation (Burt, 2004).

Landfill sources for the reclamations were earth from leveling land, dredged sand from Malaysia, Indonesia and Vietnam, marine clay and construction waste and material obtained from the construction of the underground Mass Rapid Transport system.

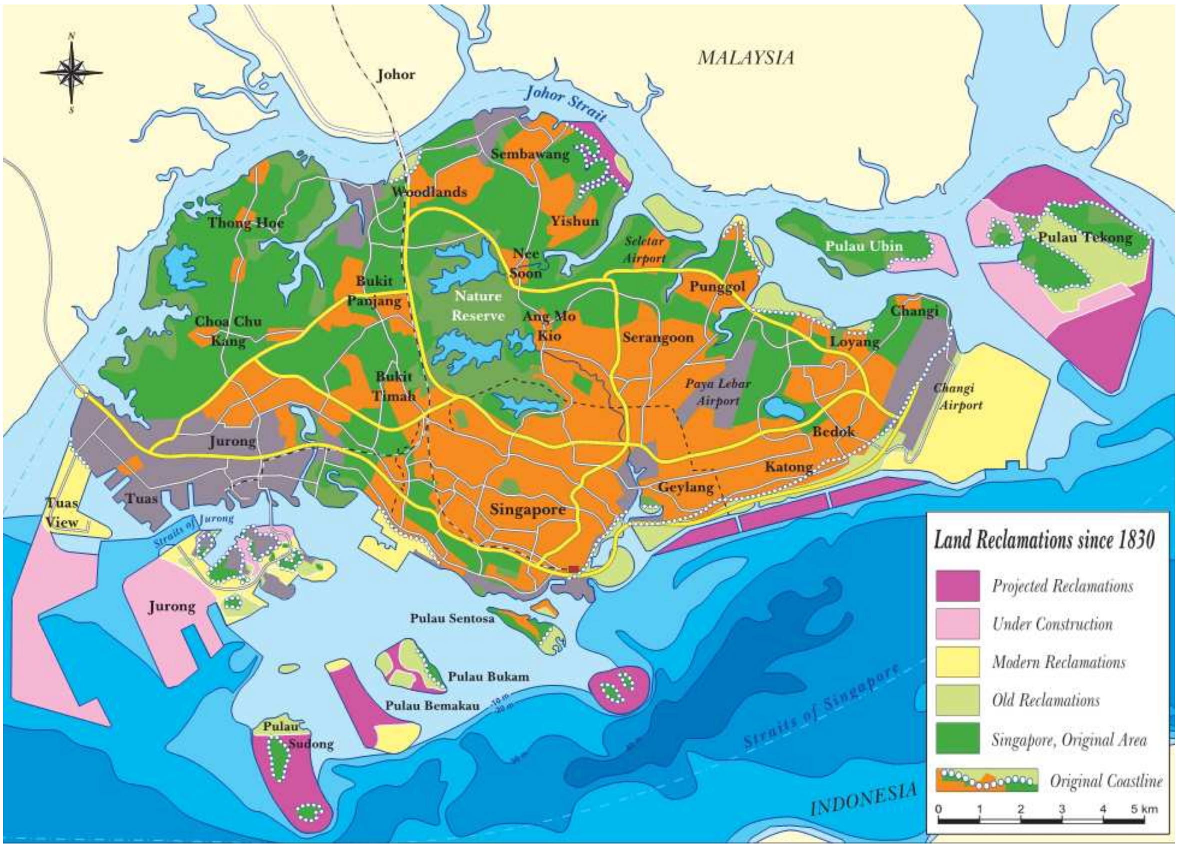


Figure 2.10 | Reclamation in Singapore (Waterman, 2008)

The South-East Coast is reclaimed from 1965 to 1976 by the Housing and Development Board (HDB). From the east of the city centre up to Changi, about 1525 hectares of land were added (Burt, 2004). Most of the landfill came from the leveling of the hills of Bedok and Tampines. The reclamation was carried out in 7 phases. To keep the reclaimed material in place, headland breakwaters were used, constructed from gabions and rip rap (S.Y. Chew, Beach Development Between Headland Breakwaters, 1974).

2.1.4 SEDIMENT CHARACTERISTICS

The current coast consists of both soft (mud) and hard (sand) sediments. The sea bottom at ECP is founded by the Kallang Formation and Old Alluvium. Soft materials prevail in both soil types. The Kallang formation consists of marine clay layers, where the average grain diameter doesn't exceed 0.002 mm. It may contain up to 40 m of clay and silt (Ting, 2002). The Old Alluvium is built up of a mixture of sand, silt and clay layers with an addition of organic materials. The diameter of grains in the later formation varies from 0.002 to 4 mm (pebbles of 40mm diameter are also found). Investigation of Atterberg limits shows that both formations consist of minerals such as kaolinite, illite, smecite and quartz (old alluvium). ECP was reclaimed during the 1970's. The foreshores are therefore covered with sand of a median grain diameter ranging from 0.63-0.76 mm.

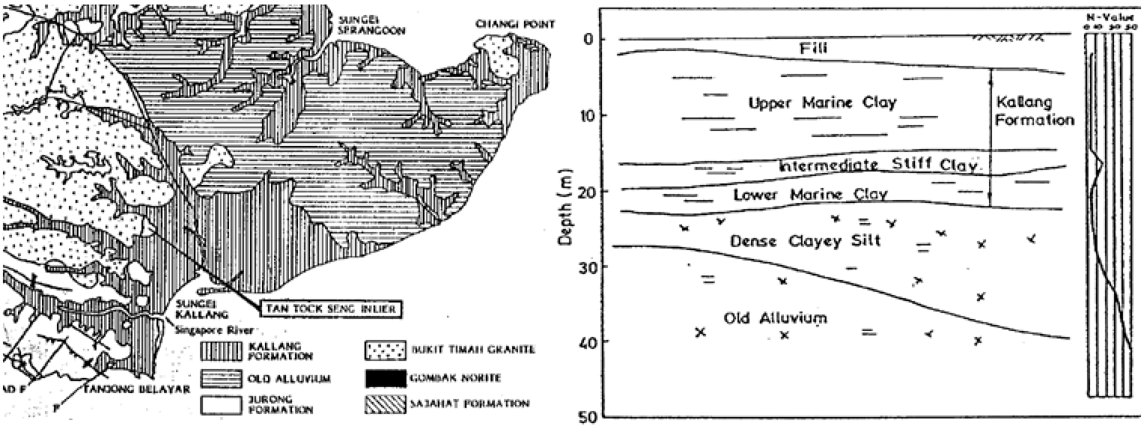


Figure 2.11 | Geological map of Singapore, from (Pitts 1984b) and the Kallang formation bottom profile, from (Ting,2002)

Conducted site investigations support the information that has been found in literature. During the survey it was found that the location of the transition from the sand at the beaches to the original cohesive sediments seemed to differ a lot. At the east side of ECP the transition was found to be further than 150 m offshore, while in front of the McDonalds the transition was found to be located at 10 m offshore. For further reading on sediment characteristics, the reader is referred to Appendix E.

2.1.5 COASTLINE AND PROFILE DEVELOPMENT

This chapter discusses the coastline development at ECP taking into account both the longshore and cross-shore sediment transport processes.

Coastline retreat

The media in Singapore has been reporting about the soil erosion at ECP since 2004:

Tan May Ping in 2004 at Habitatnews.nus.edu.sg: *'But Mr. Teh Tiong Sa, a geomorphologist (someone who studies the evolution and configuration of landforms) said it's only natural that erosion occurs, especially in areas that have been reclaimed and are not protected from the waves.'*

The Straits Times at 6 March 2006: *'This could be because the height and force of the waves have been greater than anticipated. 'In areas, the waves could have gone over or around the breakwaters, causing portions of the beach directly behind these structures to erode,' said Prof Tan. 'This is something that was quite unexpected.'*

The average erosion rate without human intervention at ECP is approximately 1 m/y. There are even spots with an erosion rate higher than 1.3 m/y (Raju, 2010). There are several vulnerable spots, which especially erode fast during storm events. The picture in Figure 2.12 was taken during the survey on the 30th of August. In 2006 a sign has been placed on the ECP beach front to warn for an unstable coastline (refer Figure 2.13).

Figure 2.12 | Erosion at The east side of East Coast Park on the 30th of August 2011

Figure 2.13 | A sign with 'Please keep away from unstable coastline', warns for an unstable coastline at ECP in March 2006, photo taken by SengKang (Wikipedia, 2011)

Cross-shore transport and profile development

If a cross-shore beach profile is steeper than the equilibrium profile, it is not stable. In case of coastline retreat, the sand from the upper foreshore is redistributed to the lower foreshore.

In accordance to both the rough hand calculation of the equilibrium profile and the measurements of the beach profiles at ECP, it can be said that the slope of the cross-shore beach profiles at ECP seem gentle enough to be stable according to the Bruun's rule, however they are not. The current cross-shore profile is slightly concave (Raju, 2010). The slope of the current profile is in the same order of steepness as the equilibrium profile of a grain with a grain size of 300 micrometer. As the equilibrium profile of the big nourished grain diameter of the beaches at ECP is steeper than the beach profiles derived from the navigational map of the Singapore Straits (Figure 2.14 and Figure 0.3 of the appendix), it can be concluded that the slopes are stable.

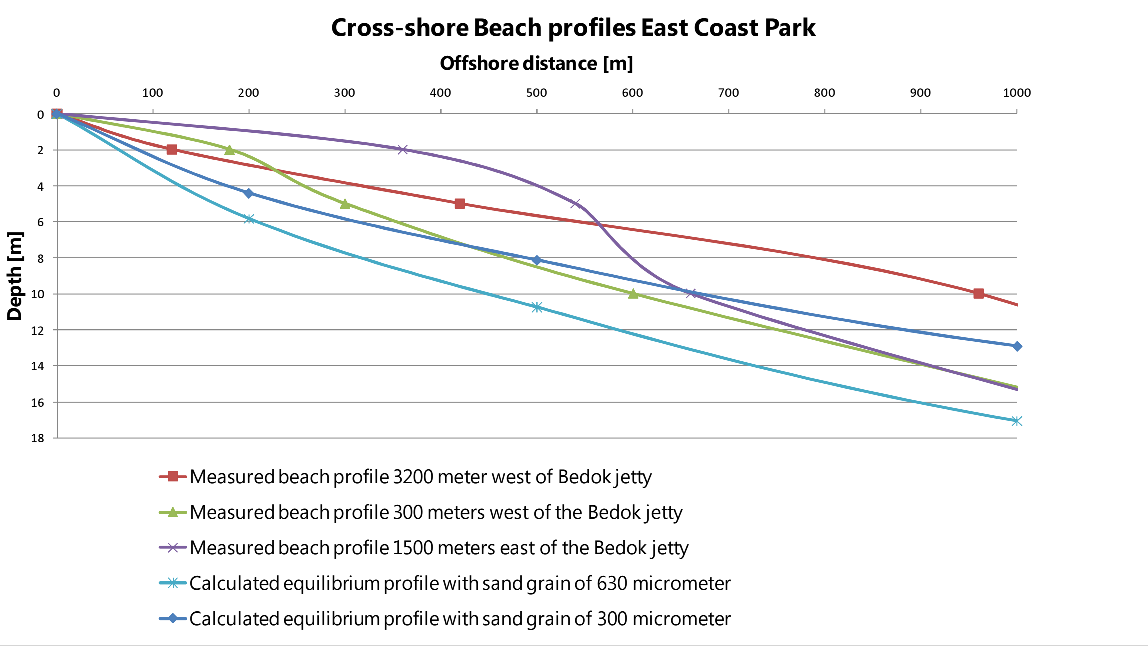


Figure 2.14 | Cross-shore beach profiles at ECP, an overview of the location of the cross-sections can be found in Figure 0.3 of the appendix

The equilibrium profiles are based on the Bruun's rule, which relates the water depth *h [m]* to the offshore distance x' [m] by using a dimensional constant A [$m^{1/3}$] and an exponent m [-]:

$$h = A * (x')^m$$

The factor A is determined by the fall velocity which is based on the grain sizes. A larger grain size implies a larger value of the factor A which leads to a steeper profile.

Another phenomenon transporting sediments in cross shore direction are the currents in combination with the groynes and breakwaters. This interaction generates current induced large scale turbulent eddies (characteristic length scale of 10 – 20 m), which can transport sediment in cross-shore direction (Figure 2.15).

Figure 2.15 | Top view of the left side of ECP, from Google Earth

A run of the SRM also shows that the semi-diurnal tide from the Indian Ocean and the diurnal/mixed tide from the China Sea meet in front of ECP at flow reversal creating large eddies just in front of ECP, which could explain additional cross- and longshore transport.

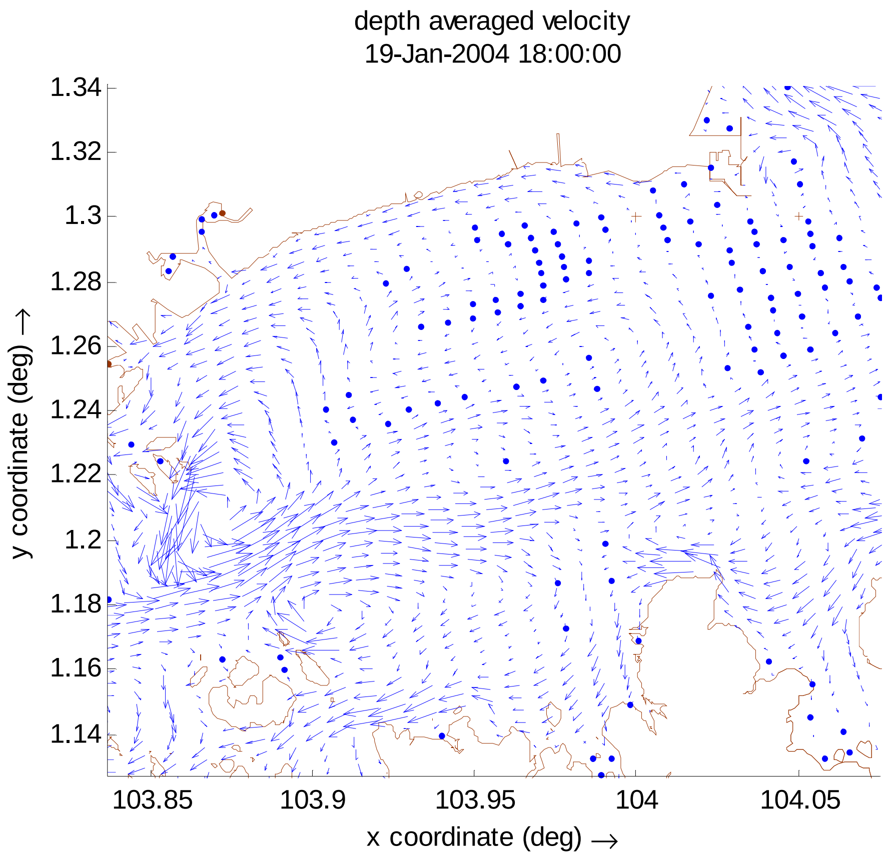


Figure 2.16 | Flow reversal at ECP on 19 January 2004, from SRM

Longshore transport and coastline changes

The coastline changes induced by gradients in the longshore sediment transport can either be caused by waves, currents or a combination of the two. This section will treat these cases separately.
It is difficult to estimate longshore sediment transport rates by looking look at the accretion volume updrift of a jetty or groyne in a certain time period due to all the interventions and the non-availability of detailed satellite pictures and data.

Longshore sediment transport induced by waves

The predominant wind direction from the southeast at ECP develops a longshore sediment transport to the west (S.Y. Chew, Beach Development Between Headland Breakwaters, 1974). The wind, swell and ship waves create a stirrup effect in the narrow breaker zone near the beach. The CERC equation for straight parallel depth contours gives an indication for the bulk longshore sediment transport that is transported in the breaker zone:

$$S = \frac{K}{32(s-1)(1-p)} c_b \sin(2\phi_0) H_0^2$$

This formula served as a rough hand calculation to estimate the wave-induced sediment transport along ECP. During the calculation, wave heights smaller than 0.20 m have been neglected.

There are 3 different wave angles of incidence along the coast as compared to the governing wave direction; 33°, 29° and 11° (refer Figure 2.17). The closer the angle of incidence is to approximately 42°, the larger the longshore transport will be, as the maximum is found at this angle. The yearly averaged wave-induced transport along the east coast is 0.002 m^3/s at an angle of 29° and 0.0007 m^3/s at an angle of 11°. This induces a gradient in the wave-induced longshore sediment transport. This implies that sediment would accrete at this transition. The same holds for the transition of 33° to 29°.

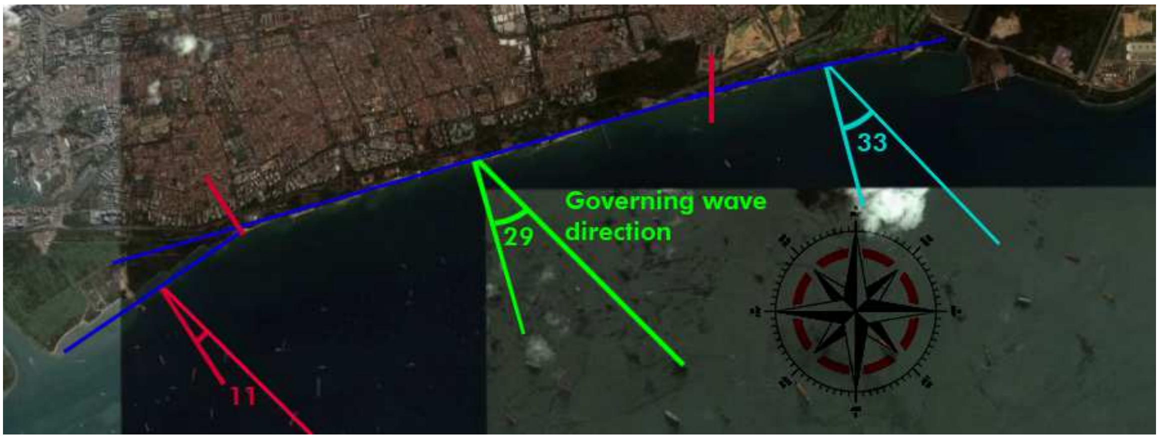


Figure 2.17 | Wave angles along the east coast

Longshore sediment transport induced by currents

Sediment transport is determined by two governing sediment transport forms. The eastward sediment transport is induced by the tidal asymmetry (larger eastward velocities). The tidal asymmetry has more influence on coarse sediment than on fine sediments, because of the difference in peak velocities. The westward sediment transport is induced by the residual flow caused by both the tide and the monsoons (total yearly averaged discharge). These residual currents mainly transport fine sediments, as fines do not respond directly to the flow (non quasi steady).

The longshore sediment transport formula by (van Rijn, 2001) could be used to calculate the combined current and wave induced transport. This formula however turned out to be too sensitive for small changes in depth, wave height and flow velocities.

Breakwaters at east coast park

The breakwaters along ECP were used during the construction of the East Coast park land reclamation by reducing the wave and current action during the reclamation (S.Y. Chew, 1974). Furthermore, the breakwaters were supposed to create tombolos and retain the sediment in between the coastal cells. At present however, ECP is eroding and as ECP is quite popular, the government decided to maintain the coastline by nourishing the beaches.

In the past, a comprehensive study with numerical models and experiments has been conducted to model the static and dynamic stable beaches between the breakwaters. Equilibrium states were found with the wind-wave model MIKE21 and GENESIS. Currents have not been included in the modeling of ECP (Prof. NJ Shankar, 2002), which could explain that the design of the breakwaters was not sufficient for the wave action.

Bricio defines characteristic conditions for the development of salients and tomobolos (Bricio, 2008). The development of these structures in the sheltered area behind the breakwaters is in agreement with the ratio of L (length of the breakwater) over D (offshore distance breakwaters). For salients, $\frac{L}{D}$ has to be between 0.5 and 1.3. For tombolos $\frac{L}{D}$ has to be greater than 1.3. To prevent erosion the gaps must satisfy $\frac{L_{gap}}{L} < 1 - 1.5$.

Where salients developed at ECP, the characteristic value of $\frac{L}{D}$ is in between 0.5 and 1.3. This means that they were not well designed to become a tombolo. Tombolos developed at spots where the ratio $\frac{L}{D}$ was bigger than 1.3. The characteristic value of $\frac{L_{gap}}{L}$ is in the range of 3-5 at ECP. Together with the unavailability of sediment, this is the reason why tombolos did not establish everywhere.

Possible reasons for the coastal retreat at ECP

The process of sediment transport consists of a combination of wind, swell and ship waves stirring up the sediments and currents transporting them. Although the waves do not create a significant current along the coast, waves do create large bed shear stresses when breaking on the beaches stirring up the coarse-grained sediment. As the breaker zone is located very close to the shore, the sediment would be retained between the breakwaters at ECP. This material however is transported offshore due to wave undertow, current induced turbulence created by the groynes and breakwaters and the large scale eddies that form during flow reversal. When the sediment reaches out further offshore, the sediment is transported by the main currents to the east and west.

The main reason for erosion is the non-availability of coarse-grained sediments in the water column as there is no updrift supply of coarse-grained sediments to the beaches. Also, the east coast does not interact with the Johor Estuary anymore. The sediment is able to flush out of the coastal cells but is not fully compensated by updrift supply. This creates a retreat of the coastline.

There are several other factors contributing to the erosion. Before the major reclamations at ECP, there used to be a coral reef in front of the coast (refer paragraph 2.2.4). This reef reduced the wave conditions, creating a sheltered area at the east coast of Singapore. It also supplied some sediment to the system. This reef is no longer present. Furthermore, sea level rise and land subsidence induce a retreat of the coastline on the longer term. Lastly, the characteristic land forms of the tide-dominated east coast of ECP are not in accordance with the current uninterrupted and straight coastline (refer 2.1.1).

There are several erosion hotspots along the coast of ECP (refer Figure 0.4). This is a common phenomenon on eroding coastlines, but the reasoning behind it is not clear (J. Bosboom and M.J.F. Stive, 2011). The hypothetical explanation for these erosion hotspots at ECP is the variable bathymetry which causes energy focusing of waves. This seems to be quite apparent for the erosion spot near the McDonald's, but does not directly hold for the other erosion hotspots.

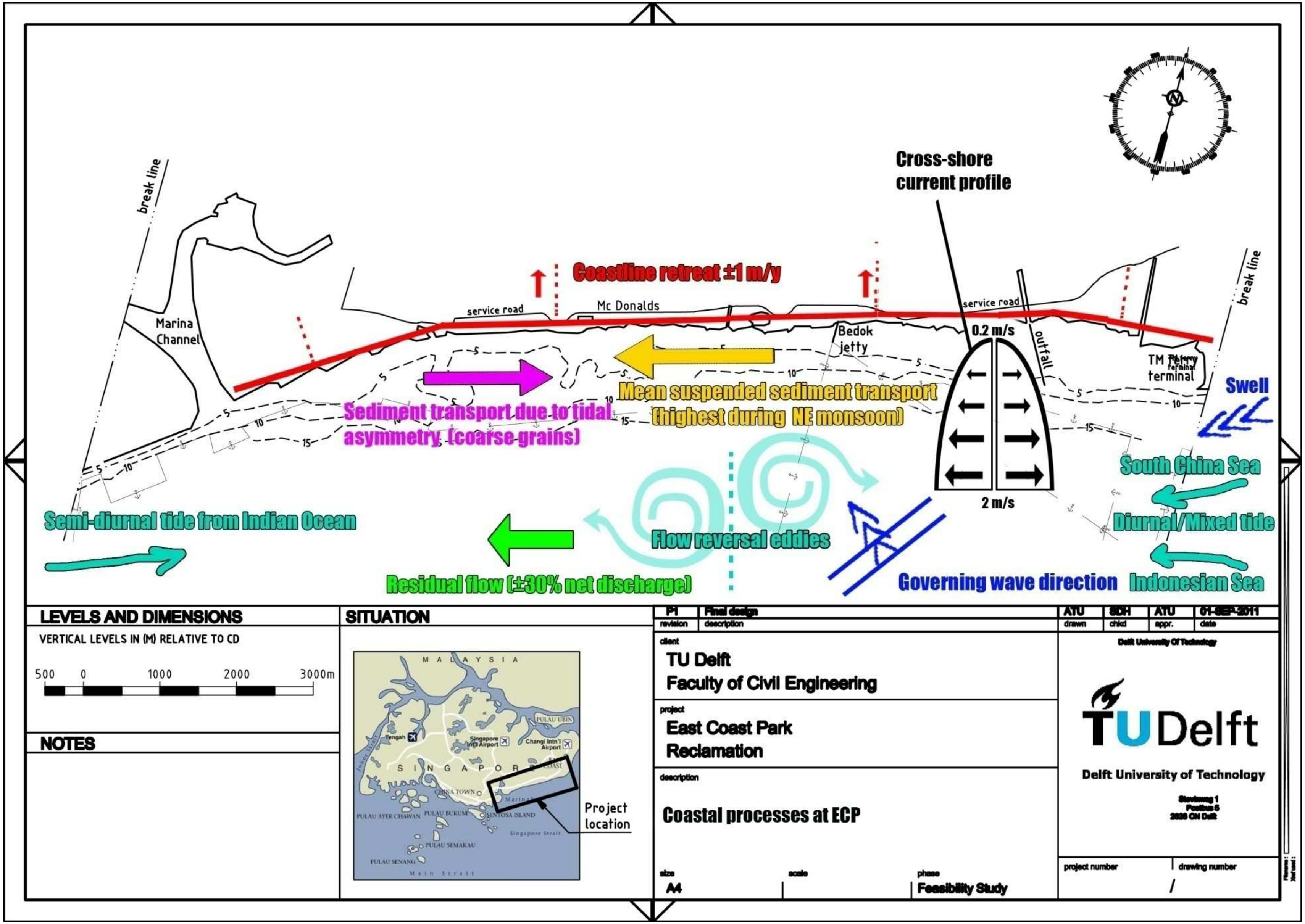


Figure 2.18 | Overview of processes influencing the Coast of East Coast Park

2.2 ECOLOGICAL SYSTEM

Seagrasses, mangroves and coral reefs provide many environmental services; whole ecosystems are even called after them. These species 'directly or indirectly modulate the availability of resources to other species, by causing physical state changes in biotic or abiotic materials. In doing so they modify, maintain and create habitats' (Jones, 1994). They provide shelter from waves and currents, contribute to the primary production and stabilize the seabed.

These 3 ecosystems that are included in the designs are described in paragraph 2.2.1 (mangroves), 2.2.2 (sea grasses) and 2.2.3 (corals). This section concludes with paragraph 2.2.4, describing the development and situation of these coastal ecosystems in Singapore and what conditions they require.

2.2.1 MANGROVES

Mangroves are tropical intertidal trees which are frequently inundated by the tide (Figure 2.19). They can deal with salty and muddy environments. Mangroves are exclusively tropical (Hogarth, 2007). These trees have seeds which are produced annually in large numbers, which flow to new sites for colonization (Lewis III, 2005).

Figure 2.19 | Mangrove forest at the West coast of Peninsular Malaysia (Hogarth, 2007)

Despite of some successful mangrove restoration projects, most of the attempts fail (Erftemeijer, P. L. A., and R. R. Lewis, 2000). There was a successful forestation of mangroves in Bangladesh of over 1600 km^2 on accreting mudflats in Bangladesh in order to provide land that was sufficiently stabilized to be used for agriculture.

Mangrove ecosystems have both ecological and coastal protection values (Vos, 2004). Mangroves serve as coastal protection by reducing wind and hydrodynamic loads. The forests attenuate waves by both bottom friction and the interaction of wave motion with mangrove vegetation. Mangroves reduce the magnitude of tidal currents as such mangroves

may fulfill the purpose of coastal protection during storm surges and typhoons (Vos, 2004). Furthermore they trap sediment and stabilize the bed.
The dynamics of sediment in between mangrove trees is far from being understood. Tidal currents, wave action, river flow, salinity gradients and the topography of mangrove habitats all interact and affect sedimentation in various complex ways.

Besides serving as coastal protection, mangrove ecosystems are also a resource of food, medical products, vinegar and fuel. Mangroves support coastal fisheries for fish and shellfish, support wading birds, timber production for construction and both the chemical and medicinal industry (Lewis III, 2005).

2.2.2 SEAGRASSES

Seagrass meadows look like flooded grass fields even though they are more related to the water lilies. They have roots, leaves and horizontal underground stems. Seagrasses are found on tidal mudflats, in shallow sandy areas and in coral reef lagoons (CRC Reef Research Centre, 2004). Algae colonized the sea and are not the same as seagrasses. Algae do not have a root system, veins and seeds.

Figure 2.20 | Seagrasses at Pulau Semakau

In contrast to the Mangrove forests, seagrass meadows are found in both tropical, temperate and arctic regions. Most seagrasses are found in shallow inshore bays and estuaries up to depths of 25 m (McKenzie L. , 2008).

Seagrasses have various hydrodynamic and morphodynamic effects. They increase the roughness of the bed and thereby slow down currents, which leads to sedimentation (McKenzie L. , 2008). The roots stabilize the bottom which reduces the erosion.

Seagrasses are also important habitat and feeding grounds for organisms. They provide nursery area for fishes, prawn and lobsters. About 40 times more animals are found in seagrasses compared to sand bottoms (McKenzie L. , 2008).

2.2.3 CORALS

Coral is a type of animal that consists of a polyp with tentacles through which they feed themselves by catching food such as small plankton (Noyes, 2011). The coral lives in symbiosis with algae (zooxanthellae). These algae live in the tentacles, providing a good pH, oxygen and food through photosynthesis. The coral provides protection, CO2 and nutrients through its wastes to the algae. The coral secretes calcium carbonate in order to form a structure to protect itself. This structure grows approximately 1 centimeter per year.

Coral reefs develop in warm water usually near land in the tropics. Higher temperature causes the algae inside the corals polyps to die. Only the skeletons remain, causing the coral to appear white (bleeching coral). Although most of the corals exist in tropical shallow water, coral reefs are also found in temperate and even arctic regions.

Coral reefs are subdivided into 3 classes; fringing reefs, barrier reefs and atolls (refer Figure 2.21). These 3 types can be distinguished based on the development of a volcanic island in combination with the growth of a coral reef. The volcanic island sinks while the coral reef keeps on growing. A fringing reef grows directly from the shoreline. A barrier reef is separated from the shoreline by a channel or lagoon and an atoll is a reef without a central island.

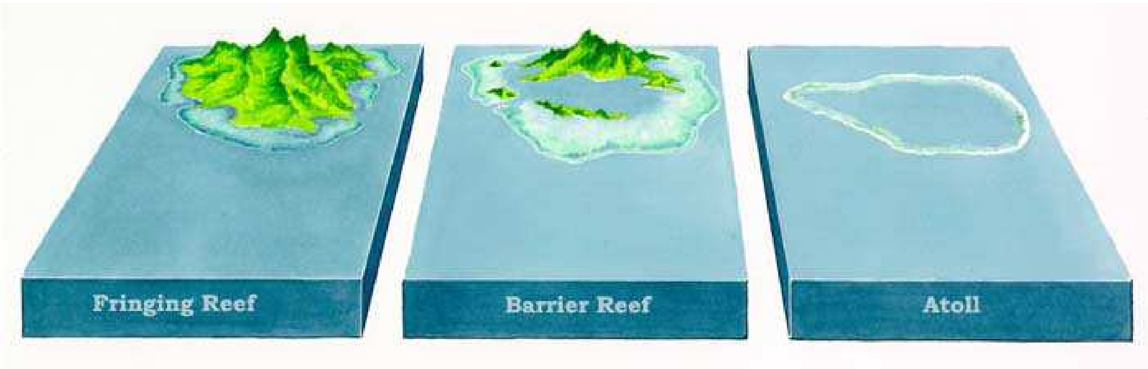


Figure 2.21 | The development of an volcanic island in combination with the type of coral reef according to Darwin (Fred H., 2008)

Coral reefs provide several services such as food, recreation and coastal protection (Moberg, 1999). Coral reefs dissipate wave energy and supply eroded coral material to the beaches. Having these characteristics, they actually create sedimentary sheltered environments. These environments are favorable for mangrove and seagrass ecosystems (refer Figure 2.22).

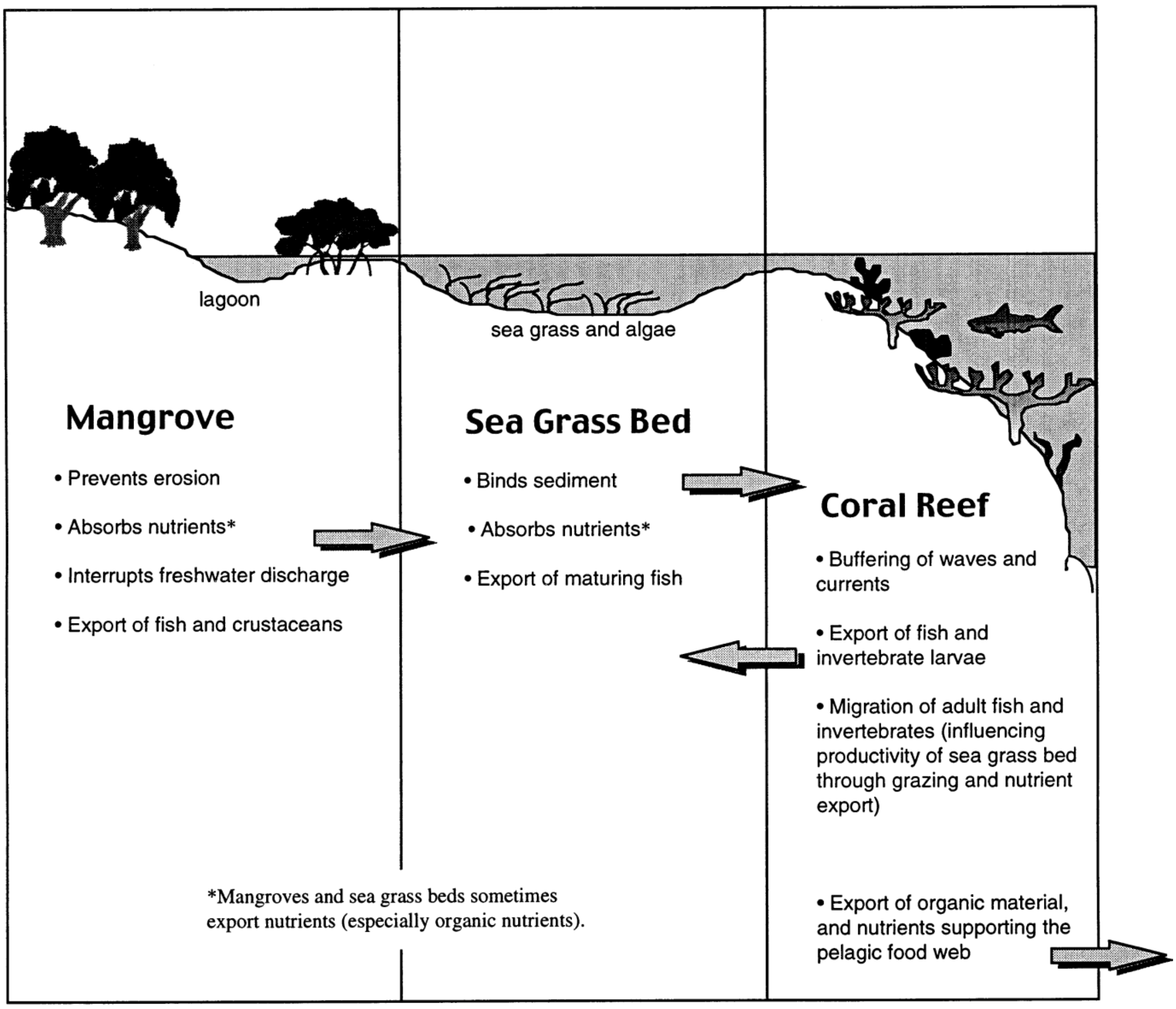


Figure 2.22 | Favorable effects of mangroves, seagrasses and corals on each other (Moberg, 1999)

When corals are removed from the coast, the erosion can be tremendous. The construction costs of replacement of declining coral reefs by an artificial breakwater in the Maladives were estimated to be US$ 12 000 000 (Moberg, 1999). In Bali and Lombok the destruction of corals led to land loss (Cesar, 1996). Measures which were needed to prevent coastal erosion in Indonesia were estimated to cost up to US$1 000 000 per km of coastline (Cesar, 1996).

Coral reefs also provide many ecological services such as spawning, nursery, breeding and feeding grounds for organisms. Reefs are very attractive for recreation. Corals also sustain people who live nearby such as fisherman and people who depend on recreation.

2.2.4 DESCRIPTION OF COASTAL ECOSYSTEMS IN SINGAPORE

Singapore's low-lying tropical coasts used to provide fruitful grounds for a diversity of habitats (Singapore Biodiversity, 2011). The ecosystems in the whole world and specifically in Singapore had to deal with the growing impact of humans such as pollution (sewage, chemicals and garbage), overfishing, overharvesting, coral mining, physical damage by tourists and ships, alteration of the coastline by humans, increased turbidity and sediment concentrations in the water and river changes (dams and irrigation).

At many locations in Singapore, the original coasts have been replaced by vertical or steeply sloped sea walls. Sea walls can extend the reclamation boundary to deeper waters, but they do not provide an intertidal zone. The intertidal zone is the area that is above water during low tide and inundated during high tide. Reclamation also had a tremendous impact on the local waters and ecology. The turbidity has increased and the current water visibility is about 2 m while it used to be 10 m in 1960.

Although highly modified, the coast still accommodates a richness of species. The original ecosystems have been replaced by new ones. Despite of the vertical character of the sea walls, they do offer niches which support biodiversity. The reclaimed land in the west of Singapore (Tuas) hosts a rich diversity of marine life.

Mangroves in Singapore

In early Singapore, mangroves area is estimated at 7500 ha (Corlett, 1991). This area reduced to 491 ha in 1993 (M.J. Hilton & S.S. Manning, 1995). Figure 2.23 visualizes these losses, which are caused by coastal development, urbanization, land reclamations and because of the damming of former rivers during the creation of several reservoirs in Singapore.

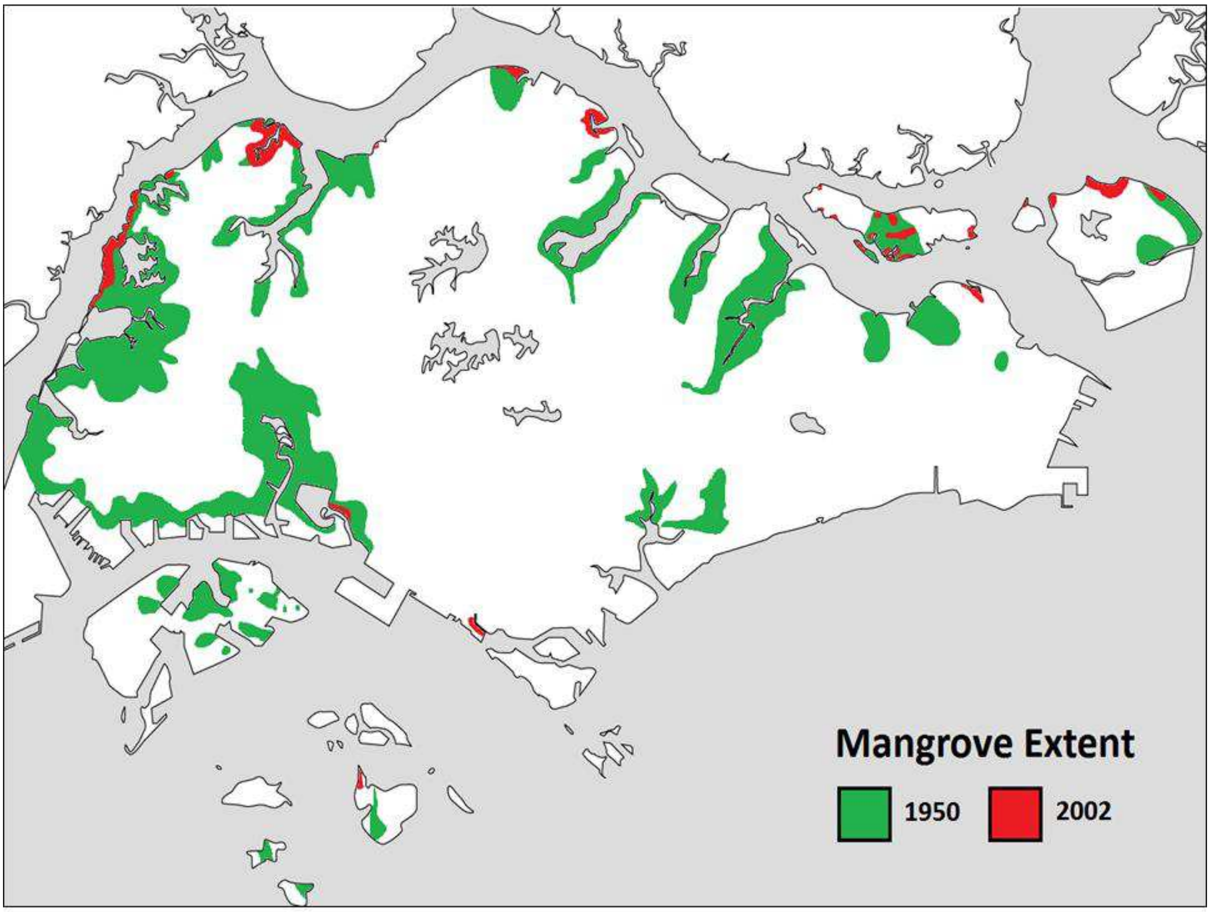


Figure - estimated mangrove loss in Singapore from 1950 to 2002
Sources: Ng & Sivasothi (1999), Daniel Friess *unpublished data*

Figure 2.23| Estimated mangrove extent in 1950 and 2002

Current mangrove patches around Singapore vary from 2 - 85 ha. The smaller mangrove forests size ranges from 2-20 ha (Daniel A. Friess, 2011). It is not known whether they are stable or not. It is known that a patch of 20 ha is dying at the moment (Friess, 2011). In the Johor Estuary in Malaysia, the minimum patch size is 15 ha (International Center for Living Aquatic Resources Management, 1992).

Although there are great losses, there are also successful restoration projects in Singapore (see Table 2).

Table 2 | Successfully restoration of Mangrove forests in Singapore (Singapore Biodiversity, 2011)

Year	Location	Restored area
1988	Pasir Ris Park	20 ha
1989	Sungei Buloh Nature Park	85 ha
1999	Pulau Semakau	13 ha

Pulau Semakau and Pulau Sakeng were two small islands 8 km south of Singapore. They were joined by a landfill from 1995 – 1999. The purpose of the island was the storage of the remaining ashes from waste incineration and non-incinerable wastes. Thirteen hectares of mangroves were replanted to replace the old, which were removed due to the landfill (Singapore Biodiversity, 2011). The combination of a landfill and the establishment of replanted mangroves had to be done with careful engineering, using different types and layers of geomembrames and geofabrics. New mudflats were created which covered 13 ha needed for the mangrove forests. These biological mitigations cost money, more than a simple landfill would have. But as it turned out much later, this was well worth the investment, because they established very well. Pulau Semakau is sheltered from waves and currents by surrounding islands, which create a sheltered environment. The Strait is wider at this point, which reduces the currents compared to ECP.

Seagrasses in Singapore

Stamford Raffles mentioned that dugong (an animal which heavily depends on the availability of seagrass) meat was frequently available in the markets. This shows that there must have been large seagrasses fields in early Singapore. Sea grass and mudflats disappeared fast during the development of Singapore (Burt, 2004).

The mapping of the seagrass distribution in Singapore is limited and the total area of seagrass is not known (McKenzie L. Y., 2007). The bigger seagrass habitats in Singapore are found on intertidal flats such as Cyrene Reef (60 ha), Pulau Semakau (100 ha) and Chek Jawa (50 ha) (Singapore Biodiversity, 2011). Smaller seagrass patches are found at Tuas, Labrador and Sentosa (Seagrass-Watch HQ, 2011). Just eastward of Marina reservoir a parallel breakwater has been constructed. Due to the resulting reduction in hydrodynamic energy a mudflat developed on which seagrass established.

A seagrass area is present near the Tanah Merah Ferry terminal. A seawall has been constructed there to protect the reclaimed land (Chia Lin Sien, 1989). The seawall is replaced by breakwaters along the rest of the east coast. A sandflat behind this seawall developed into a seagrass and coral area. A variety of species and marine life is present over here

(Tanah merah life behind the seawall, 2009), (Yaakub, 2011). Sheltered areas therefore have to be created at ECP in order for seagrasses to establish.

Figure 2.24 | Seawall with seagrass and corals at the Tanah Merah Ferry Terminal, from Google Earth.

Coral reefs in Singapore

Singapore used to have over 60 offshore islands with fringing reefs and several patch reefs. Most of the reef flats of the offshore islands have disappeared during the reclamations. The main island of Singapore had several fringing reefs until 1970 (Singapore Biodiversity, 2011). There used to be a lot of coral at East Coast Park itself (Sin, 2011). During the land reclamation, the coral disappeared.

Sixty percent of the original coral reefs in Singapore have directly been s
mothered due to coastal reclamation (Singapore Biodiversity, 2011). The rest is continuously exposed to increased turbidity by the reclamation works. Dredging navigation channels and dumping earth on the sea bottom also affects corals. Besides direct smothering, the increased sediment impact reduces sunlight penetration, reducing the growth of symbiotic algae (Singapore Biodiversity, 2011). Nowadays there are no alive corals found beyond 6 m water depth in Singapore, while they used to be found until a water depth of 10 m in 1970 (NUS Reef Ecology Study Team, 2011).

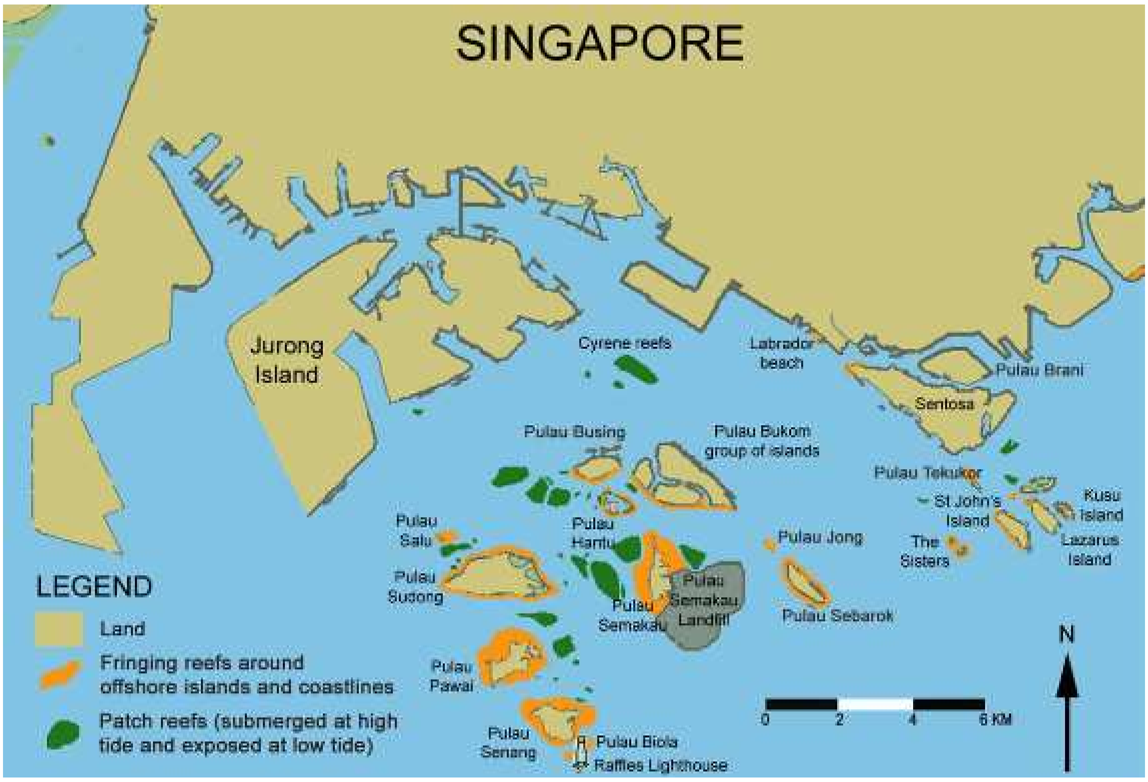


Figure 2.25 | Coral reefs in Singapore (REST, 2011)

At present in Singapore coral communities, mainly exist on the southern islands and at Labrador Park, refer Figure 2.25. There are also some coral communities at East Coast Park. There is a larger community at the seawall near the Tanah Merah Ferry terminal (Sin, 2011). Coral has also been found at the Bedok Jetty in 2008 (Wong H. W., 2008) and at the hard revetment near the Marina Channel (REST, 2011). There are several artificial reef and reef restoration projects in Singapore. There is even a coral nursery at Pulau Semakau. Naturally fragmented corals grow at the nursery to enhance their survival and growth. More hard and bare substrates at ECP probably stimulate the establishment of coral.

2.2.5 BOUNDARY CONDITIONS INFERRED FROM THE ECOLOGICAL HISTORY OF ECP

From Figure 2.23 it becomes clear that there probably never has been a mangrove forest in front of the east coast, only in the Marina Bay. The reason is that there is no sheltering of waves and currents at the east coast, which is necessary for mangroves to establish (Friess, 2011). This implies that at least some of the habitat requirements of a mangrove forest need to be engineered. In the parts of Singapore where there is sheltering from waves and currents mangroves are or have been present.

There have been mangroves in the rest of Singapore. There have been a lot of coral reefs at ECP before the reclamation and there are still some in the eastern and western parts. This fact states, that the conditions are available to grow coral if hard substrata are available. The same conclusion holds for seagrasses. Moreover, sheltering has to be provided to grow seagrasses in front of ECP.

The water quality at ECP seems to be good enough to grow coral and seagrass, as some of these species are present at ECP. However the port traffic creates a large risk for ecology in terms of oil spills and pollution (refer 3.2). There are signs placed at Sentosa that warn for oil spills. Now and then there is oil found at the beaches. Mangroves are particularly sensitive to oil spills, but only if the oil is present in large quantities at the water surface, covering the aerial roots of the mangroves (IPIECA, 1993).

2.3 SOCIO-ECONOMICAL SYSTEM

This section includes a stakeholder analysis and describes the survey at ECP performed by the project group.

2.3.1 STAKEHOLDER ANALYSIS

This section gives an overview of stakeholders and their corresponding mission, interests and responsibilities.

Identified ECP Stakeholders are:

- BCA (Building and Construction Agency)
- HDB (Housing & Development Board)
- URA (Urban Redevelopment Authority)
- MPA (Marine Port Authorities) / SPA (Singapore Port Authorities)
- NEA (National Environmental Agency)
- NParks (National Parks Board)
- NGOs (Non-Governmental Organizations)
- Public

BCA

The BCA is responsible for creating a safe, high quality, sustainable and friendly building environment. The tools they have are building control, quality training, seminars, inspections on safe building design and the stability of slopes, green building legislation and guidebooks. The BCA is since 2008 responsible for the national planning of coastal management and helps the industry with the supply of landfill for construction purposes. An interview carried out by Ecoshape with the BCA revealed that they will apply “Building with nature” strategies if there is proof of long term sustainability. They have an interest in making hard revetments more natural i.e. stimulate the establishment of coral reefs (Bolman & Janssen, 2011).

HDB

The HDB has the aim to provide quality and affordable housing, vibrant towns, and living environments that focus on the human community. They are searching for new construction areas for housing, but they also develop recreational areas and facilities like at ECP.

URA

The URA is Singapore’s national land use, planning and conservation authority. In the concept plan 2001 additional land plans at ECP are mentioned.

MPA/ SPA

The mission of the MPA is to maintain the port of Singapore as a global hub. They are protecting Singapore's strategic maritime interests. Everything that is being constructed in the waters surrounding Singapore is subjected for permissions to the MPA. All restrictions concerning navigational channels, mooring areas and construction in the marine environment are their responsibility. Construction has to stay clear of the navigational and mooring areas. They can provide construction materials from maintenance dredging.

NEA

The NEA protects the air, land and water resources in Singapore, ensures public health and makes environmental policies. They manage offshore landfills for waste material, where they have experience with coral growth on the barriers surrounding the landfill. They have an interest in enhancing the biodiversity in their marine infrastructural works (Bolman & Janssen, 2011).

NParks

NParks is enhancing the green environment of Singapore and manages 50 major parks and 4 nature reserves in Singapore. One of them is ECP. Furthermore NParks tries to sustain Singapore's biodiversity and tries to improve the landscape industry. They have several nature rehabilitation projects running e.g. 'the coral nursery project' and coral and sea grass surveys. One of the sub clusters of NParks is the National Biodiversity Reference Centre (NBRC). They collect data about the biodiversity around Singapore and represent NParks as the Scientific Authority on Nature's conservation. They have the most up-to-date information about biodiversity in Singapore. NParks is the policy maker for biodiversity; eco-dynamic engineering initiatives must comply with their rules and regulations. NParks is interested in the “Building with nature” principle and their applications in the coastal zone (Bolman & Janssen, 2011).

NGOs

Three relevant NGOs for the support of eco-engineering are the Singapore Environment Council (SEC), the Nature Society Singapore (NSS) and Blue Water Volunteers (BWV).

The SEC aims to be a partner for sustainable city development in Singapore. They want to set new standards for the sustainability of urban development, conserve biodiversity in Singapore and empower people to a greener lifestyle. The NSS is putting effort to preserve Earth's biodiversity and promotes nature awareness and conservation in Singapore. The BWV aims to reach the public and trains people to access reefs in a scientific way. They are supported by NParks, the PADI project Aware and Wild Singapore (Bolman & Janssen, 2011).

The public

The public opinion and interest are gathered from the ECP survey (refer paragraph 2.3.2).

Some stakeholders are interested in the “Building with nature” principle. The only restrictions that follow from this analysis are the restrictions from the MPA to stay clear of the mooring and navigational areas and to not interfere with Singapore's port interests. All stakeholders need to be informed in case there will be a future ECP design. Regulations, laws and requirements follow from the BCA, HDB, URA, MPA, NEA and NParks. The MPA and HDB can help with the provision of landfill.

2.3.2 SURVEY AMONGST VISITORS OF EAST COAST PARK

On the 30th of August a survey has been held among 96 visitors of ECP. The target group consisted of 67% common visitors, meaning they come to ECP more than 5 times a year (Appendix G, Figure 0.25). The main reason for this survey was to investigate the feasibility of islands or an eco-dynamic design in front of East Coast Park.

77% of all ECP visitors do not swim over there (Appendix G, Figure 0.28); they think the water is too filthy. The beaches are full of debris, especially in the eastern part and the ships nearby imply that the water can be polluted with oil and chemical spills. The beaches have a big influence on the perception of ECP, the view and feeling of leisure. Beaches that would disappear by the construction of the islands, do not have to be fully replaced, but must be replaced by better quality beaches. This seems to be especially important for common visitors. The interest in nature at ECP is still big. However, leisure, sport activities and the view are of more importance. Interesting is the fact, that among common visitors, the predominate preference of the waterfront view is the beach rather than nature. Often the opinion among respondents was: "If I want to see nature I go to neighboring islands such as Bintan or Batam or the Botanical garden in the city centre". This suggests that ECP is considered as a recreational and leisure area, some of the respondents would even prefer ECP as a residential area. On the other hand, people who visit ECP occasionally think about ECP as a zone of nature and that is what they would like to see over there.

The opinion on the most preferable ECP extension, among both groups (all and common visitors) is similar (Appendix G, Figure 0.29). Preference is given to an extension of the coast and a combination of extension and islands, rather than to create one or multiple islands only. A frequently used argument for the extension was a necessity of enlarging the space for sport and leisure activities in order to reduce overcrowding of lawns and cycling / walking paths. Respondents who are in favor of islands support their opinion with a wish to cover or remove the view of vessels stationing at the anchorage. These answers confirm the statement that ECP is considered mainly as a recreational area. Nature and views are of lesser importance.

The majority of questioned people (85% - (Appendix G, Figure 0.32) is interested in creating a bio-diverse island with ecology, however only 34% is willing to pay for visiting such an area. Naturally the will to pay an entrance fee is bigger among nature enthusiasts who prefer nature instead of beaches on the waterfront (47% - Appendix G, Figure 0.33).

Finally respondents do not have a clear and consistent opinion on the location of a possible extension (Appendix G, Figure 0.29). Accessibility is the main reason to extend ECP in the middle and west part of ECP. Extension of the east part is advised mainly to invest in and to improve poor infrastructure and facilities in this zone.

Awareness about the "Building with nature" concept is limited and could be improved. 76% of the visitors are not familiar with the ' Building with Nature' principle (Appendix G, Figure 0.29).

3 DESIGN

This chapter gives a summary of the design process and the resulting preliminary designs. The design process covers the gap between the end of the analysis of the system and the resulting designs. The design process started with brain storm sessions performed by the project group. These brain storm sessions resulted in the design decisions (Paragraph 0) and design considerations (Paragraph 3.5). After these brainstorm sessions, the question arose how to structure the design process in order to present a descent design. The decision was made to generate alternatives by:

1. Grouping the design decisions and design considerations per category
2. Combination the design considerations resulting in a number of combinations
3. Transferring each combinations into a top view of the additional land
4. Detailing these land forms by drawing more detailed top views and cross sections

Section 0 and 3.5 describe the result step 1. Paragraph 3.6 describes the combination of these design considerations (step 2). Paragraph 3.7 covers the further elaboration of these characteristics to designs (step 3 and 4).

Although the system analysis has led to the current lay-out of the designs, this is not explicitly expressed in the text. The designs do take into account the system description. The input from the analysis is distributed throughout this whole chapter.

3.1 DESIGN ASSUMPTIONS

This section discusses assumptions made for the designs.

3.1.1 SCOPE OF THE PROJECT

This project investigates the construction of additional land mass(es) in front of ECP with the "Building with Nature" philosophy and the inclusion of at least 1 ecosystem. A redevelopment of ECP was not considered, only the addition of land mass for recreational space in front of ECP. The project is part of

3.1.2 DESIGN

This paragraph lists several assumptions made during the design including the reasoning behind it.

Design period

The design period is assumed to be 50 years. This lifespan holds for both the additional land as for the ecology implemented.

Ceteris Paribus

The designs were made assuming that all the other variables remain constant. Examples of variables which were assumed to be constant are:

- The lay-out of ECP
- Bathymetry

- Soil conditions
- Climate
- Public perception
- Profitability of additional land

Surface area

The total recreational surface area of ECP is 1.691.000 m^2 in 2011. The original plan of the long island in front of ECP consisted of an area of additional land of 300 m by 7000 m which is 2.100.000 m^2. This seems too much in relative sense. The surface of the ECP reclamation is therefore assumed to be approximately 50% of the existing recreational area. During the design process it already turned out that it was not that straight forward to make all the designs with the same surface area. The surface areas are given and compared in Table 3.

Table 3 | Area of ECP compared to possible areas of additional land

	Area [m2]	Area [%]
ECP in 2011	1691000	100
Long island	2100000	124
Assumed approximate area surface additional land	845500	50

Extreme conditions

The additional land is not designed for extreme conditions as they are very rare and not well known

Recreational area

The main purpose of the reclaimed land is creating extra space for recreation at ECP. This implies that the existing space for recreation at ECP may not be demolished or that it should be fully compensated. From this two design assumptions are drawn:

– The beaches that disappear by the construction of the islands do not have to be replaced instead, if better quality beaches are created
– There may not be any interference with the present locally concentrated surf, canoeing and water sports area. These spots are located in the eastern part of ECP (Sea Sports Centre, PA East Coast Sea Sport Club and National Sailing Centre).

3.2 RISK ANALYSIS

The qualitative risk assessment for the project has been divided per stage of the project. The full table of the risk assessment is listed in Appendix F. The highest risks pose the biggest threat to the project and are listed below:

- Feasibility study:
    - Problems with acquiring landfill material
    - Governmental agencies are not interested in the project (goal Ecoshape ≠ goal government)
    - MPA blocks the project due to influence on marine traffic

- Design phase:
  - Insufficient / inaccurate sediment concentration data
  - Model not accurate enough to investigate impact of designs on hydrodynamic and morphological processes
- Construction phase:
  - Shortage of construction materials (e.g. landfill)
- Realization:
  - Ecology will not establish

The main threats for the project are related to the stakeholders and industrial related risks (feasibility and construction phases) and uncertainty of the availability of data at the required level (design and realization). Mitigation of these risks must be pinpointed and implemented already in early stages of the project. Most important is the landfill material purchase (investigating sources, alternative material usage), contact and negotiations with governmental agencies and acquiring pre-agreements for construction activities. With respect to the design, additional research (habitat requirements) and data collection (sediment concentration, wave conditions, ECP coastal development processes) have to be conducted.

3.3 DESIGN REQUIREMENTS AND RESTRICTIONS

The requirements and restrictions which have to be fulfilled by the design are given in section 3.3.1 and section 3.3.2. The design assumptions which were made are given in section 3.1.

3.3.1 DESIGN REQUIREMENTS

The design requirements from Ecoshape are:

- Design additional land for recreational purposes as an extension of ECP
- Include at least mangroves, seagrass or coral reefs in the design

The wishes of Ecoshape are:

- Use nature itself and the forces of nature to serve engineering purposes (e.g. the prevention of erosion) by stimulating the establishment of mangroves, seagrasses or corals.
- Focus on the reduction of hydrodynamic energy by the design
- Make a feasible design taking the wishes of the public into account

These requirements and wishes were translated in the following principles:

1. Enlarge the area suitable for recreation (main purpose)
2. Improve biodiversity and ecology (main purpose) and create habitat requirements
3. Prevent and reduce erosion
4. Use nature for engineering purposes, combine functions and thereby create added value
5. Make an constructible and economic design

3.3.2 DESIGN RESTRICTIONS

The restrictions for the design of the islands have been subdivided into restrictions concerning navigation and construction. The visualization of these restrictions resulted in an overview of the restriction for the location of the additional land (refer Figure 3.1).

Navigational restrictions

- Stay clear of the Singapore Strait shipping and mooring area.
- Stay clear of the Singapore Strait navigational channel.
- Stay clear of the leisure harbor and the access channel.
- Stay clear of the Tanah Merah ferry terminal.
- Make non-reflective coasts, in order to allow vessels to navigate safely.

Construction restrictions

- The maximum water depth suitable for reclamation is 15 m.
- Reduce the use of normal sand as landfill for economic reasons.
- Keep the settlements after the construction period smaller than 0.3 m.
- Stay clear of pipelines and be aware of the outfalls.

Stakeholders restrictions

- Limit the maximum current velocity near the surface to 0.6 m/s in accordance with the safety of swimmers.
- There may not be any interference with the present locally concentrated surf, canoeing and water sports areas indicated in red and orange in Figure 3.1.

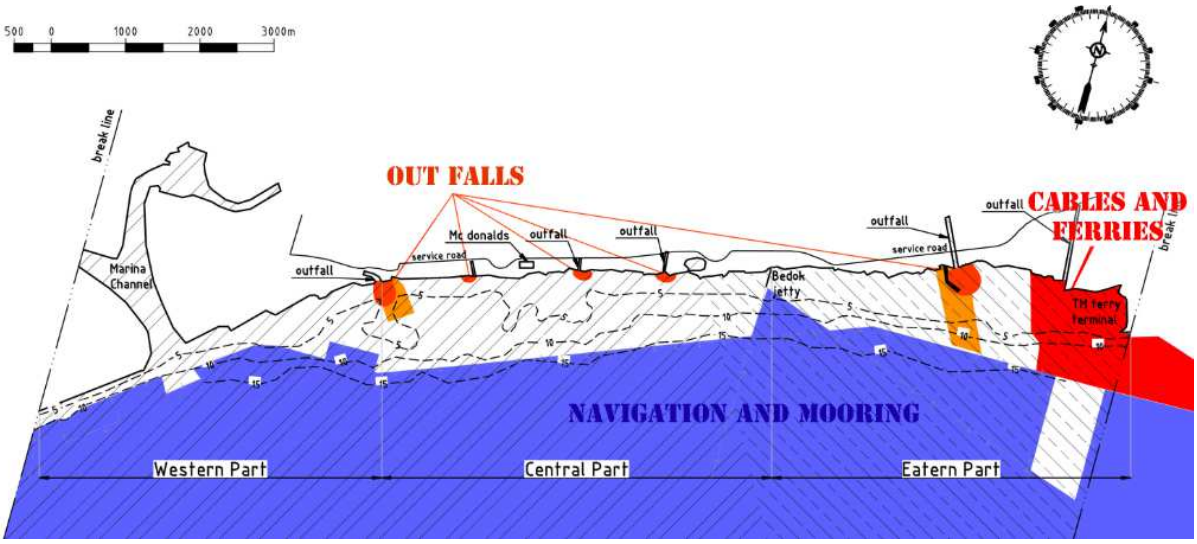


Figure 3.1 | Sieve analysis for the location of the additional land at ECP

3.3.3 HABITAT REQUIREMENTS

The habitat requirements that are presented in Table 4 has been acquired from different sources. An overview of the requirements has been compiled by Ecoshape partners. These requirements have been extended by interviewing Daniel Friess (mangroves), Dr. Sin Tsai Min (coral) and Siti Maryam Yaakub (seagrass).

The different ecosystems that are incorporated in the designs all consist of many different species. Each of these species has their own specific requirements that have to be met in order for the ecology to establish. It is therefore difficult to distil one requirement that suits all these species. Furthermore, many of these requirements are very site specific. The general requirements presented in this chapter will suffice for a feasibility study such as this, but in general, these requirements should be investigated separately for each individual case.

The most important requirements are the hydraulic and morphological boundary conditions (waves, currents and sedimentation) and the dimensions of the ecosystems (patch size, slope and depth). Requirements concerning nutrients and biochemistry have been omitted from the table as the designs do not have a direct influence on these conditions. Furthermore, the waters surrounding Singapore seem to meet most of these requirements as mangroves, seagrass and corals all exist in Singapore.

Table 4 | Habitat requirements for mangroves, seagrass and coral (sources see below)

Criteria	Mangroves	Seagrasses	Coral
		Hydrosphere	
Salinity	3-27 psu, Sonneratia Alba <35 psu	10-50 psu (optimal 30-35 psu)	25-40 psu
Sedimentation rate	> 2-5 mm/y and <80-100 mm/y	< 50 mm/y	< 50 mg/cm^2/day
Sediment concentration	< 300-600mg/l	Depends on light intrusion	Depends on light intrusion
Sediment type	Fine and muddy	< 15% silt-clay, mud-sand	Sensitive to silt, hard substrate
Pollution	Sensitive to oil spills and contaminated water	Herbicides, heavy metals and petrochemicals affect seagrass	Oil, heavy metals, petrochemicals and other pollutants affect coral
Waves	Sheltered	< 3.5 10^6 REI	Unknown
Current	Unknown	< 25 cm/s	Unknown
Tidal regime	Inundation <400-800 min/day	No requirements	No requirements
Depth	Dependend on inundation time	From intertidal up to 25 m depth *[4]*	< 6m depth in Singapore *[5]*
Temperature	< 40°C	10-40°C (Optimal 27°C)	> 15°C (optimal 30-33°C)
Soil	Mud	Mud-Sand	Sand or Silty
		Lithosphere	
Morphology	> 150 m wide mudflat in front with a convex shape:	Reefs, flats, lagoons, beaches, pools	Reefs/hard revetments are necessary
		Biosphere	
Establishment	Artificial planting/seeding is necessary, because natural mangroves are not nearby.	Build up seed bank and vegetative reproduction or natural succession	Breeding is necessary to speed up the establishment of the coral reef
Height	0,5-20 m (grow 0 - 6 m year) *[1]*	0-50 cm (5-23 cm is healthy) *[2]*	Collonies: 75-1500 mm Polyps: 3-56 mm
Area/Patch size	Minimum is 15 ha, minimum width is 400 m. Maximum size per family is 3 ha. *[3]*	1*1 m for establishment. Healty patches of 50x50 m exists in nature, no further information	No minimum area known
Pollination	Wind and insects	Current and wind	Current and fish
		Atmosphere	
Light	There may not be shading of the forest and light is necessary for the seedlings.	> 20 % SI	2-40% SI

All habitat requirement are from Ecoshape partners except:

[1] (Danone Group, 2009)

[2] (T.J.T. Murdoch, 2004)

[3] (International Center for Living Aquatic Resources Management, 1992)

[4] (McKenzie L. , 2008)

[5] (NUS Reef Ecology Study Team, 2011)

[6] (Great Barrier Reef - Coral Facts)

Mangroves (Daniel A. Friess, 2011)

The hydrodynamic requirements for mangroves apply to the establishment phase (the first month) of a mangrove forest.

<u>Inundation time</u>
The required inundation time varies largely for different species of mangroves and is dependent on the slope of the bottom, light intrusion and the tidal range. A large tidal range in combination with a suitable bottom slope will increase the possible accommodation space for a mangrove forest. These two factors therefore determine the width (cross-shore) of the mangrove forest. There are mangroves that can grow with an average inundation time of less than 800 min/day (probably very clear water), whilst others only grow in an environment with an inundation time of 100 min/day. As ECP has a meso-tidal regime of 2.65 m (refer 2.1.1), a slope of 1:200 will give the forest at ECP an average width of around 400 m.

<u>Sedimentation rate and concentrations</u>
The required sedimentation rate is a consequence of sea level rise and land subsidence, of which the first follows from the IPCC sea level rise prediction. Although the SDWA has started land subsidence measurements in August 2011, the subsidence rates in Singapore are not known for ECP yet.

The sediment concentrations have an influence on light intrusion, which in return influences the required inundation time. Sedimentation rates have an upper bound as well, as mortality of trees can occur when too much sediment covers the pneumatophores (aerial roots).

<u>Currents and waves</u>
The main purpose of the mudflat in front of the mangrove forest is to reduce the wave attack during high water levels. The required width of the flat therefore is very site specific and is determined by the slope of the flat, the wave climate in the area and roughness of the flat itself. Furthermore, the mudflat provides accommodation space for accretion, which implies that sedimentation rates need to be known. The requirements for flats can vary greatly as some mangrove sites in Singapore have no mudflat at all, while sites in Malaysia have a mudflat of over 2000 [m] width. Concluding, at ECP, the mudflat has to be designed to dampen the ship and wind waves.

There are no current restrictions known for mangroves. Critical bed shear stresses which different root lengths can handle however are known, as shown in Figure 3.2. This graph has been obtained from laboratory tests, not from real life field experiments.

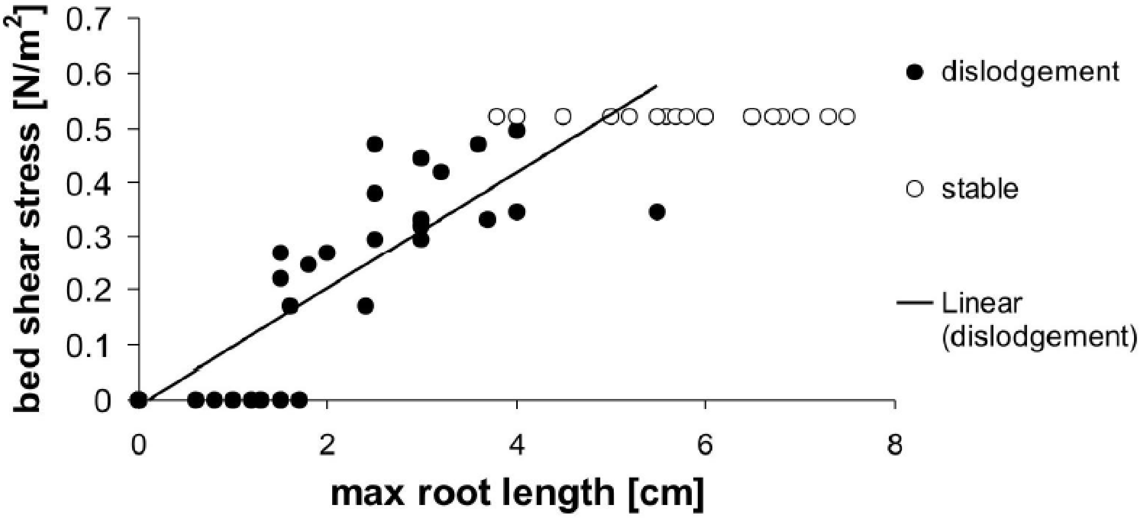


Figure 3.2 | Thresholds to Avicennia establishment, from (Thorsten Balke, 2011)

This graph shows that seedlings cannot withstand bed shear stresses during the first day when they have no root length (average growth of [cm] per day). However, an established mangrove forest will create areas where currents are negligible and seedlings can grow.

<u>Area/patch size</u>
The area and patch size varies largely for different types of mangrove species. Based on data of mangrove patch sizes in Malaysia and Singapore (refer 2.2.4), the minimum patch size is assumed to be 15 ha at ECP.

<u>Slope</u>
The slope depends on the required inundation time and sheltering from waves and currents. There are no specific slope requirements, but common slopes are 1:200 and 1:300. For the mudflat slope requirements do exist.

<u>Depth</u>
The maximum depth depends on the inundation time. Mangroves normally can grow up to the high tide water level line (2.95 m above LAT) and sometimes even higher.

<u>Pollination</u>
Without pollination and transport of genes from other mangrove forests nearby, the lifespan of a forest is limited. Life spans of up to 50 years are possible without pollination from other forests. As there are no other mangrove patches at ECP, the expected lifespan of the planted trees will be in the order of 50 years.

Seagrass (Yaakub, 2011)

<u>Sedimentation rate</u>
The sedimentation rate depends largely on the type of species and is further related to light availability, sediment type and the burial of photosynthetic tissue.

Currents and waves
The necessary wave reduction for seagrass depends on the exposure to waves. This exposure depends on the water depth, the sediment grain size and the wind speed and direction. It is found however that the more the seagrasses are sheltered, the easier they establish.

Current velocity restrictions depend strongly on the size of the seagrass. In general, bigger seagrasses can withstand higher currents than smaller species, as their roots are longer and stronger.

Area/patch size
There is no minimum patch size for seagrass. The bigger patch sizes known in Singapore are about 50 - 100 ha (refer 2.2.4). Much smaller patches, e.g. 50*50 m (0.25 ha), do exist in nature. If a patch of 1 m^2 of fast growing species is artificially planted at ECP, changes are high that the seagrass will spread out over the whole sheltered area.

Depth
Seagrasses need light to convert carbon dioxide and water into oxygen and sugar (photosynthesis). The water depth up to which they grow is therefore directly related to the clarity of the water (McKenzie L. , 2008). Most of the seagrasses in Singapore grow in intertidal areas where they can be exposed for a maximum of 3-4 hours a day. This implies that seagrass can grow up to 1 m above chart datum (see Appendix I). The maximum depth at which seagrasses are found is 25 m below MSL, but in Singapore the depth is limited to 8 m below M.S.L. because of the high turbidity of the waters.

Slope
Seagrass can grow on gentle mud or sand slopes. The gentler the slope, the easier it establishes. There is no maximum slope known, but 1:5 is regarded as a good estimate.

Pollination
Pollination of seagrasses is not necessary and very rare in Singapore as most seagrasses do not flower. A possible reason could be that they are stressed out by the turbidity, traffic and pollutants in the water. This implies that the new seagrass areas at ECP will not receive pollination. However, the provision of broken leafs and fractions that could settle at the new patch is abundant, as there are many other seagrass spots near the east coast. Therefore, there is a good change that without artificial establishment, seagrasses will develop naturally.

Corals (Sin, 2011)

The persistence of corals depends on a large collection of parameters such as physiochemical factors, geophysical and biochemical processes.

Sedimentation rate and type of sediment
The maximum acceptable sedimentation rate for corals strongly depends on the species and their historical exposure and sedimentation regime. Corals are very sensitive to the sedimentation regime as an extended exposure of 50 mg cm^{-2}/day can already result in mortality. Corals can survive higher sedimentation rates of 250 mg cm^{-2}/day, but only for very short periods.

The type of sediment also plays a role. Generally, fine sediments are more troublesome than sand, as it is coarser grained and less suspended.

Current and waves

There are no current and wave requirements known for coral. The currents and wave requirements are related to the species, the calcification, skeletal density and shape of the coral. Encrusting and boulder shaped coral can withstand greater hydrodynamic energy. Furthermore, these corals can create habitats for less robust corals in their sheltered area.

Area/patch size

There are no minimum patch size requirements known for coral. Although it is unlikely that eco-engineering efforts can re-create an entire coral reef, it should be possible to engineer a relatively large area of coral communities.

Slope and reef

Coral has to grow on a reef (hard and bare substrate). Corals can grow on granite, cement/concrete, terracotta or even steel hulls or tires. The best substrate for a reef is a slightly porous and coarse surface, which has a micro-scale roughness and a good wettability. There can be no silt or prior occupancy by other organisms on the revetment. The reef itself can be divided into three zones: reef flat (0-2 m depth), reef crest (2-10 m depth) and reef slope (10-30 m depth).

The flat may vary in width and depth. It may even stand dry at very low tides. The reef crest is the richest part of the reef, which hosts most of the coral and marine life. The three zones can be situated on one slope. The slope can be convex or straight as long as there is no accommodation space that can fill up with sediment. Therefore, a concave slope does not suffice. Horizontal terraces on the slope are desired, because this increases the surface area for coral. If there is a muddy or sandy slope attached at the top of the reef, the sediment transport from this slope over the reef must be kept at a minimum.

Depth

The depth up to which corals can grow depends on the light availability, with the absolute lowest light availability in literature being 2% of the Surface Irradiation (SI). The 6 m water depth presented in Table 4 is probably not the absolute lower vertical limit for coral growth in Singapore, but because of the turbidity of the water, it is assumed to be the lowest limit for ECP. The upper limit is set by the exposure during low tide. Exposure of more than four hours a day is not recommended. This implies that corals can grow up to 1 m above chart datum (see Appendix I).

Pollination

For the long term sustainability of coral, pollination from other reef genes is a must. It ensures the genetic diversity of the reef and provides resistance against diseases. These genes are mainly transported by currents. As coral is present at ECP and at the southern islands, pollination should not be a problem.

3.3.4 BACKGROUND ON REQUIREMENTS

This section provides background on some requirements and restrictions presented in the previous sections.

Maximum depth of land used for reclamation

Land reclamations in Singapore have taken place in between 5 and 10 m water depth. Nowadays deeper waters are entered for reclamation, which go up to 15 m below MSL ((Waterman, 2008). Singapore is at present investigating options to extend the reclamation depth up to 30 or 40 m.

Sand availability

Permission from neighboring countries is required when sand is extracted from waters outside the territory of Singapore.

Swimmer safety

Restrictions for swimmer safety are shown in Figure 3.3. A swimmer can physically handle a current velocity up to 0.9 m/s, but the acceptable maximum is 0.6 m/s.

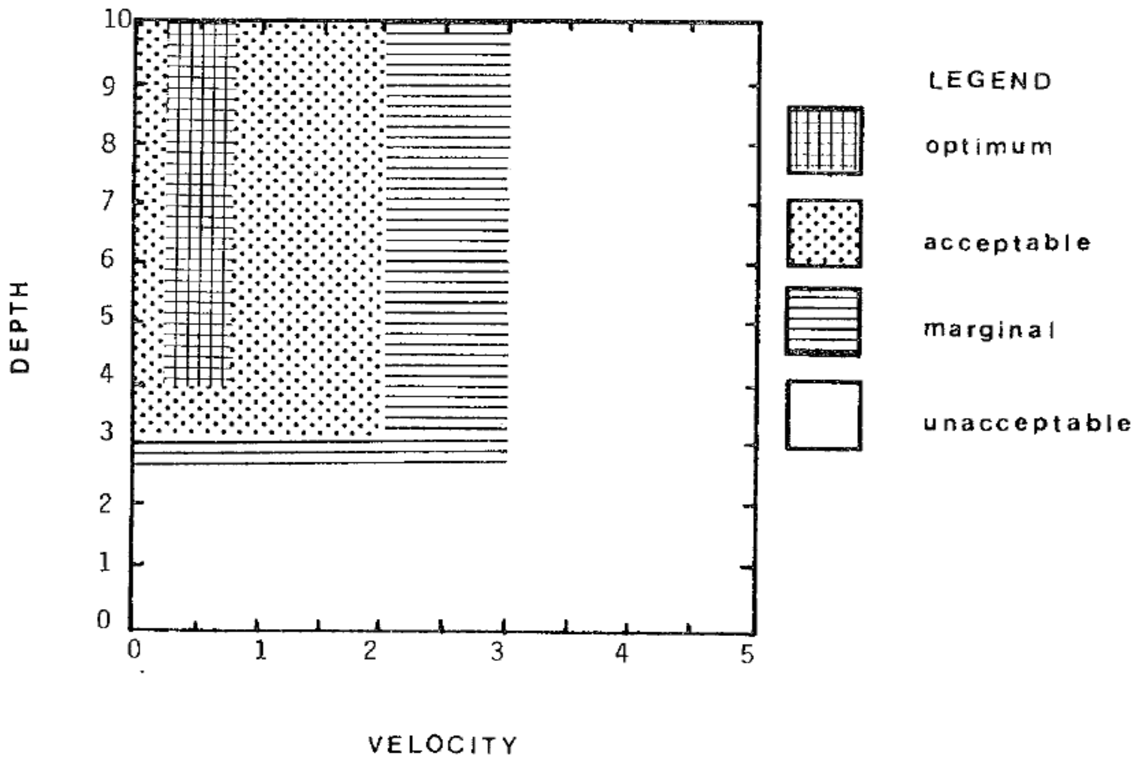


Figure 3.3 | Swimmer safety restrictions in feet and feet per second, from: (Hyra, 1978)

3.4 DESIGN DECISIONS

This paragraph lists the design decisions that were made before the actual design of the islands. These choices were made concerning the location (paragraph 3.4.1), the type of additional land (paragraph 3.4.2) and the number of islands (3.4.3).

3.4.1 LOCATION

The sieve analysis, soil conditions and accessibility are determining factors for the selection of the location of the island.

ECP can be subdivided in 3 distinct parts (

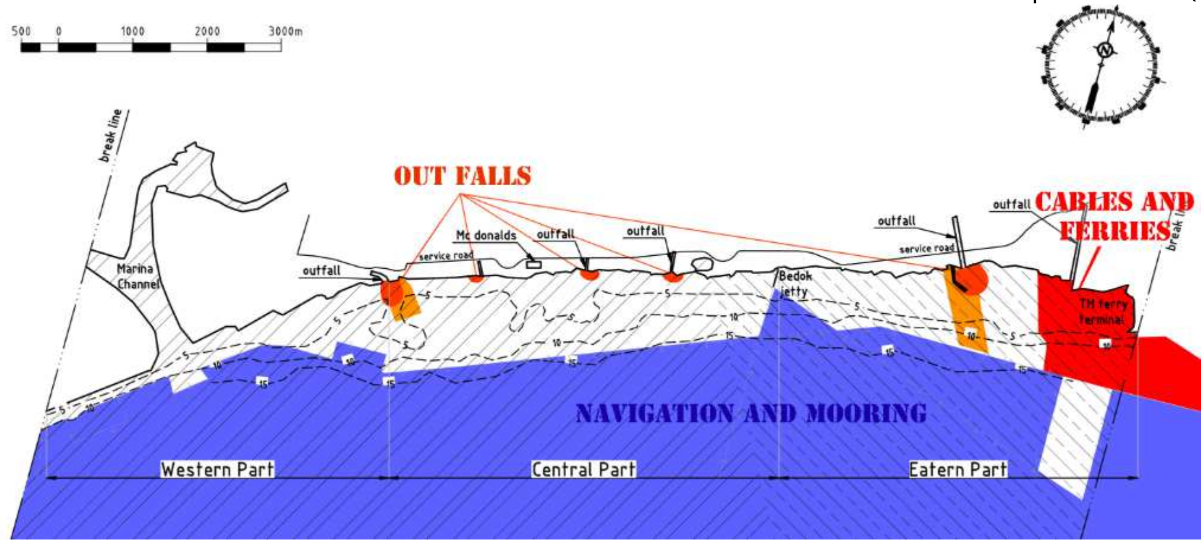


Figure 3.1):

1. The western part (from the Marina Channel till the first big outfall breakwaters)
2. The middle part (from the big outfall breakwaters till the Bedok Jetty)
3. The eastern part (from the Bedok Jetty till the Tanah Merah Ferry Terminal)

Table 5 lists the advantages and disadvantages of these 3 parts as location for new land

Table 5 | Advantages and disadvantages of the 3 parts of ECP

	West	Middle	East
Advantages		Muddy shore which is preferable for mangroves	
		Shallow area which reduces the amount of landfill	
		Located in the most crowded area	
		Located in the most accesible area	
Disadvantages	Less accecible because it is located in front of a forest		Restricted in space in longshore direction
	Restricted in space in cross-shore direction		Less demand for additional land in the more quiet area of ECP

The ECP survey didn't exclude a location for the islands. The middle part was preferred by 37% (1% more than the eastern part).

The project group suggested to make a kind of sand engine (as applied in the Netherlands) in the east part. Due to the eastward peak velocities, the coarse grains will not supply sediment to ECP but to Changi. The predictability of the behavior of such a sand engine is quite difficult, due to the higher eastward peak velocities and the netto discharge and littoral drift to the west.

The middle of ECP was chosen as best location for all the designs as it has many advantages over the other locations concerning soil conditions, water depth and accessibility.

3.4.2 TYPE OF ADDITIONAL LAND

There are different types of creating additional land:

1. Reclamation
2. Polder
3. Land on piles
4. Floating land
5. Gravity based land

Table 6 lists the advantages and disadvantages of these types.

Due to the reduced amount of required landfill the polder solution is favorable in Singapore. However a polder is considered to have a high risk of flooding and the Singaporeans are unfamiliar with the idea of inhabitants living below sea level. At the moment this type of island is not feasible for Singapore. An island on piles reduces the amount of landfill, but it does not provide enough sheltering for ecology. It also lacks slopes that provide the necessary habitat for ecology. The same reasons hold for a floating island. The gravity based island is only suitable for small surface islands.

Table 6 | Properties of the different types of additional land

Criteria	Reclamation	Polder	Land on piles	Floating land
Economical size	Small and large	Large	Small and Large	Small and Large
Amount of landfill	Large	Small	Small	Small
(Creates) Beaches	+ +	+ +	--	--
Morphological impact	Large	Large	Small	Small
Settlements	Large	Large	Average	Small
Construction time	--	-	0	0
Ecology		More options to include ecology at the island itself	Turbulence creates unfavourable conditions for ecology	Sudden transition to to the bottom which is unfavourable for ecology
Wave reduction	Large	Large	Small	Small
Provide sheltering	+ +	+ +	--	--
Light	+ +	+ +	--	--
Others	Costs depth dependent	Dikes block the view from the island	Need for scour protection	No restriction on construction depth
	Volume	Safety issues regarding (perception of) flood risk	Not a proven technique	Not a proven technique
		Needs impermeable revetments and installations to pump water out		Stability could be a problem in high tide and current area
		Needs impermeable revetments and installations to pump water out		Stability could be a problem in high tide and current area

The reclamation was chosen as best type of additional land for all the designs as it has many advantages over the other options.

3.4.3 NUMBER OF LAND MASSES

Additional land can be constructed as follows:

1. One big land mass
2. Multiple smaller land masses

Table 7 lists the advantages and disadvantages of both options.

One land masses reduces the amount of landfill and the construction time compared to multiple land masses.

Table 7 | Advantages and disadvantages of one land mass compared to multiple land masses

	One big land mass	Multiple smaller land masses
Advantages	Lower cost due to lesser length of revetment needed	Greater length of coastline per m^3 of land fill
	Greater amount of surface per m^3 land fill	Construction can be divided in parallel processes
	Less construction time	Creates spots with different characteristics for ecology
	Less space needed	Easier to create sheltered areas
	Prefered option by participants to ECP survey	
	More predictable development morphology and flow	
Disadvantages	Blocks the view from the main land	More space needed
		Greater length of revetment needed
		More landfill needed
		Unpredictable development of morphology and flows

Sheltered area is difficult to realize in the case of an extension of the coastline in the form of 1 single land mass. Most of the extensions are therefore designed as 2 smaller land masses. Detached offshore land masses however directly create sheltered area, and therefore preference is given to 1 big island for all the designs as it has many advantages over constructing multiple smaller islands.

3.4.4 HEIGHT OF THE ADDITIONAL LAND

The height of the land should take into account

1. The design high water level according to the standard
2. The sea level rise during the life cycle of 50 year
3. The additional storm surge height
4. The wave set-up height
5. The wave run-up height which corresponds with a certain overtopping (1 l/m/s)
6. The setting of the land mass itself, the settlements due to the extra land mass and local subsidence during the design period

Table 8 contains the calculated values and their summation. The calculations are made below this table. The height of the land of the current coastline is estimated based on measured cross-shore profiles (Raju, 2010) at 4.5 m + CD. The results as described by Table 8 seem to be in accordance with this value taking into account the added values for the vertical deformation.

Table 8 | Contributions to the construction level of the land mass

Parameters	Land height 1:90 slope		Revetment height 1:2 slope	
Mean Sea Level	1.6	m + CD	1.6	m + CD
Mean High Water Spring	2.8	m + CD	2.8	m + CD
Sea level rise height	0.3	m	0.3	m
Storm surge set-up height	0.8	m	0.8	m
Design high water level	3.9	m + CD	3.9	m + CD
Wave run-up height	0.1	m	2.4	m
Design crest height after design period	4.0	m + CD	6.3	m + CD
Subsidence of the substratum during design period	0.1	m	0.1	m
Setting and settlement during design period	1.8	m	1.3	m
Construction crest height	5.8	m + CD	7.6	m + CD

The Mean Sea Level (MSL) is 1.637 m + CD and the Mean High Water Spring (MHWS) is 2.8 m + CD (Wong, 1992). These levels differ from the ones used in Delft3D models. For the correct interpretation and application of the modeling results, such as water levels, the MSL (+1.637) from the ENC was equaled to the MSL (0.00) from the delft3D (see Figure 0.1 in the Appendix A)

The sea level rise is set at 0.3 m which is the global average (IPCC, 2007). The storm surge set-up is based on the scenario of a typhoon crossing near Singapore generating extreme water levels (Xin, 2010). The number $Ru_{2\%}$ [m] is the wave run-up level which is exceeded by 2% of the incoming waves. The wave run-up height is calculated using the following formula (Van der Meer, 2002):

$$Ru_{2\%} = 1.6 * \zeta_{op} * H_S = 1.6 * \frac{\tan\alpha}{\sqrt{\frac{H_S}{L}}}$$

$$= 1.6 * \frac{\tan\alpha}{\sqrt{\frac{2\pi * H_S}{gT^2}}} * H_S = 1.6 * \frac{\frac{1}{90}}{\sqrt{\frac{2\pi * 0.6}{9.81 * 3^2}}} * 0.6 = 1.6 * \frac{\frac{1}{90}}{0.2} * 0.6 = 0.05\ m$$

The wave run-up for a slope of 1:2 is 2.4 m.

Vertical deformation can be subdivided into:

1. Subsidence of the substratum
2. Setting of the material of the extra land mass
3. Settlement of the substratum due to the load of the extra land mass

The total vertical deformation is calculated by adding these 3 factors. The subsidence of the substratum is estimated at 1 mm/year as no detailed information is available. For the settling of clay, a value 10% of the increase in height is recommended (Weijers, 2009). This value is used for the setting of the material of the extra land mass. As no detailed information is available of the soil layers at ECP, the settlement of the substratum due to the load of the extra mass is estimated as 10% of the increase in additional land. During the Changi reclamation project it became clear that the reclaimed land will need soil improvements to speed up the settlements (see paragraph 2.1.4).

3.4.5 LANDFILL MATERIAL

The landfill (which is the core of reclamation) can consist of primary materials such as sand, clay, gravel and rubble. However, the availability of these primary materials in Singapore is limited. The HDB and MPA could provide land fill materials of the rest products of leveling hills, tunneling, the demolition of buildings and maintenance dredging (see section 2). The maintenance dredged mud and other secondary materials can provide a promising alternative to primary materials as sand. Secondary reused materials can be applied as strengthened sediment. The use of strengthened sediment is an innovative technique which was successfully applied in a pilot projects in the Netherlands.

Strengthened sediment is excavated or dredged (contaminated) sediment or other soft materials which are strengthened by using primary or secondary binder materials. The soft materials are mixed with a binder (bottom ash, fly ash or cement). This mixture is pumped to the construction side. An initiator (such as alkaline silicate) is added to convert the liquid mixture into a solid material. Contaminants if present are immobilized within the structure of this material. The strength, density, permeability and plasticity can be influenced by varying types and concentrations of the binder and initiator. The use of strengthened sediment is both sustainable (e.g. also a lower CO_2-footprint may be possible) and economical. It reduces the use of primary building materials. There is no unnecessary transportation and storage because the sediment is dredged / excavated and directly pumped to the construction side. Finally, the reuse of the excavated or dredged sediment makes the use of land to dump the contaminated sediment redundant.

The decision on which type of landfill is not made during this project, as it is not considered to be the scope of the project.

3.4.6 CHARACTERISTIC CROSS-SECTIONS OF REVETMENTS AND SLOPES

There are different types of revetments possible:

1. Soft revetments
    a. Unsheltered
    b. Sheltered
2. Hard revetments
3. Ecological revetments
    a. Mangroves
    b. Seagrasses
    c. Corals

Table 9 lists the advantages and disadvantages of these 3 types of revetments. The ecological slopes are based on the habitat requirements (see paragraph 3.3.3). Figure 0.56 in paragraph H.3 in Appendix H visualize the cross-sections of these types. Paragraph H.3 also describes the trade-offs made during the design of these cross-sections.

Soft revetments consist of natural, fine material such as clay, sand or gravel. A sheltered soft revetment is located in an environment that is sheltered from waves and currents. Hard revetments consist of steel, rocks, concrete such as a rubble mound defense or a caisson-type seawall or sheet piles. Ecological revetments consist of soft slopes stabilized by flora and fauna such as mangroves, coral reefs or seagrasses.

As by the wishes of the public, the demolished beaches must be replaced or better quality beaches have to be created. At the new beaches a special attention must be paid to the prevention of erosion. New coastal beach cells can be created, designed with respect to the governing wave angle of incidence. They need groynes or breakwaters that are large enough to prevent the cross-shore exchange and longshore transport. Another option is to use a coarse grain, which at the moment is present in the breaker zone at ECP (see measurements). The smaller grain sizes are washed out at ECP, leaving the largest grain sizes behind.

Table 9 | Advantages and disadvantages of soft, hard and ecological revetments

	Extending existing land	Island
Advantages	Construction from landside possible	Creates new beaches and protects them
	Only 1 side requires revetment	Directly creates sheltered wet area
	Less space in cross-shore direction needed	Partialy protects present coast
	Reclamation in shallow water	
	Maintain the existing view and character	
	Prefered by ECP survey participants	
Disadvantages	Does not lengthen the coastline	Greater amounts or landfill needed
	Demolishes old beaches	More space needed
	Ecology near the coastline is demolished	Hindrance of the sea view
	Does not create directly sheltered area	Reclamation in deeper water

The decision concerning the kind of revetment to use is determined separately for each slope in each design.

3.5 DESIGN CONSIDERATIONS

This paragraph deals with the design considerations that were made during the actual design of the islands. The design considerations are grouped by type of reclamation, the foundation of the island

3.5.1 EXTENSION OF THE COASTLINE OR ISLAND?

There are three types of additional land that can be designed:

1. An extension of the existing coastline
2. An island
3. A combination of the abovementioned types

Table 10 lists the advantages and disadvantages of the first 2 types.

Table 10 | Advantages and disadvantages of extending existing land or constructing an island

	Extending existing land	Island
Advantages	Construction from landside possible	Creates new beaches
	Only 1 side requires revetment	Directly creates sheltered wet area
	Less space in cross-shore direction needed	
	Reclamation in shallow water	
	Maintain the existing view and character	
	Prefered by ECP survey participants	
Disadvantages	Does not lengthen the coastline	Greater amounts or landfill needed
	Demolishes old beaches	More space needed
	Ecology near the coastline is demolished	Hindrance of the view
	Does not create directly sheltered area	Reclamation in deeper water

The main advantage of an extension of the coast is the reduction of the amount of landfill compared to an island. An extension of the existing coastline does not directly provide sheltering.

An island is much more favorable for protecting ecology, because an island directly creates sheltering by reducing wave heights. From the analysis of the existing ecology it comes clear that sheltering needs to be created along ECP to provide a habitat for ecology. Islands create local gradients in the longshore sediment transport (by these reduced wave heights) which cause accretion in the sheltered area behind the island.

Surprisingly the combination of an extension and an island excludes the profits of both if they are aligned in cross-shore direction. An extension offsets islands offshore which decreases the available space for ecology. The additional land is also located in the wet sheltered area created by the island. The combination creates 2 land forms which increases the costs (see paragraph 3.4.3).

The preliminary designs are therefore subdivided in only 2 kinds of additional land, namely an extension of the existing land and an island.

3.5.2 PROTECTED OR UNPROTECTED ECOLOGY?

Ecology can roughly be subdivided in 2 kinds:

1. Protected ecology (exposed to hydrodynamic loads)
2. Unprotected ecology (sheltered from hydrodynamic loads)

Table 11 lists the advantages and disadvantages of these two kinds.

Table 11 | Advantages and disadvantages of protected and unprotected ecology

	Unprotected ecology	Protected ecology
Advantages	Protects shore against erosion	Higher chance of establishiing and growth
Disadvantages	Uncertainty of the extent of protection	It doesn not serve as shore protection
	Risk of extinction	

3.5.3 MANGROVES, SEAGRASSES OR CORALS?

There are three types of ecosystems that can be implemented:

1. Mangroves
2. Seagrasses
3. Corals

Table 12 lists the advantages and disadvantages of the first 2 types.

Table 12 | Advantages and disadvantages of different types of ecosystems

	Mangroves	Seagrass	Corals
Advantages	Stabalize the shore	Stabalize the shore	Grow on hard revetments
	Slow down currents	Slow down currents	Attractives for public
	Reduce wave attack	Traps sediments	Attenuate hydrodynamic energy
	Attractiveness for public, possibility to create a botanical garden	Improve quality of water	
Disadvantages	Vulnarability to oil spills	Attracts people during low tide	Limited to a water depth of 6 meters
	Block the view from original coastline	Limited to a water depth of 6 meters	
	Unattractive for the public, association with swamps		

Mangroves in the middle of ECP can be interpreted differently than for instance seagrass and coral. Mangroves can grow up to 20 m height, blocking the total sea view. There are also a lot of people in Singapore that associate mangroves with swamps (Maryam, 2011). The aforementioned arguments could mean that the establishment of coral and seagrass instead of mangroves in front of ECP is a better alternative.

3.5.4 THE DEMAND OF VISITORS OF ECP

The inclusion of the demand of the visitors of ECP in the designs will make the designs more feasible and realistic. The demand of the visitors of ECP is based on the survey which is described in Appendix G and on the conversations with visitors on both the day of the measurements and the survey. This paragraph will highlight the interesting points that were pointed out by the survey which have an effect on the design.

Of all the participants in the survey, 77% does not swim at ECP. There is still a significant amount of people that goes to ECP because of the beaches. The view, nature, leisure and sports are the main reasons to go to ECP. People prefer beaches over nature as view on the waterfront. All these findings probably mean that the view on the beach is an important characteristic of ECP, and that people don't actually physically make use of the beach to go swimming. This implies that it is not obligatory to create beaches which are focused on swimming, but these beaches should look good.

The participants prefer an extension over an island, which could be related to the wish of maintaining the character of ECP. This doesn't exclude an island, but does imply to give preference to extension and to strive to maintain the character of ECP.

Of all the participants of the survey, 85% is interested in creating a bio diverse island with ecology. This suggests that the public opinion won't be the constricting factor in the way to the realization of a bio diverse additional land. 34% of the participants is even willing to pay for this type of additional land.

3.5.5 BUILDING WITH NATURE

The “Building with nature” philosophy has many aspects which can be incorporated in the design. Nature itself, the current situation, but also the materials of nature, forces of nature and interactions with nature (Waterman, 2008) can be used in the design.

Nature itself can be used by stimulating the establishment of ecosystems which contribute to coastal protection, improve water quality and are attractive to the visitors. The effects of mangroves, seagrasses and corals are described in the ecology part of the system description. Furthermore nature can adjust itself to new circumstances e.g. sea level rise and land subsidence.

The current situation can be used by locating the reclamation in a shallow area which reduces the amount of landfill.

The materials of nature can be used by the reuse of maintenance dredging materials, demolition materials and materials which originate from the leveling of hills in Singapore. By making soft solutions, the design becomes more flexible. Mud is available in the water, while the coarse-grained sediment is not. This is a good argument for making soft revetments that consist of mud instead of sand.

The forces of nature are the wind, waves and tides. The tide can be used to flush bays. The waves and both tide-induced and wind-induced currents can be used to distribute sediment. By using this kind of distribution of sediments, the soft material is distributed according to these forces of nature which also reduces the amount of attack on the coastline.

The interactions can be the interaction between marine organisms and sand / silt / coral. The interaction between the soil and vegetation stabilizes the soil.

3.5.6 ORIENTATION, SHAPE AND OFFSHORE DISTANCE

It became clear from the analysis that the hydrodynamic energy needs to be attenuated to enable establishment of ecology. Sheltered area is also favorable for the reduction of erosion. The shape of the islands is such that it provides shelter from waves and/or currents from westward and/or eastward direction. The designs should be able to withstand and provide sheltering from both wind, swell and ship waves. The wind and swell waves typically arrive at approximately 30 degrees (see Figure 2.17 on page 19). The most severely attacked parts that are made of sand will need to be protected by groynes in order to create a coastal cell in which the amount of sediment is preserved. This has to be done because there is no updrift supply of course-grained sediment.

The turbulence created by the new land has to be kept as small as possible to reduce:

1. the transport of sediments
2. the danger of swimmers which are taken offshore by eddies

The shape has a big influence on the maximum current velocity at the beach. This velocity has to be as small as possible with regards to swimmer safety.

The offshore distance has implications on the safety with regards to oil / chemical spills and collision with ships. The greater the offshore distance the closer to the mooring area and the greater these risks become.

Another factor that contributes to the determination of the distance offshore is the amount of landfill needed. The more shallow areas are used for the additional land, mangrove flats or beaches to reduce the required amount of landfill. These areas are generally located closer to the shore.

In the new designs the beaches are concave shaped to reduce the wave attack. The sediment at the beaches is protected by groynes which extend cross-shore into the deeper parts. If the groynes are longer than the extend of the cross-shore processes, the sand will be trapped. This will reduce the erosion rates as the sand is only transported within such a coastal cell. The further the extend of the groynes, the less sand will be lost. The deeper and convex parts further offshore are protected by a hard revetment. These revetments had to be hard because the attack by waves is more severe and because the transition to depth had to be made before the anchorage line.

The islands do not have any soft revetments (beaches) because of the constriction in space in cross-shore direction. The beaches had to have a slope of 1:90 which needs a depth on the available space from the coastline until the anchorage line.

The island is kept narrow to maximize the sheltered area created behind it. The island hinders flows in the cross-shore direction and therefore decreases the redistribution of sand in this direction.

3.6 COMBINATIONS OF DESIGN CONSIDERATIONS

The location was already set during the design considerations. The remaining considerations which have a large influence on the land form of the additional land are:

1. Extension of the coastline or island(s)
2. Protected or unprotected ecology

Mangroves, seagrasses or corals as main ecological design component

Table 13 lists the combination of the different options. The combination results in 9 distinct combinations. Figure 0.37 in Appendix B gives an overview of the sketches of the designs that were made based on the combinations made in this paragraph.

Table 13 | Combination of the design considerations resulting in 12 combinations

Extension or island	Protected or unprotected ecology	Mangroves, Seagrasser or Corals
Extension	Protected ecology	Mangroves
		Seagrasses
		~~Corals~~
	Unprotected ecology	Mangroves
		Seagrasses
		Corals
Island(s)	Protected ecology	Mangroves
		Seagrasses
		~~Corals~~
	Unprotected ecology	~~Mangroves~~
		~~Seagrasses~~
		Corals

Some of the combinations were canceled because they did not seem feasible. Protected coral reefs were canceled because coral doesn't need any sheltering from waves or currents. As corals do not require any sheltered condition but do require a hard rocky bottom, the remaining distinct characteristics with corals were incorporated in the designs with mangroves and seagrass. The combination of unprotected ecology and an island does not generate a lot of interaction of the island with the ecology. The seagrasses or mangroves would have to be located beside the island, because ecology on the seaside is not feasible due to distance constrictions in the cross-shore direction. Unprotected mangroves and unprotected seagrasses were therefore not considered to be feasible.

3.7 PRELIMINARY DESIGNS

Every paragraph in this section presents a preliminary design. Each paragraph presents the decisive reasons for the choice of a particular land form and the effects of the land form as modeled in Delft3D. The drawing presented on the next page presents overviews of all eleven designs.

Only a part of the habitat requirements were taken into account in the design phase: sedimentation rate, sediment type, waves, current, tidal regime, depth, soil, morphology, area/patch size and pollination. This was mainly because these habitat requirements the numerical model was able to quantify these requirements and because these requirements were directly influenced by the design.

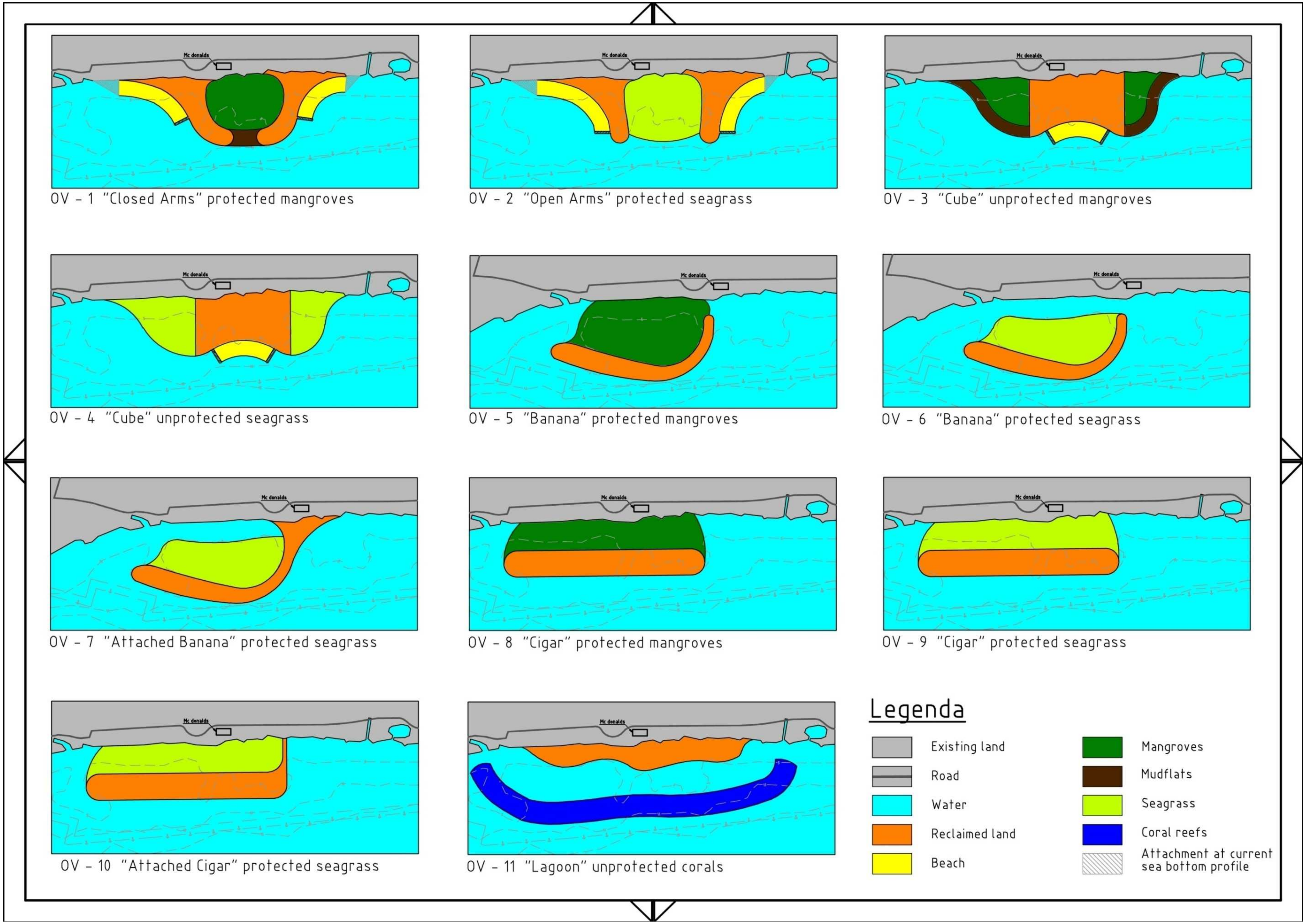


Figure 3.4 | Overview of the preliminary designs

3.7.1 CLOSED ARMS PROTECTED MANGROVES (DESIGN 1)

The overview of this design is located in Appendix H, section 0

The shape of the design provides shelter for mangroves from both eastward and westward directed currents and waves. The additional land masses are almost symmetric to take into account both the westward and eastward flow in the Singapore Straits. The additional land mass in the west is extended in the west direction to enlarge the created land area. The additional land mass in the east is not enlarged to prevent sedimentation of the outfall. The size of mudflat in front of mangroves is kept at a minimum in order to stay out of the deeper water.

3.7.2 OPEN ARMS PROTECTED SEGRASS (DESIGN 2)

The overview of this design is located in Appendix H, section 0

Seagrasses for establishment in principle require protection from waves unless they are situated deep enough, but do need protection from currents (see paragraph 3.3.3 on the habitat requirements). The land masses protect the seagrass from eastward and westward flow. The distance between the land masses is increased compared to design 1 to get uniform in and outflow patterns and to prevent stagnant water. The additional land masses are almost symmetric to take into account both the westward and eastward flow in the Singapore Straits.

3.7.3 CUBE UNPROTECTED MANGROVES (DESIGN 3)

The overview of this design is located in Appendix H, section 0

The shape of the extension is rectangular, to create more additional land with less revetments. Because of the large mudflats on the east and west side of the extended land, the design is smoothed to decrease the amount of turbulence created by currents. The symmetric design shelters the east side of the rectangular shape from westward directed flow and vice versa. The mangroves will provide protection for the extended land mass:

- o When the mangrove forest is developing, it will have to be protected by some structure until it is strong enough to withstand the hydrodynamic conditions
- o During the southwest monsoon the sheltered area in the west can be used to protect the seedlings.

3.7.4 CUBE UNPROTECTED SEAGRASS (DESIGN 4)

The overview of this design is located in Appendix H, section 0

The shape of the extension is rectangular, to create more additional land with less revetments. The seagrass patches on the east and west side of the extended land will decrease the current velocities of the eddies created behind the island. The seagrass will also provide protection for the extended land mass and adjacent coastline by increasing sedimentation. When the seagrass is developing, it will have to be protected by some structure until it is strong enough to withstand and attenuate the hydrodynamic conditions.

The land mass protects creates a sheltered area on either the west or east side depending on the monsoon which creates favorable conditions for the development of seagrasses

3.7.5 BANANA PROTECTED MANGROVES (DESIGN 5)

The overview of this design is located in Appendix H, section 0

The mangrove forest is attached to the shore to reduce the current velocities which could erode the shore due to the creation of a funnel shaped channel behind the island. The purpose of a curved island is twofold. The curved shape creates sheltered wet area. The curvature could also influence and actually set the way the water flows behind the island.

3.7.6 BANANA PROTECTED SEAGRASS (DESIGN 6)

The overview of this design is located in Appendix H, section 0

The seagrass is not attached to the shore to maintain the beaches. The purpose of a curved island is twofold. The curved shape creates sheltered wet area. The curvature could also influence and actually set the way the water flows behind the island.

3.7.7 ATTACHED BANANA PROTECTED SEAGRASS (DESIGN 7)

The overview of this design is located in Appendix H, section 0

By attaching design 6 to the shore, the area of the land mass is increased and the currents are reduced. The attachment will be made on the eastern side of an island to create sheltering from the westward residual flow and governing south east wave direction.
The reduction of the currents will reduce the amount of eroded material and increase the protection of the seagrass. The purpose of a curved island is twofold. The curved shape creates sheltered wet area. The curvature could also influence and actually set the way the water flows behind the island.

3.7.8 CIGAR PROTECTED MANGROVES (DESIGN 8)

The overview of this design is located in Appendix H, section 0

This design is based documents and articles that appeared after the publication of the concept plan of 2001 in which the possible additional land in front of ECP is mentioned. The shape will provide sheltering to the governing wave direction. The mudflat behind the island in combination with the island will decrease the flow velocities and will create the desired sheltering for mangroves. The shape and location of the island will provide more distance from the mooring lines than the banana shaped island and the same time allows increasing size of the land. This reduces the amount of landfill, steep slopes and interference with the navigational area during construction.

3.7.9 CIGAR PROTECTED SEAGRASS (DESIGN 9)

The overview of this design is located in Appendix H, section 0

The same arguments for this design as the cigar protected mangroves hold.

3.7.10 ATTACHED CIGAR PROTECTED SEAGRASS (DESIGN 10)

The overview of this design is located in Appendix H, section 0

This design is based documents and articles that appeared after the publication of the concept plan of 2001 in which the possible additional land in front of ECP is mentioned. By attaching this island to the land, the current velocities are reduced and an access road is created. The attachment will be made on the eastern side of an island to create sheltering from the westward residual flow and governing south east wave direction.

3.7.11 LAGOON UNPROTECTED CORALS (DESIGN 11)

The overview of this design is located in Appendix H, section 0

This design tries to simulate the environment of a coral reef as can be found in nature (see Figure 2.22 on page 26). The coral reef reduces the currents and waves which creates favorable conditions for seagrasses and mangroves. The human intervention in this design limits itself to only constructing the extension of the land and a hard flat, crest and slope under water. The design presumes that ecology will establish by itself. The water depth above the hard crest is decreased to approximately 1 m below MSL which a few 100 m offshore. The presumption of this design is that this crest will create a large sheltered sedimentary lagoon behind it which is suitable for the growth of mangroves and seagrasses. The crest is suitable for the growth of coral because it is hard and in shallow water. The shape of the extension is adjusted according to the bathymetry contours to reduce the amount of landfill.

4 EVALUATION

The preliminary designs were evaluated using a multi-criteria analysis (MCA) and Delft3D model results of the designs.

4.1 NUMERICAL MODEL USED IN THE EVALUATION

This section deals with the purpose of the model (paragraph 4.1.1), the nesting of the model (paragraph 4.1.2) and the setup of the nested model (paragraph 4.1.3). Appendix J describes the numerical model in more detail.

4.1.1 PURPOSE OF THE MODEL

The 2 main reasons to build a model for this project are:

1. To assess the influence of the designs on the hydrodynamic and morphological conditions and vice versa
2. To check whether the habitat requirements for ecology are met in the designs

4.1.2 NESTING OF THE MODEL

For this project, a model has been nested inside the Singapore regional model for 3 distinct reasons. Firstly, nesting in an existing model saves a lot of work. The overall model has already been calibrated and validated. Secondly, the model is nested to increase the accuracy of the results of the nested model, as the grid cell size in the area of interest is greatly reduced. Finally, as the nested model contains less grid cells than the overall model, nesting decreases the amount of computational time needed.

Figure 4.1 visualizes the Singapore regional model (SRM). This model has been developed by Deltares. The model used in this project has been nested in the SRM.

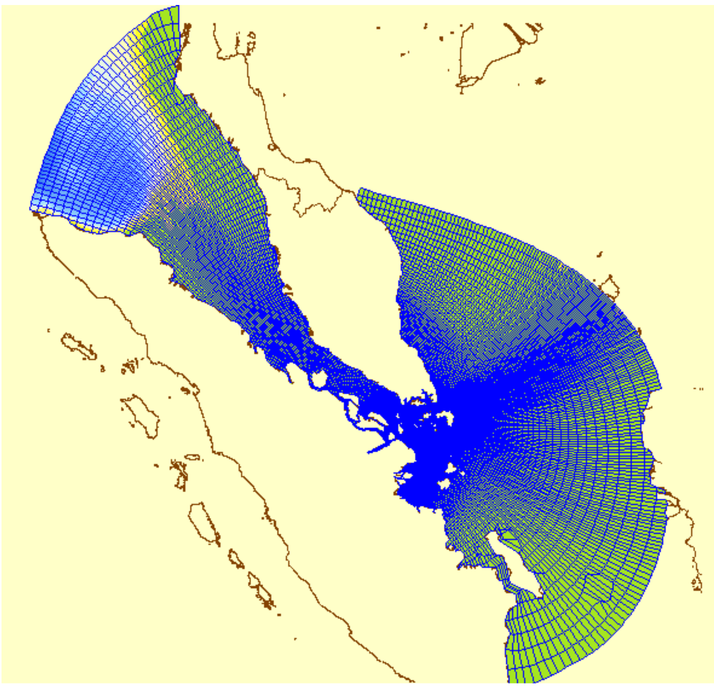


Figure 4.1 | The Singapore Regional Model (SRM)

4.1.3 SETUP OF THE FINAL NESTED MODEL

During the process of nesting, a lot of parameters have been adjusted. The setup of these parameters in the final nested model is presented below in Table 14.

Table 14 | Setup of the nesting parameters in the final nested model

Nested in	Grid	Location of boundary	Type of open boundary	Boundary segments
'normal' SRM	1	east	current	multiple
		south	water level	
		west	current	
Time step	Bathymetry	Reflection parameter α	Time interval nesting	
0.5 [min]	SRM smoothed + ENC	0	20 [min]	

The grid used in the final nested model is presented below in Figure 4.1:

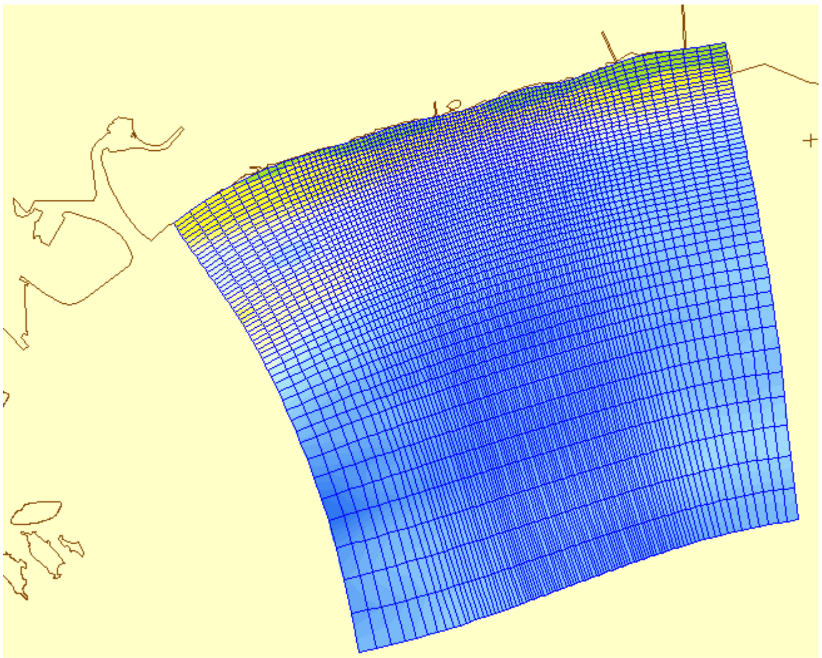


Figure 4.2 | Grid used in final nested model

The reader is directed to Appendix J for extensive further readings on the development of the nested model.

The preliminary designs have been implemented in Delft3D to analyze the effects on the hydrodynamic conditions and the sedimentation of fines. The results of this analysis are described in this section. From each design the following data has been analyzed:

- Vector fields of the depth averaged velocities
- Maximum velocities within entire time domain
- Difference in maximum velocities within the entire time domain between the base run and the design run
- Maximum bed shear stresses within entire time domain
- Cumulative sedimentation of fines within entire time domain
- Discharges

The figures that show the results of Delft3D for each design are shown in Appendix I, paragraph K.1. The results from these plots are described in the tables in Appendix I, paragraph K.1.1. The tables in that appendix are summarized in this section.

4.2 RESULTS PER DESIGN

This paragraph discusses the Delft3D results that are visualized in the figures shown in Appendix I, paragraph K.1.

The "closed arms protected mangroves" (design 1, results visualized in Figure 0.67 in Appendix I) creates a sheltered basin for mangroves, however the opening is too small to fill and empty the tidal basin without high flow velocities. Large bed shear stresses of about 2.5 N/m^2 develop due to the high flow velocities in the opening. These bed shear stresses decrease the sheltered area for mangroves according to the bed shear stress requirements (see Figure 3.2 on page 40). Furthermore these bed shear stresses can cause major erosion in and around the opening.

The "open arms protected seagrass" design (design 2, results visualized in Figure 0.68 in Appendix I) creates a sheltered basin and sheltered areas on both the east and west side of the land extensions. Two large eddies with the length scale of the extension develop on the east and west side of the land extension and large maximum flow velocities of about 0.7 m/s develop around the tips of the island. This is caused by the tips which are aligned perpendicular to the flow direction.

The "cube with unprotected mangroves" (design 3, results visualized in Figure 0.69 in Appendix I) provides sheltering from currents. The design is streamlined by the mangrove mudflats, which only give a small eddy development with a length scale smaller than the extension. The bed shear stresses are highest at the edges of the mudflat (0.6-0.8 N/m^2).

The "cube with unprotected seagrass" (design 4, results visualized in Figure 0.70 in Appendix I) provides some sheltering for seagrass. However the extension also creates large eddies (larger than the length scale of the extension) on the east and west side of the extension and high maximum flow velocities of about 0.75 m/s around the corners of the extension. This is due to the deep waters surrounding the extension.

The "banana protected mangroves" (design 5, results visualized in Figure 0.71 in Appendix I) provides sheltering for mangroves. High maximum flow velocities develop in between the island and the coast, because the island is located close to the coast. The banana shape creates a round basin, which was meant to improve the circulation. However the results show that this had no effect on the circulation in the basin.

The same conclusions hold for the "banana protected seagrass" (design 6, results visualized in Figure 0.72 in Appendix I). It provides sheltering, but also creates high flow velocities.

The "attached banana protected seagrass" (design 7, results visualized in Figure 0.73 in Appendix I) provides more sheltering than the banana island. It also reduces the maximum flow velocities behind the island and it streamlines the flow around it.

The "cigar protected mangroves" (design 8, results visualized in Figure 0.74 in Appendix I) provides sheltering for mangroves, but there is no sheltering created on the east and west side of the island. As seen earlier, large maximum flow velocities of about 0.75 m/s develop around the corners of the island. This is acceptable when considering the swimmer safety. The reason for these flow velocities is that the corners are not well streamlined.

The "cigar protected seagrass" (design 9, results visualized in Figure 0.75 in Appendix I) provides no sheltering.

However, "the attached cigar protected seagrass" (design 10, results visualized in Figure 0.76 in Appendix I) does provide sheltering. It has high maximum flow velocities of about 0.75 m/s around the corners, but very small maximum flow velocities and bed shear stresses of about 0.1 N/m^2 behind, to the east and to the west of the island.

The "lagoon unprotected corals" (design 11, results visualized in Figure 0.77 in Appendix I) provides almost no sheltering. The currents increase on the barrier and are not reduced. This could be solved by making a higher barrier, but this exceeds the exposure limits for coral. It must be addressed that the barrier is difficult to model correctly with Delft3D.

4.3 DISCUSSION OF THE MODEL RESULTS

The Delft3D results of the designs give an overview of the hydrodynamic effects of the additional land. This paragraph describes the general conclusions which were drawn from the model results.

Additional land can create the desired sheltering for ecology. An island can create sheltering but in all island designs the flow was accelerated at a certain location behind the island. The maximum flow velocities become higher when the size of the opening between the island and the coast is reduced.

An island that is located parallel to the coastline creates no sheltering from currents, as seen by the cigar protected seagrass. Attaching the island on one side to the main land can solve this problem. It creates a basin which provides sheltering from waves and currents. The depth in combination with the width of the opening of a basin should be large enough to reduce the flow velocities caused by the discharge of the tidal prism.

The design should be streamlined to prevent acceleration of the flow at the tips and corners of the additional land.

Many designs create large eddies which are assumed to increase the cross-shore transport and coastal erosion. High bed shear stresses near corners and tips give rise to local erosion spots. These large scale eddies can be reduced by streamlining the design and by placing the design as close as possible to the current coastline. Blocking the flow by placing the tips of an extension perpendicular in the flow increases the eddy formation.

A large accumulation of fine sediments appears at the locations where large eddies develop. On the mudflats the sedimentation rate is limited. These flats fill and empty by the tide. This filling and emptying is associated with a continuous flow, which prevents the settlement of fines. All yearly sedimentation rates at the desired ecology spots fulfill the required conditions for seagrass and mangroves.

Stagnant water can be a problem in the basin designs. However, this is unlikely to happen in a meso-tidal regime with large current velocities.

4.4 MCA

In order to evaluate the provisional designs a multi-criteria analysis (MCA) is used. The results are described in paragraph 4.4.1. The results are discussed in paragraph 4.4.2.
A summary of the results is shown in Table 15. The scores are not weighted relative to 1 overall best design of the MCA. The score which a design gets on a certain criterion is weighted relative to the design that scores the best on that certain criterion.

The MCA was not only used as an evaluation tool, but also to structure our thoughts about what the "best design" should take into account.

4.4.1 RESULTS OF THE MCA

This paragraph discusses the results of the qualitative MCA per criteria group (utility, ecology, coastal protection, "Building with nature" and costs).

Utility

In addition to the purpose of ecology, the utility requirement contributes significantly to the final score.

Designs 6, 7 and 11 are the only alternatives in which the current length of the beaches is not decreased.

Seagrasses and corals are areas that are especially attractive for visitors and can be used for recreational purposes. On the other hand, as described in mangroves are not considered to improve the recreational value of the land. In light of these arguments designs: 2, 7, 10 and 11 meet the requirements of nature and recreation the most.

There are 2 safety factors included in the design: safety of the swimmers (against high current velocities) and external safety against dangerous events, which is dependent on the buffer zone from locations of objects containing toxic and explosive materials. In the first criterion "detached banana" land forms (designs 5 and 6) create the least severe environment for swimmers. In these alternatives seagrass and mangrove areas reduce the flow velocity next to the coastline. In the "attached banana" land form on the other hand, in the artificially created bay, the habitat areas do not influence the flow velocities that greatly. For the external safety, design 11 comes out best, as it results in the creation of additional land in the most distant location from the anchorage line and the vessels carrying hazardous cargo.

Ecology

In terms of ecology, the designs that create much sheltered space for undisturbed existence of habitats receive the highest score. The largest area for the growth of corals is created in design 11 – "lagoon unprotected coral", by constructing a whole coral reef with its flats and crest. In the ten precedent designs, corals were only planted on a c.a. 13.5 m long hard revetment (see cross-section drawings in Appendix H). The seagrasses "attached" islands, "open arms" and "lagoon" forms (respectively designs 7, 10, 2 and 11) result in the most suitable environment for seagrass. Bays created in these designs provide sufficient shelter, according to the habitat requirements for current velocities (<0.25 m/s – conservative value). The detached islands in the form of banana and cigar (respectively designs 5 and 8) provide the largest sheltered area for the growth of mangroves.

Coastal protection

Erosion is an important issue at ECP. The purpose of the new land must therefore also serve as prevention against erosion. Naturally islands are more beneficial in these terms; they provide shelter against waves and currents which is the main reason of erosion at ECP.

Among these designs, the elongated shapes of the "cigar" designs (8 and 9) protect the longest segment of the current coastline. As contrasted, the designs that protect the least of the current coastline are the "closed and open arms" land forms.

Erosion is mainly affected by the turbulence and bed shear stress. As can be foreseen, the land masses that stick out roughly in the waters, create the most turbulent eddies caused by detachment of the flow patterns. Therefore, designs 1, 2 and 4 perform the worst in this criterion. Design 3 ("Cube unprotected mangroves") has a better result than design 4, due to higher bottom level where mangroves grow, which streamline the flow. Following the same principle, designs 6 and 11 create the least turbulence. The largest shear stress occurs in the "closed arms" design in the gap between two peninsulas; this is due to high flow velocities in that area. Again, the "lagoon" design due to its relatively smooth coastline and submerged coral reefs causes the smallest flow accelerations and therefore bed shear stresses.

Last but not least, the criterion of vulnerability for erosion of reclaimed coastline is assessed. The beaches constructed as soft revetment are the most exposed to the wash out and erosion effect. The designs with the longest segments of these revetments (1 and 2) naturally give the worst grade.

Building with Nature

For the criterion of the effectiveness of ecology on coastal protection, the "unprotected" designs obviously score the highest. In these designs (3, 4, and 11) all three types of habitats attenuate hydrodynamic conditions. Designs 2 and 5 protect the coastline to a smaller extent. As for the use of the forces of nature in the overall engineering purpose, all designs are comparable. Tides help to flush the water out of the enclosed areas providing its circulation and therefore reduce the risk of stagnant water. Rainwater outfalls, which are surrounding the designs, on the other hand may cause problems for the quality of water in the area.

Costs

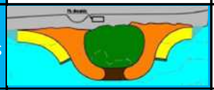
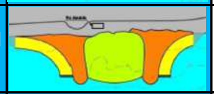
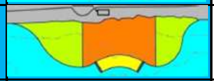
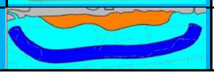
In the criterion of costs of construction the most influential indicators are the length of hard and soft revetments and the amount of landfill material used for the construction. The evaluation only considers the construction costs and does not look at the cost of the whole life cycle.

In design 11 the whole coral reef requires a hard revetment; therefore costs related with this design become the largest. Designs 1, 2 and again 11 create the largest segments of soft revetments mostly due to beaches incorporated in these alternatives. In terms of amount of landfill needed, the designs including mangroves (1,5 and 8) are the most costly, due to the high level of the mangrove flats (+1.53 m above CD). Planting of seedlings turns out to be an issue influencing total costs as well, especially considering the high price of mangrove seeds and seedlings. Again the designs 1, 5 and 8 due to the largest area created for mangroves influences the total costs the most. On the contrary, expenses related to seagrasses are negligible. Therefore, the designs including seagrasses, that is: 2, 4, 6, 9 and 10 are less costly.

In terms of the complexity of construction all the "island" designs require seaborne equipment. Extending land on the other hand may be at least partly conducted from the shore what in the end reduces the total construction costs. Designs 1-4 and 11 are therefore the most beneficial. An attached island provides space for an access road, so no bridge or other construction is necessary. This access road also makes the construction easier.

Another aspect is the flexibility of the design for or future adaptation or extension. This criterion is evaluated based on the area available for this purpose (distance to the anchorage line). The average distance of the reclaimed area to the anchorage line is the shortest in the designs 1, 2 and 11. This means that the largest amount of area is available for future extension.

Table 15 | Summary of the Multi-criteria analysis

Criterion		Area suited for recreation				External safety	Swimmer safety	Stagnant water	Area suitable for ecology			Prevention of erosion				Effectiveness of ecology	Effectiveness forces of nature	Materials and construction					Construc-tability	Flexibility in terms of future plans
Indicator		Total area created	Extra length of the beaches	Extra length of the coastline	Added value of ecosystem	Minimum distance from the mooring line	Current velocities next to beaches	Discharge through opening / wet area in top view	Area of mangroves	Area of seagrass	Area of corals	Length of the sheltered current coastline	Turbulence visible in Delft3D	Impression of the bed shearstresses	Length of the beaches	Ecology serves (protects) the land	Use of forces of nature	Cost of establishing the ecology	Required amount of landfill material	Length of hard revetment	Length of soft revetment	Length of ecology revetment	Complexity of construction method	Average distance from the mooring line
Closed arms protected mangroves (design 1)		+	0	0	--	--	+	++	+		0	-	--	--	-	0	-	-	-	0	+	0	0	+
Open arms protected seagrass (design 2)		-	+	0	+	-	++	0		++	+	-	--	-	--	+	-	0	++	--	+	-	0	+
Cube unprotected mangroves (design 3)		+	-	--	--	+	0	++	+		0	0	-	+	0	++	-	0	++	0	++	+	0	-
Cube unprotected seagrass (design 4)		+	-	--	+	+	-	++		+	0	0	--	-	0	++	-	+	++	+	++	++	0	-
Banana protected mangroves (design 5)		--	-	++	--	-	--	++	++		0	0	+	-	+	+	-	--	--	+	0	-	--	--
Banana protected seagrass (design 6)		--	0	++	+	-	--	++		+	0	0	+	--	+	0	-	+	+	+	0	0	--	--
Attached Banana protected seagrass (design 7)		0	++	++	+	-	++	0		++	0	0	+	-	+	0	-	0	-	+	0	0	-	--
Cigar protected mangroves (design 8)		++	--	++	--	+	0	++	++		0	++	+	+	+	0	-	--	-	0	0	--	--	-
Cigar protected seagrass (design 9)		++	--	++	+	+	-	++			0	++	+	+	+	0	-	+	+	0	0	--	--	-
Attached Cigar protected seagrass (design 10)		++	--	+	+	+	++	0		++	0	+	-	-	+	0	-	0	--	0	0	--	-	-
Lagoon unprotected coral (design 11)		+	++	-	++	++	-	++		+	++	-	++	++	+	++	-	-	+	--	--	0	0	++

4.4.2 DISCUSSION OF THE MCA RESULTS

Provisional designs that scored well concerning utility and ecology turned out to give the highest total score. The best designs that fulfill one of the main purpose of the design – combining recreation with nature coastal protection are: “open arms, protected seagrasses”, “banana and cigar, protected mangroves”, “attached banana and cigar protected seagrasses” and “lagoon unprotected corals” (respectively: design number 2, 5, 8, 7, 10 and 11).

“Open arms” does not serve the purpose of erosion prevention due to the creation of large turbulent eddies. Newly designed beaches in this design also increase the vulnerability of erosion of the coastline. These two criterions make the design less beneficial.

After considering the purpose of space for recreation it turns out that “banana and cigar, protected mangroves” designs do not serve this requirement, due to fact that mangrove forests are not desired for recreation and leisure. Furthermore they decrease the total length of the beaches at ECP the most. In addition the “banana, protected mangroves” alternative creates high and dangerous current velocities that affect swimmer safety.

Designs 7, 10 and 11 still present the best results after considering the utility purpose. The lagoon unprotected coral design is the only design that incorporates the “Building with Nature” philosophy. This is due to fact that the coral reef in front of the coast creates a sedimentary lagoon and attenuates hydrodynamic energy to the largest extent, in contrary to the “attached designs”, where nature artifacts are protected by land masses. This last aspect of the “lagoon” is so significant, that it balances the high construction costs of this design caused by the long segment of hard revetment in front of the coral reef. The only question is wheter low frequency ship waves will cross the reef with or without dissipating energy. However all the aforementioned project purposes make, in the end the design number 11: “lagoon, unprotected corals” the most beneficial. Optionally, in this design seagrasses may be incorporated, which would improve water quality.

5 CONCLUSION

Although mangroves are present in Singapore they have never been present at East Coast Park. This implies that most of the habitat requirements of this ecosystem have to be engineered. A sheltered area has to be created, which protects the seedlings from currents and the forest from wave action throughout the lifetime of the forest. Muddy slopes on which the mangroves grow have to be engineered as the present slopes at ECP are too steep. Finally, seedlings have to be bought and planted, which is a costly undertaking.

Implementing seagrasses in the designs looks promising, as seagrasses are present to the east of ECP, sheltered by a submerged breakwater. Seagrasses should be sheltered from waves and currents (<0.25 m/s) and can grow up to 8 m below MSL in Singapore. The pollination of seagrasses will probably take place naturally as seagrasses are present in large numbers near ECP.

It is expected that relatively large communities of corals can establish on longer time scales, provided that appropriate substrata is offered. at ECP as they have been present in abundance in the past. Nowadays, corals are still found on the hard revetments near the Tanah Merah Ferry terminal. Corals require hard and bare substrata from 6 m below MSL up to LAT. Corals cannot grow deeper in Singapore due to the high turbidity of the waters which attenuate light. Furthermore, the substrata should be engineered in a convex or horizontal shape to prevent sediment from accumulating in between the corals.

The design of additional land involves determining its location, type of land fill, sediment type and shape. The middle part of ECP provides the most space for additional land and is the best location in terms of accessibility, bathymetry and soil conditions. The cross-shore location of the different designs is heavily depth-limited by the mooring area and navigational cross-shore distance in front of ECP. The supply of land fill material poses a big problem in Singapore as sand is scarce. Strengthened sediment and maintenance dredged materials however could provide a solution. Soft revetments of coarse-grained sediments are more vulnerable to erosion than fine sediments as there is no updrift supply of coarse-grained sediment. Lastly, the shape of the islands is not determined by its main purpose, recreation. In an eco dynamic design the shape is determined by the habitat requirements of the eco system in the design. The shape also has an influence on the erosion as the additional landmasses could either increase or decrease the current erosion at ECP.

There is a conflict of interest between the slopes required for ecology and the anchorage area situated offshore. A mangrove forest requires a very gentle slope. There is not enough room to extend this slope naturally up to the anchorage area. A hard revetment must be implemented to cover this transition in height from the gentle slope up to the ocean bottom. Furthermore, a coral reef consists of a flat, a crest and a slope, where a typical hard revetment would only consist of a relatively steep slope. The growth of coral be stimulated by creating staircases on this slope.

It has proven to be difficult to use the ecology to protect the additional land; during establishment, mangroves and seagrasses require sheltered areas but at the same time they are also meant to create sheltering. Another reason is the vulnerability of the seedlings of the various ecosystems. The seedlings require at least a temporary protection, which could be costly. The 'Building with Nature' strategy however can add value to a design and provides an alternative to the traditional coastal engineering concepts. Furthermore the strategy can cut costs in the long term by reducing the maintenance. Nature can adjust itself to new circumstances such as climate change, sea level rise and land subsidence. The forces and materials of nature should be used in the design as they can provide soft coastal solutions and protect the coast.

Coral reefs and seagrass patches increase the recreational value of an area whereas mangroves, being generally considered by the public as swamps, do not. Furthermore, a mangrove forest cannot be combined with beaches and they block the open view on the ocean. In general, recreation and ecology do not blend well as people tend to damage ecology by means of pollution and other activities.

Concluding, tropical ecosystems can be incorporated in the design of additional land in front of ECP. All ecosystems are present in Singapore and some have even been present at and near ECP. If not already present, the habitat requirements concerning sedimentation rate, sediment type, waves, current, tidal regime, depth, soil, morphology, area/patch size and pollination of corals, seagrasses and mangroves can probably be engineered.

6 RECOMMENDATIONS

The recommendations are divided in 3 paragraphs; the recommendations that follow from the system description, the recommendations that follow from the design and the recommendations that follow from the modeling appendix.

6.1 RECOMMENDATIONS FOLLOWING FROM THE SYSTEM DESCRIPTION

There is a lack of data and information to fully elaborate a detailed design for additional land with ecology at ECP. It is very useful to gain more information on several topics:

- Detailed nearshore ship, wind and swell wave data can be determined by offshore wind and swell wave data and nearshore ship wave measurements. This data is useful to calculate the crest height of th erevetments, revetment strength, and longshore sediment transport rates and to determine if the sheltered area for ecology suffices.
- Sediment transport rates and sediment concentrations can be used to run morphodynamic simulations in Delft3D and to model increase understanding of coastal erosion.
- Detailed habitat requirements for the targeted species that will be implemented can be used for a more detailed design.
- More data concerning soil layers and land subsidence rates add information for a more precise crest level calculation. The land subsidence rate should also be used to determine the required sedimentation rates for seagrass and mangroves.
- More detailed information about navigational restrictions is required to make the design more feasible.

Further research could provide an alternative location for the establishment of a mangrove forest. The analyses made clear that the middle of ECP is not a feasible location for the establishment of mangroves.

More alternatives could be designed for combined ecosystems which could improve the reciprocity between the different ecosystems. Different ecosystems can interact with each other in a favorable way. In the current design alternatives only one ecosystem is considered.

It is recommended to incorporate more experts on ecology during the design stages in order to make the right decisions during the design. The collaboration with experts on ecology during the formulation of the habitat requirements was useful to gain background knowledge about the habitat requirements. Most of the habitat requirements are dependent on species and are very site specific and should be interpreted by an expert during the design.

6.2 RECOMMENDATIONS FOLLOWING FROM THE PRELIMINARY DESIGNS

To create the largest space for ecology, an attached island or land extension has to be created. There are three designs which are favorable for a more detailed design step; the "attached banana protected seagrass" (design 7), the "attached cigar protected seagrass" (design 10) and the "lagoon unprotected corals" (design 11).

The lagoon with unprotected coral did not provide the required amount of sheltering in the preliminary design, but scored high in the MCA. This design is promising for the reciprocity between the different ecosystems and the use of the “Building with nature” principle. The design may provide protection against erosion by attenuating hydrodynamic energy. It has similar aspects compared to the seawall near the Tanah Merah Ferry terminal which works quite well as an ecology hotspot. Behind the coral reef, seagrasses can establish. By making the barrier higher, the wave and current energy can be further reduced.

Further research is required to determine the optimal distance between the island and the coastline. More research can be conducted on the streamlining of the flow. This could be done by adjusting the slopes and bathymetry in the designs, by changing the shapes and offshore distance of the island and construction of submerged breakwater.

6.3 RECOMMENDATIONS FOR THE MODEL

In an attempt to improve the nested models results further, flux instead of velocity boundaries can be described on the boundaries of the small nested grid.

Another boundary setup that needs further research is the water level east, water level west and Riemann south configuration. Special attention should be given to the corners of the grid, where the different boundary types meet. In these corners, the information provided by the boundaries should coincide.

Ways of improving the model and to make it fit for full morphodynamic calculations are:

- The models area should be enlarged. The boundaries should be located far away from the area of interest to reduce the effect of the boundaries on the models results.
- The spacing of the grid near the boundaries should be as large as possible to dampen out numerical disturbances.
- With the area of the nested grid enlarged, the type of boundaries to be used should be investigated again. Using boundaries of the water level type on all open boundaries could prove to be successful in this case.
- The resolution of the grid should be in the order of 30 x 30 m in the area of interest.
- The open boundaries should be chosen such that they do not cross complicated flow patterns such as large eddies.
- The model should be run for a full year to incorporate the monsoon.
- Waves should be added to the simulations to assess their influence on the hydro- and morphodynamics.
- A bcd file should be created to make the distinction between mud and sand on the bottom.
- Layers should be added to the model to improve the accuracy of the modeled results.

Before full morphodynamic calculations can be made, more information of the coastal system at ECP is needed; sediment transport rates, sediment concentrations, detailed locations of erosion and accretion spots, sediment compositions and locations (sand vs. silt / mud) and detailed information on dredging and dumping activities in the area.

7 LIMITATIONS

This section discusses the limitations of the system description and design of the project. Some crucial information for both stages was not gathered mainly due to restricted access to the information and data. In these cases assumptions were made and simplified formulas were used.

7.1.1 SYSTEM DESCRIPTIONI

This paragraph describes the limitations of the system description.

Erosion at ECP

The information which was obtained concerning the coastal retreat describes the coastline development for a specific part of ECP. As no information about the rest of ECP was gathered, the validity of the erosion rates given is limited. It is generally known that the whole coast in front of ECP is retreating, which is also confirmed by researchers, but data about this retreat was not available.

The applicability of the equilibrium profiles is limited. The soil mainly consists of cohesive sediments. Cross-shore equilibrium profiles were calculated for non-cohesive sediments only. This is due to fact that recently developed formulas available for calculations of the profiles with cohesive sediments are not fully reliable and therefore were not advised to use by coastal experts.

Nearshore wave data

Another limitation concerns the reliability of the wind and swell wave data in the Strait of Singapore. Historical wave data are in possession of companies or agencies and only accessible upon payment. This applies also to the detailed, historical offshore wave data from a particular area of interest. Historical wave data from Global Wave Statistics were considered to be not accurate enough for further transformation to nearshore data. Therefore the wave climate in the Strait of Singapore was assessed based on literature, interviews with experts and site investigations.

7.1.2 DESIGN

This paragraph describes the limitations of the design.

Ecology

The general requirements for each of three habitats (seagrasses, mangroves and corals) were provided and investigated. Habitat requirements for all the habitats however, vary per species of each ecosystem.

Soil conditions

The current investigation of soil conditions at ECP was limited by the lack of information about soil layers and their strength parameters.

Wave statistics

The crest height of the revetments is influenced by the significant wave height during the design storm. Lack of historical wave data did not allow conducting an extrapolation to calculate the significant wave height during the design period of 50 years. Instead the wave run-up height was calculated with the use of the "maximum significant wave height" as given in a paper (Burt, 2004).

7.1.3 MODELING

This paragraph describes the limitations of the model.

Grid

The resolution of the final grid does not meet the demands as laid down in paragraph *A.1.6 required resolution of the grid*; the size of the grid cells in the area of interest is too big. The possibility of placing the island close to the shore generates the biggest restriction on the gird cell sizes; as small as possible. The models results however have shown that the flow velocities increase to unacceptable values when the islands are placed to close to shore (<200 m). This observation raises the question whether such a fine resolution really is needed.

Tidal forcing

The tidal forcing has been omitted from the models. This forcing are the gravitional forces by the earth, moon and sun. The tides however are included by the boundary conditions. The reason for omitting the forcing is a software conflict. The SRM has been setup in an older version of Delft3D than the version of Delft3D used in this report (version 4.00.00). This however is not a big problem because the effect of the tidal forcing would be in the range of centimeters (Kurniawan, 2011). The simulations of the SRM that have been used to compare results have also been run without tidal forcing. The effect is thus not noticeable when comparing results, but the results that have been used to compare with are off by a few centimeters.

Accuracy

The mudflats on which the mangroves grow have been modelled at MSL. In reality flats have a slope. As a consequence, the flats in the designs are inundated for a shorter period of time than would be the case in reality. The nested model however is not used to determine the inundation times. Furthermore, higher flow velocities are found near the edges of the flats because there is no smooth transition between the mudflat and the water level at MSL.

It is not possible to include land masses above MSL in Delft3D, which could influence the hydro- and morphodynamics of the mudflats of the mangrove forests (e.g. not possible to assess accretion of fines above MSL).

The SRM bathymetry is very coarse near the coast. The time series that generated by the SRM are based on this coarse bathymetry. This could imply that wrong information is fed to the model as the area of the nested model is more detailed. This does not have to be a problem if the area of interest is located far enough from the boundaries. In this case however, the boundaries are relatively close to the area of interest.

Morphology

It is not possible to perform a full morphodynamic calculation with the current model setup for multiple reasons:

- The time domain of the model is only two weeks, the monsoon is not included in the runs. This implies that the influence of the monsoon on the longshore sediment transport rates cannot be evaluated
- The area of the model is too small as sediment exiting on the boundaries cannot return into the model as the boundary condition is set at a certain value.
- Current velocities and directions have to be reproduced more accurately to incorporate asymmetrical aspects of the flow
- There is a lack of necessary input data such as sediment concentrations in the water and on the boundaries, location and influence of dredge and dump areas, sediment compositions and locations (sand vs. silt and clay).

Waves

Waves have not been included in the design runs. This affects vertical mixing processes, mass fluxes, long-shore currents, cross-shore set-up and bed shear stresses (Deltares, Delft3D - FLOW User Manual, 2011). These quantities and processes also affect sedimentation rates and morphodynamic processes. It is therefore important that waves are included in morphodynamic runs.

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APPENDIX A DEFINITION REFERENCE LEVEL

The reference level of the project is Chart Datum (CD) which is the standard to measure tide levels (Wong, 1992). Figure 0.1 presents the different reference systems and bathymetries used during the project. The reference level and tides of the designs are based on the paper written by Wong (1992). The design uses the bathymetry from the Electronic Navigational Charts (ENC). However, the SRM model uses the MSL as reference level and has a different bathymetry. The nested model uses the same reference frame as the SRM. The bathymetry of the nested model consists of the SRM bathymetry offshore and the more detailed ENC bathymetry nearshore.

There are unknown differences between the reference levels of the different reference frames (indicated by question marks in Figure 0.1). This was not a problem as the model results and the designs were not compared in an absolute way.

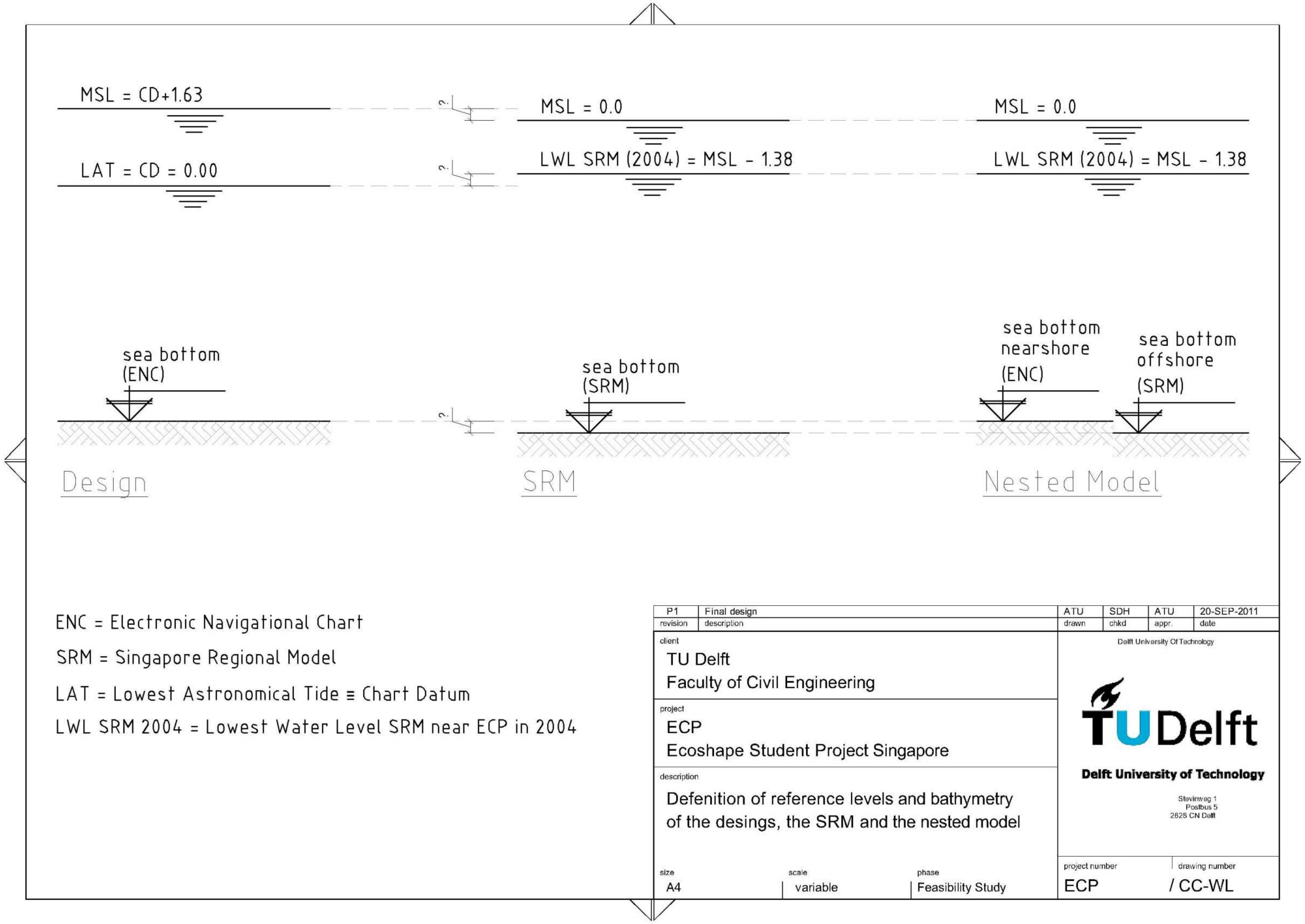


Figure 0.1 | Definition of reference levels and bathymetry of the design, SRM model and nested model

APPENDIX B ANLAYSIS DRAWINGS

This appendix shows sketches and overviews made during the analysis.

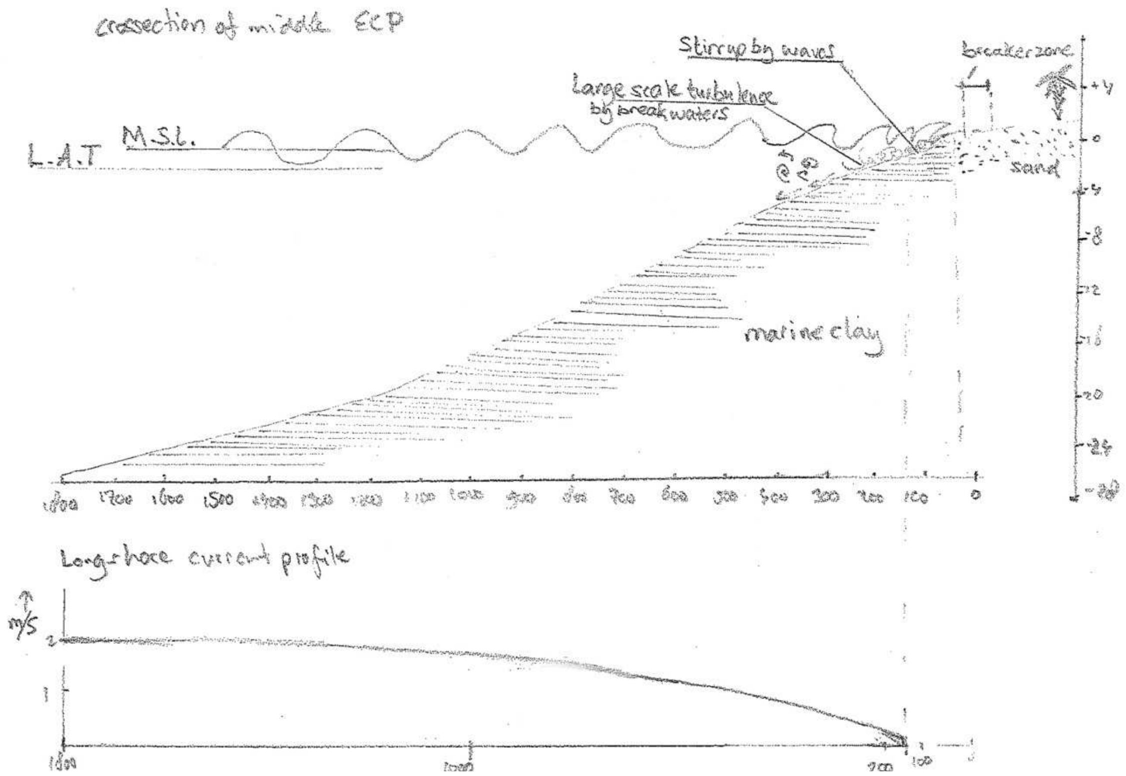


Figure 0.2 | Cross-shore profile and processes

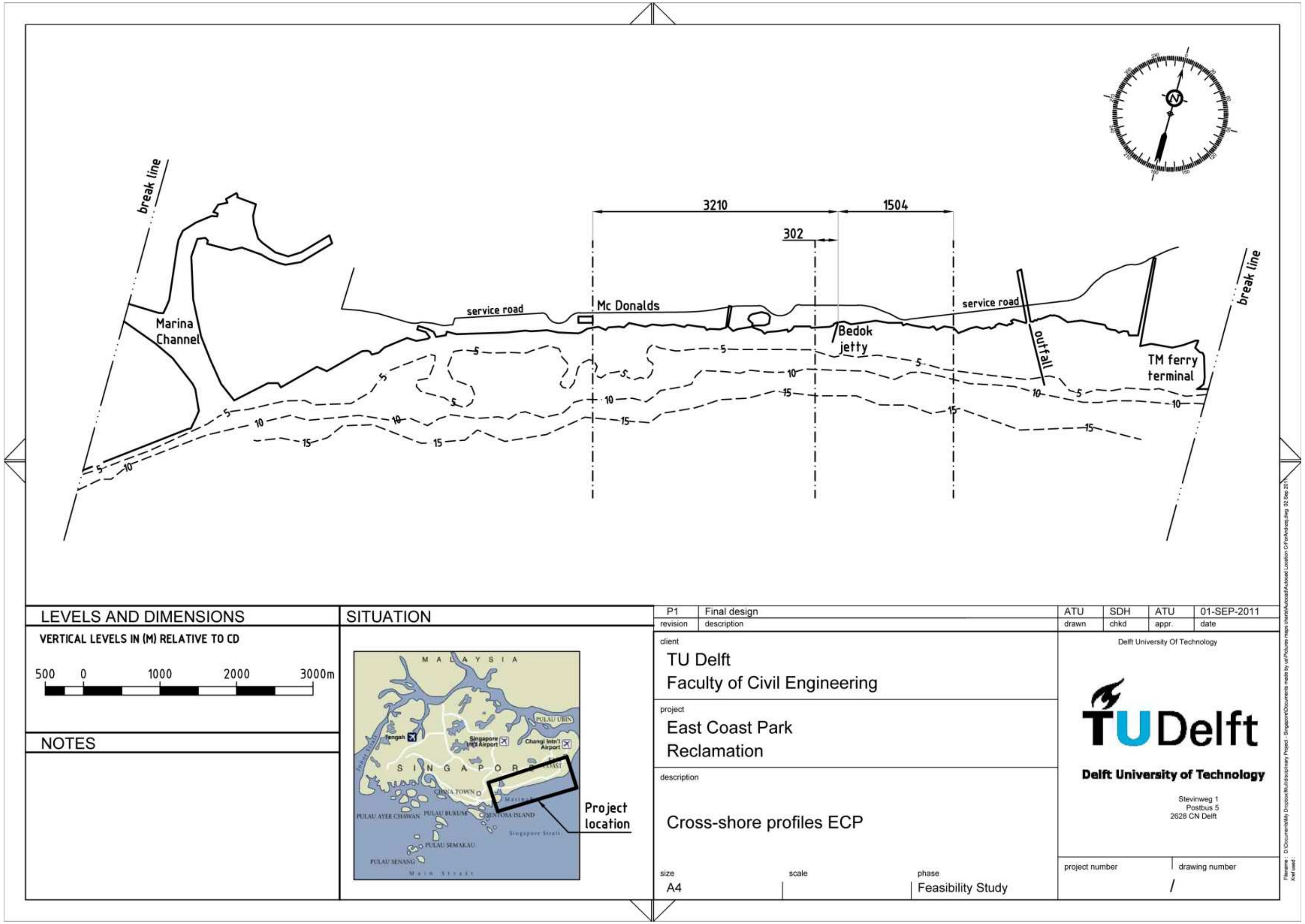


Figure 0.3 | Cross-shore profiles ECP

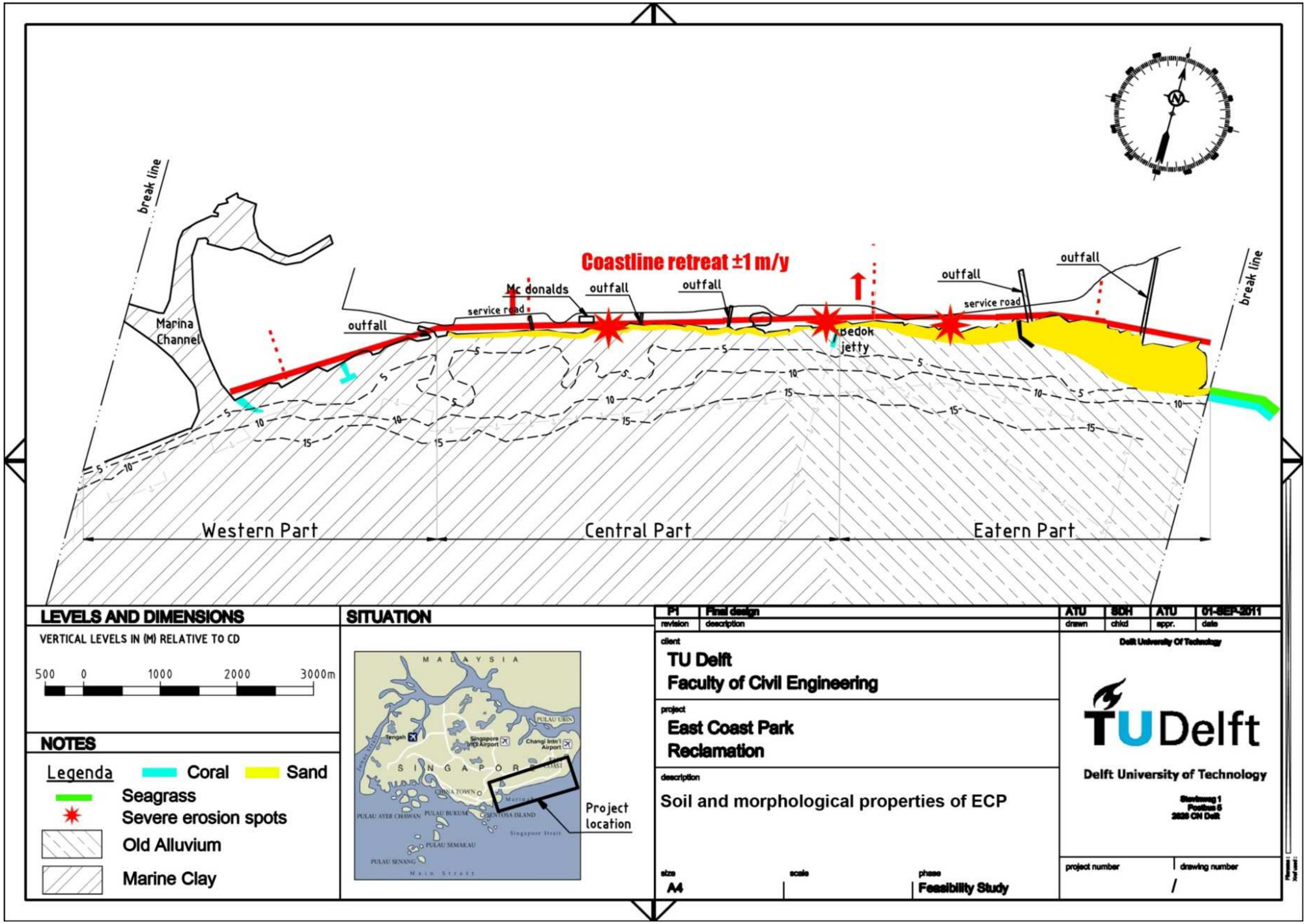


Figure 0.4 | Soil, morphological properties and ecology spots at EC

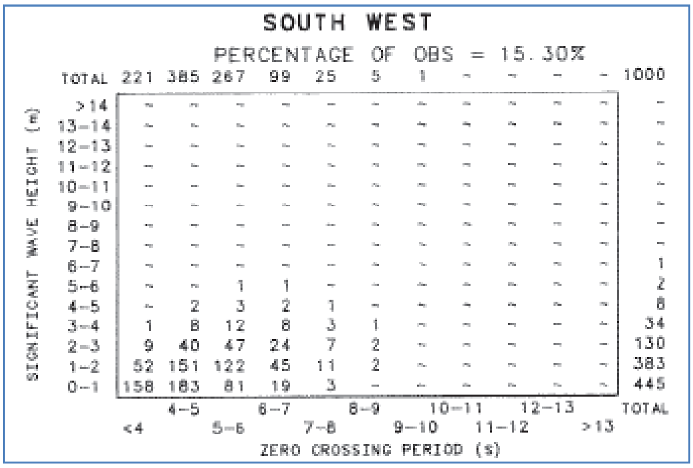
APPENDIX C WAVES

C.1 WIND WAVES

To gain a general view of the wave climate near ECP, offshore wave data collected in the area 62 need to be analyzed (Tkalich et al., 2004). Figure 0.5 and Figure 0.6 present wave observations collected in the area of Singapore. Annual average values Tzu and Hs are listed in the Table 16.

Table 16 | Average annual deepwater wave data heading towards Singapore Strait (based on Figure 0.5 and Figure 0.6)

	Zero-Crossing Period [s]	Significant Wave Height [m]
Southwest	4.7 s	1.1 m
Northeast	5.9 s	1.6 m

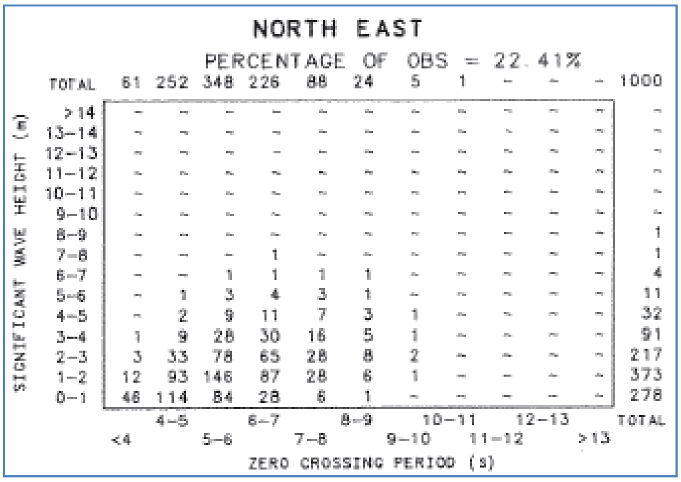


SOUTH WEST

PERCENTAGE OF OBS = 15.30%

SIGNIFICANT WAVE HEIGHT (m) \ ZERO CROSSING PERIOD (s)	<4	4–5	5–6	6–7	7–8	8–9	9–10	10–11	11–12	12–13	>13	TOTAL
TOTAL	221	385	267	99	25	5	1	-	-	-	-	1000
>14	-	-	-	-	-	-	-	-	-	-	-	-
13–14	-	-	-	-	-	-	-	-	-	-	-	-
12–13	-	-	-	-	-	-	-	-	-	-	-	-
11–12	-	-	-	-	-	-	-	-	-	-	-	-
10–11	-	-	-	-	-	-	-	-	-	-	-	-
9–10	-	-	-	-	-	-	-	-	-	-	-	-
8–9	-	-	-	-	-	-	-	-	-	-	-	-
7–8	-	-	-	-	-	-	-	-	-	-	-	-
6–7	-	-	-	-	-	-	-	-	-	-	-	1
5–6	-	-	1	1	-	-	-	-	-	-	-	2
4–5	-	2	3	2	1	-	-	-	-	-	-	8
3–4	1	8	12	8	3	1	-	-	-	-	-	34
2–3	9	40	47	24	7	2	-	-	-	-	-	130
1–2	52	151	122	45	11	2	-	-	-	-	-	383
0–1	158	183	81	19	3	-	-	-	-	-	-	445

Figure 0.5 | Annual wave statistics – SW direction (N. Hogben, et al., 1986)



NORTH EAST

PERCENTAGE OF OBS = 22.41%

SIGNIFICANT WAVE HEIGHT (m) \ ZERO CROSSING PERIOD (s)	<4	4–5	5–6	6–7	7–8	8–9	9–10	10–11	11–12	12–13	>13	TOTAL
TOTAL	61	252	348	226	88	24	5	1	-	-	-	1000
>14	-	-	-	-	-	-	-	-	-	-	-	-
13–14	-	-	-	-	-	-	-	-	-	-	-	-
12–13	-	-	-	-	-	-	-	-	-	-	-	-
11–12	-	-	-	-	-	-	-	-	-	-	-	-
10–11	-	-	-	-	-	-	-	-	-	-	-	-
9–10	-	-	-	-	-	-	-	-	-	-	-	-
8–9	-	-	-	-	-	-	-	-	-	-	-	1
7–8	-	-	-	1	-	-	-	-	-	-	-	1
6–7	-	-	1	1	1	1	-	-	-	-	-	4
5–6	-	1	3	4	3	1	-	-	-	-	-	11
4–5	-	2	9	11	7	3	1	-	-	-	-	32
3–4	1	9	28	30	16	5	1	-	-	-	-	91
2–3	3	33	78	65	28	8	2	-	-	-	-	217
1–2	12	93	146	87	28	6	1	-	-	-	-	373
0–1	48	114	84	28	6	1	-	-	-	-	-	278

Figure 0.6 | Annual wave statistics – NE direction (N. Hogben, et al., 1986)

Nearshore wave data of ECP is shown in Figure 0.7, Figure 0.8 and Figure 0.9.

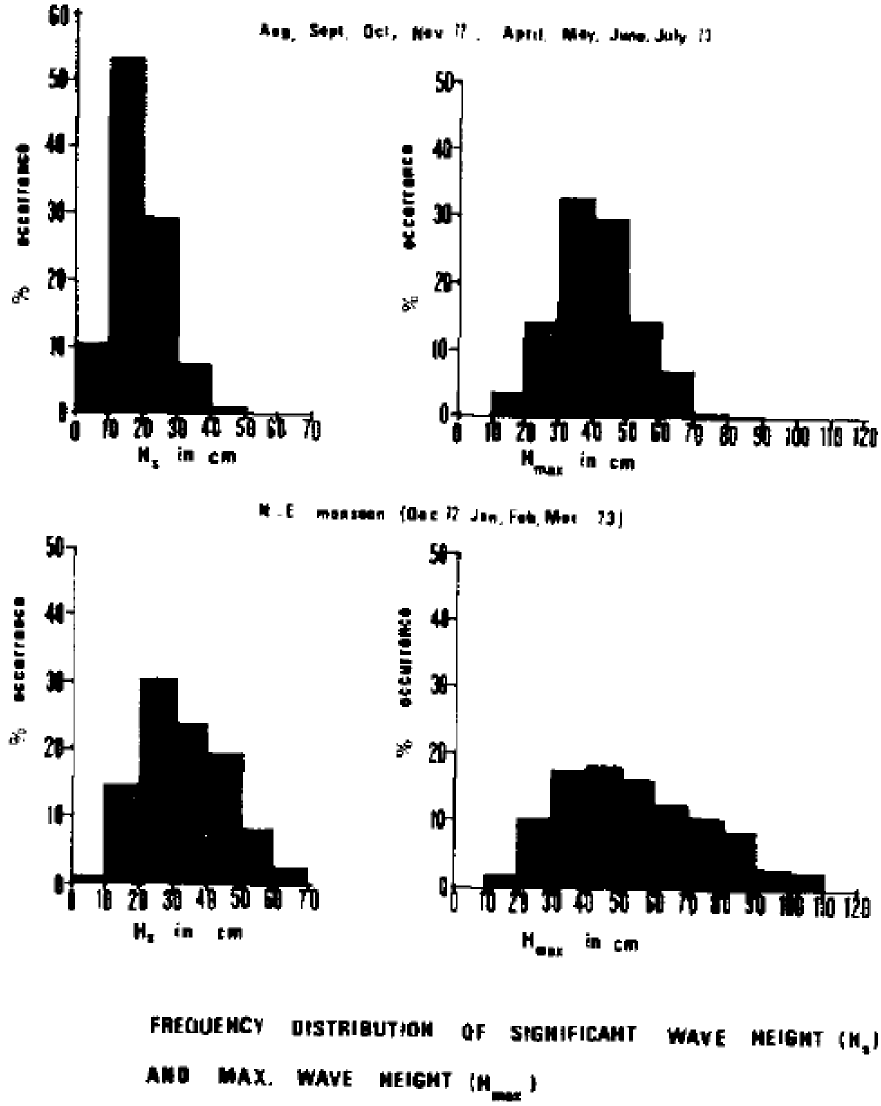


Figure 0.7 | Nearshore wind waves at ECP measured from 1972-1973 (S.Y. Chew, Beach Development Between Headland Breakwaters, 1974).

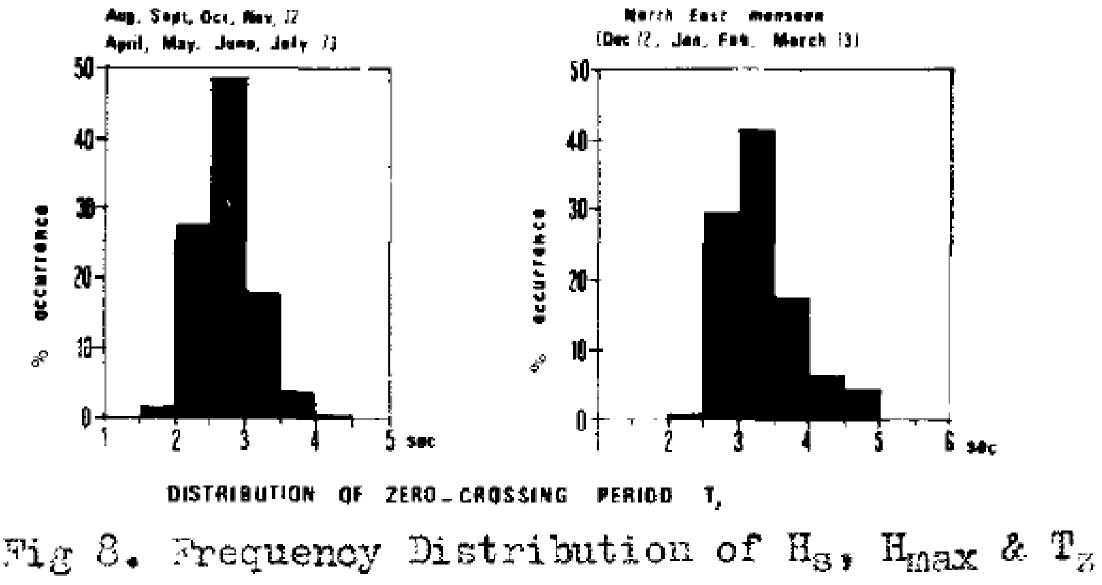


Figure 0.8 | Frequency Distribution of Hs at ECP (S.Y. Chew, Beach Development Between Headland Breakwaters, 1974).

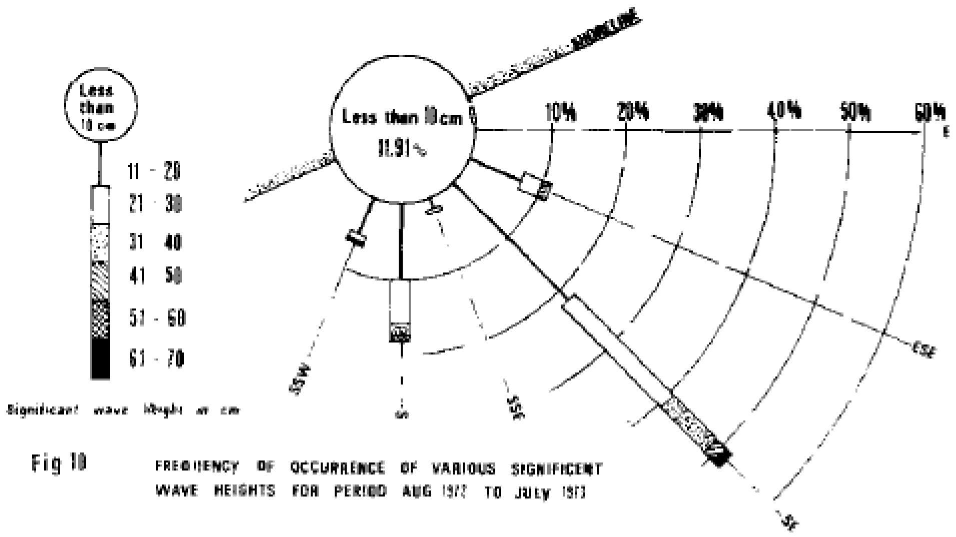


Figure 0.9 | Frequency of occurrence of various significant wave heights at ECP (S.Y. Chew, Beach Development Between Headland Breakwaters, 1974).

C.2 SHIP WAVES

High speed ferries can reach speeds up to 50 knots, but most of them have operating speeds between 25 and 36 knots, see Table 17.

Table 17 | High speed ferry details, from (Kurennoy Dmitry, 2010)

Ship	Type	Length [m]	Width [m]	Operating speed [Knots]	Ave. Wave Height [m]
High-Speed Ferries					
SuperSeaCat	Monohull	100	17.1	35	0.9
Baltic Jet	Catamaran	60	16.5	36	0.6
Nordic Jet					
Conventional ferries with increased cruise speed					
Start	Monohull	186	27.7	27.5	0.9
Superstar	Monohull	176	27.6	27.5	1.0
Viking XPRS	Monohull	185	27.7	25.5	0.6
Superfast	Monohull	203	25	25.5-27.1	0.6

Ships produce primary and secondary waves. The primary waves arise from the water level depression by the vessel movement and have a wavelength about the length of the ship (Schiereck, 2004). The secondary waves arise from the hull of the ship and are usually much shorter. Only high-speed ferries also have long secondary waves. The primary waves of large cargo vessel or oil carrier are more important than the secondary wave of these ships, because they are very long. The propeller wash does not affect the islands, because the navigational channel is too far away for scouring from propeller wash.

The average wave height of the wake of these vessels is about 80 cm, see Table 17. It can reach up to 1.5 m and even higher with interference of wind waves. The waves travel in wave groups with different periods and amplitudes. The first group has the highest amplitude and longest period of about 10-15 s (Torsvik, 2009). The waves of the first group are cnoidal, which results in high bottom velocities and a high mass flux onshore (Kurennoy Dmitry, 2010).

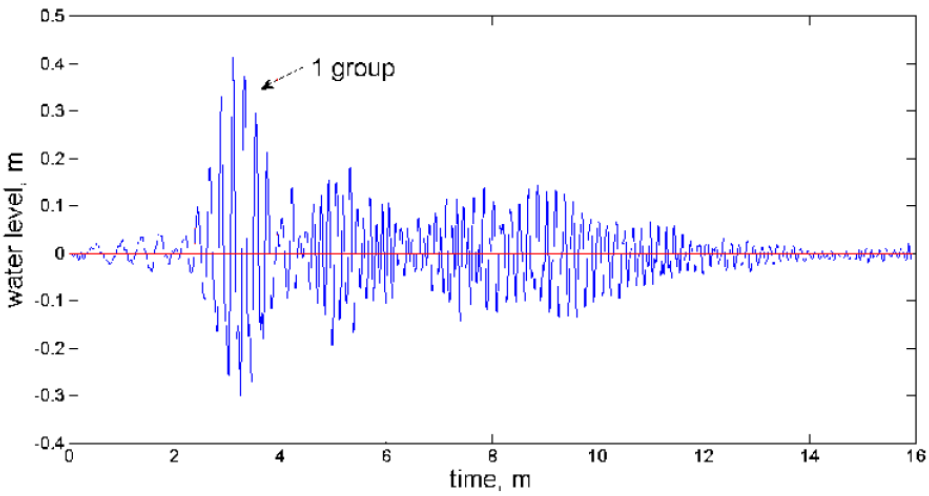


Figure 0.10 | Typical high-speed ferry wave groups, from (Kurennoy Dmitry, 2010).

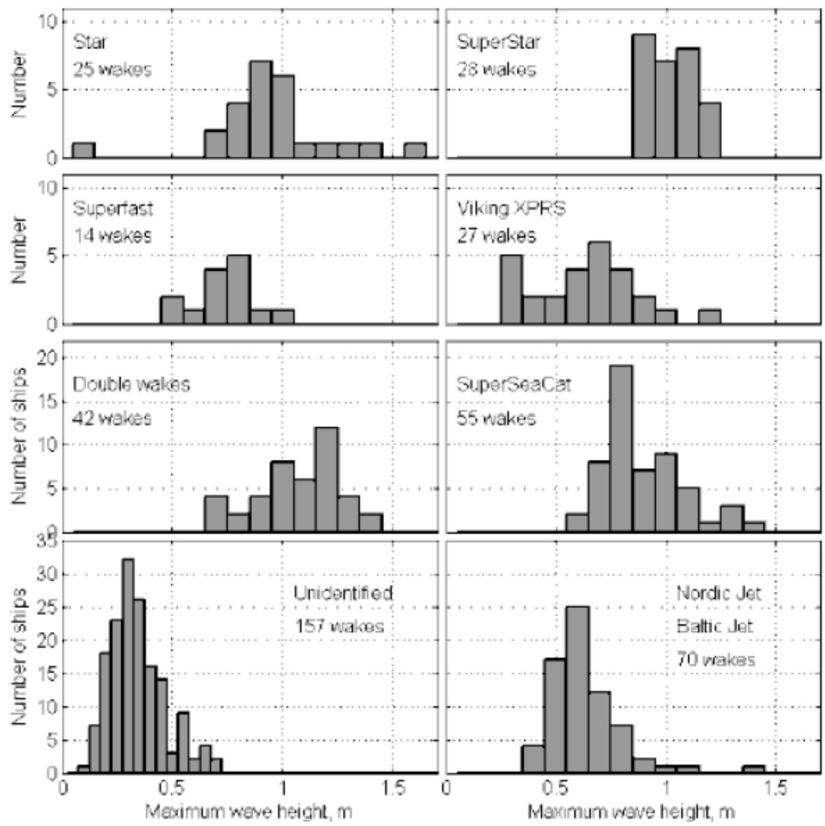


Figure 0.11 | Wave height distributions for different high speed ferries, from (Kurennoy Dmitry, 2010).

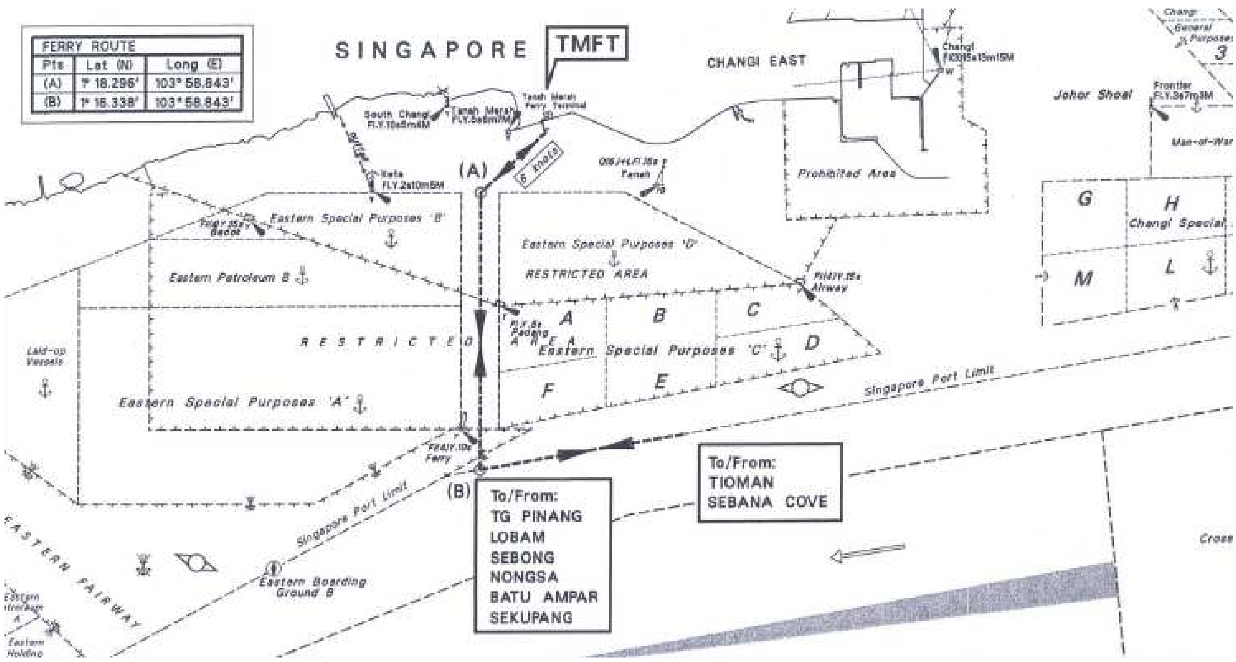


Figure 0.12 | Ferry routes and speed limits at ECP, from (MPA, 2003).

Nearshore the high-speed ferry speeds are limited, but after about 700 m the speed limit voids. The speed limit is there because of protection of the coast and coral just in front of the

Tanah Merah Ferry Terminal. Every day about 90 ferries arrive and depart from Tanah Merah Ferry Terminal (Singapore Cruise Centre, 2011).

In Figure 0.13 the typical primary and secondary waves of a large cargo vessel are shown. The primary wave is situated in the red box, the secondary waves in the blue and green boxes. The primary wave height is about 50 cm with a period of about 69 seconds.

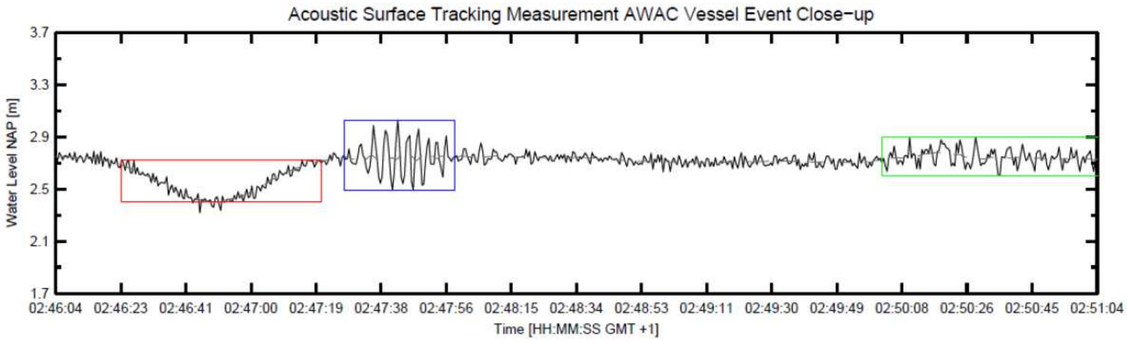


*Figure 0.13 | Typical primary and secondary wave pattern from a large cargo vessel iIn this case the 'JAZAN' L * B = 306*40 m., deadweight=79030 tons, average speed: 9 knots), from (M. Schroevers, 2010).*

C.3 FIELD MEASUREMENTS

At the 13th of August 2011 the project group performed field measurements at ECP. The measurements give an impression of the wave heights and the longshore currents at 2 locations (see Figure 0.14) at a specific point in time. As stated previously the results have no quantitative application during the analysis or design.

The wave period and height were measured at the seaside of the breaking zone, approximately at a water depth of 1.50 m. The direction and velocity of the wave-induced longshore current were measured at as close to the point of breaking as possible.

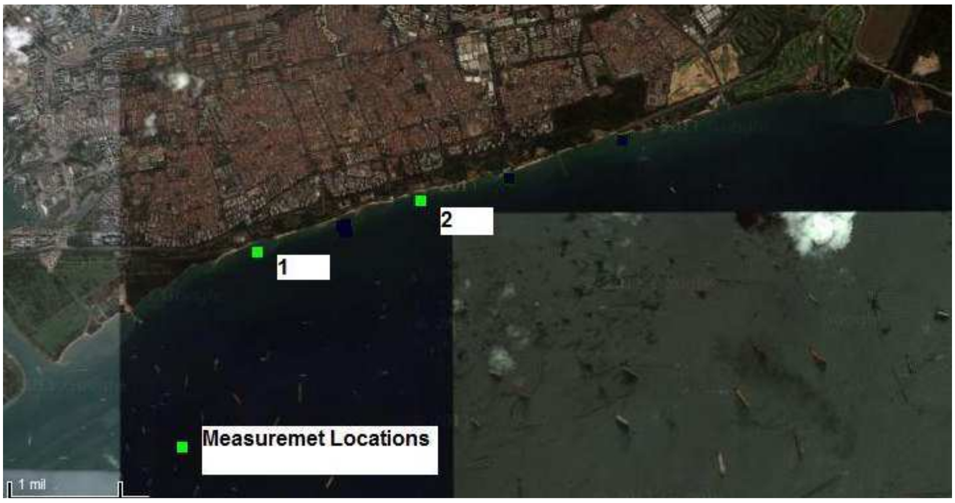


Figure 0.14 | Measurement locations

C.3.1 MEASUREMENT PROCEDURE

This paragraph describes the procedure to determine the wave height, the wave period and the longshore current.

Wave height

The average wave height is determined by measuring heights of 12 waves within a period of 5 minutes. The measuring device was a measuring pole with a ruler attached to it. The accuracy of measurements is estimated to be 0.2 m. The extreme wave heights are discarded (one maximum and one minimum). The wave height is the average of remaining 10 measured wave heights.

Wave period

The average wave period is determined by measuring the total time during which 5 wave crests pass the investigator. This time is the sum of 4 wave periods. This action is repeated 5 times. The average wave period results from averaging the measurements.

Wave-induced longshore current direction and magnitude

The measurement of longshore current is conducted with the use of oranges. The fruits are released at a specified location as close to the point of breaking as possible. The distance which is covered and period of time needed to travel from point A to point B is measured. With these data the current velocity and direction is specified.

C.3.2 RESULTS

Table 18 presents the results of the measurements at the first measurement location. Table 19 presents the results of the measurements at the first measurement location. The order of magnitude of average wave heights was 0.3 m with an average period of 3.0 s. The measurements indicate that there was no wave-induced longshore current. This corresponds with the coast being tide-dominated.

Measurement 1

Location: 1 - ECP infront of underpass

Date & time: 13-08-2011, 14:15

Mean water depth: 1,35 m

Wave Height:			**Wave Period:**		
1	0,42	m	*1*	9,50	s/4 waves
2	0,24	m	*2*	10,15	s/4 waves
3	0,26	m	*3*	10,00	s/4 waves
4	0,45	m	*4*	10,25	s/4 waves
5	0,45	m	*5*	10,30	s/4 waves
6	0,40	m	avg.	10,04	s/4 waves
7	0,44	m	**avg.**	**2,51**	**s/waves**
8	0,34	m			
9	~~0,22~~	m	**Long shore current:**		
10	0,50	m	Distance covered:		
11	0,46	m		0	m
12	~~0,54~~	m			
avg.	**0,40**	**m**			

Table 18 | Results of measurement 1

Measurement 2

Location: 2 - ECP infront "Island Resort"

Date & time: 13-08-2011, 15:55

Mean water depth: 1,25 m

Wave Height:			**Wave Period:**		
1	0,20	m	*1*	11,97	s/4 waves
2	0,22	m	*2*	12,36	s/4 waves
3	0,24	m	*3*	11,35	s/4 waves
4	0,22	m	*4*	11,98	s/4 waves
5	0,24	m	*5*	12,74	s/4 waves
6	0,19	m	avg.	12,08	s/4 waves
7	0,28	m	**avg.**	**3,02**	**s/waves**
8	0,25	m			
9	~~0,18~~	m	**Long shore current:**		
10	0,28	m	Distance covered:		
11	~~0,29~~	m		0	m
12	0,22	m			
avg.	**0,23**	**m**			

Table 19 | Results of measurement 2

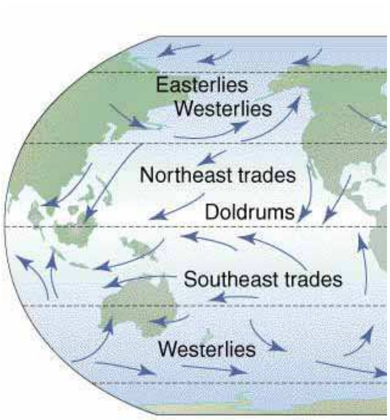


Figure 0.15 | Tradewinds, from (Gende, 2011)

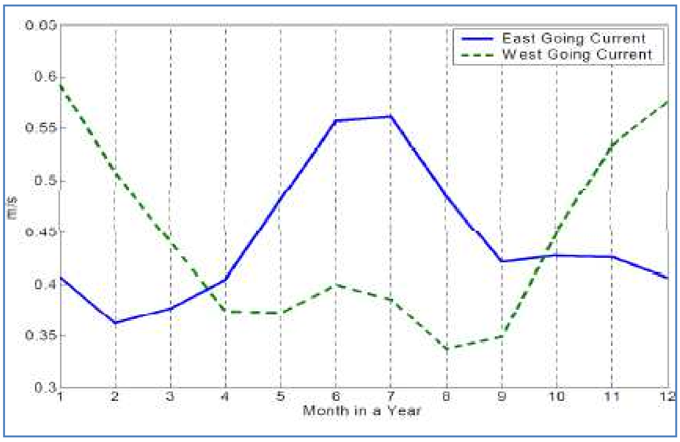


Figure 0.16 | Mean eastward and westward current at the middle of Singapore Strait in each month of typical year, from (Paola Rizzou, 2011)

The residual flow is the yearly averaged discharge in the Singapore Strait as visualized in Figure 0.17 and Figure 0.18. The mean discharge (going to the east or the west) is 2.52×10^5 m^3/s. This means that the total discharge is 7947 * 10^9 m^3/y. From this discharge approximately 2500 * 10^9 m^3/y is the cumulative discharge to the west.

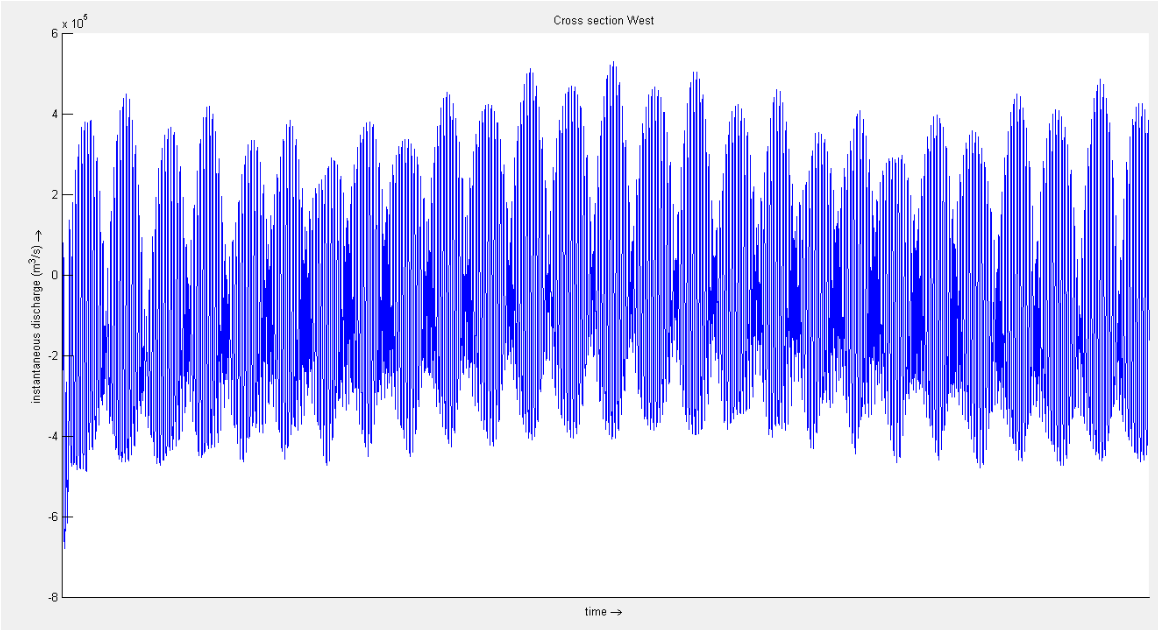


Figure 0.17 | Instantaneous discharge [m^3/s] in the west of the Signapore Straits, from Delft3D SRM

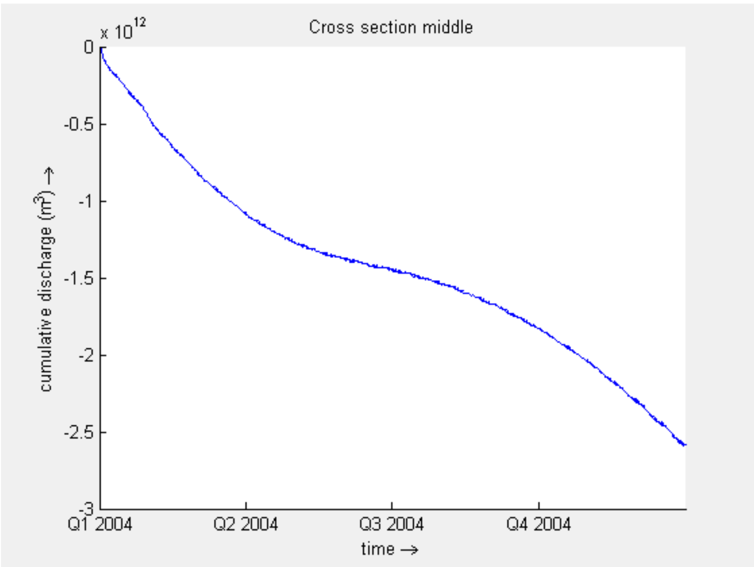


Figure 0.18 | Cumulative discharge in the middle of the Singapore Strait, from Delft3D SRM.

APPENDIX E SEDIMENT PROPERTIES AND SOIL CONDITIONS

This appendix describes the characteristics of the soil at ECP and the site investigation performed by the project group.

E.1 SOIL CHARACTERISTICS

The subsurface in front ECP consists of two soil types; the Kallang formation (Ting, 2002) and the Old Alluvium (Quing, 2005), see Figure 0.19. The Kallang formation consists of Upper Marine Clay and Lower Marine Clay. Table 20 describes the characteristics of these soil types. The parameters of the reclaimed land are based on a report concerning the land reclamation history at ECP (S.Y. Chew, Beach Development Between Headland Breakwaters, 1974).

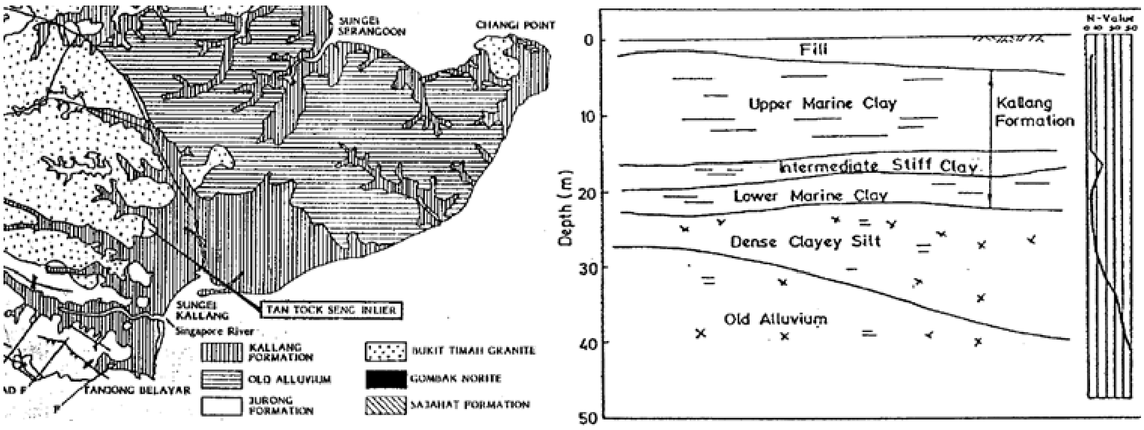


Figure 0.19 | Soil layers and overview

The decisive parameter for construction, the undrained shear strength, is more favorable in the marine clay layers then in the Old Alluvium (45-70 and 11-30 kN/m^2 respectively), due to the fact of non uniformity of the Old Alluvium layer and the presence of organic material. A reclaimed sand layer, even after improvement, does not possess those strong characteristics (24-36 kN/m^2). Important parameters from a hydrodynamic point of view, such as settling velocity and critical shear stress for erosion have been calculated manually (refer Table 20 in Appendix E). They coincide with the standard values for clay and sand.

At the Changi East Reclamation Project, just east of ECP, the 50 m thick clay layer had to be improved in order to speed up the settlement. The ground was improved by 170 million m of vertical drains, 200 ha of deep compactions and 630.000 m^2 of geotextile (M.W. Bo, 2005). A common CPT at the sea bed of the Changi Reclamation site is given in Figure 0.20 in Appendix E.

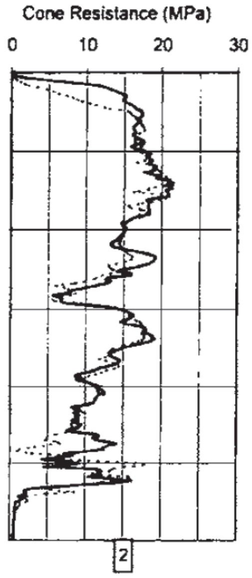


Figure 0.20 | Cone Penetration Test at Changi Reclamation Site, from (M.W. Bo, 2005).

Table 20 | Sediment characteristics of both the original material and reclaimed sand at ECP

	Lower marine clay	Upper marine clay	Old Alluvium	Sand (reclaimed ECP)
Clay fraction [%]	62-70	55-70	20	-
Liquid limit [%]	63-80	65-120	varies widely	-
Plastic limit [%]	22-24	20-45	varies widely	-
Sensitivity (Sr)	3-5	1,5-6	?	-
Specific gravity (Gs)	2,62-2,79	2,50-2,75	2,65	2,65
Activity (Ac)	0,50-0,90	0,95		-
Minearology	Kaolnite, Illite, Smectite, Quartz	Kaolnite, Illite, Smectite, Quartz	Clayey sand (quartz, but rhyolite, argillite), Silt (quartz), Clay (kaolinite, illite, smectite)	quartz
Compression index (Cc)	0,45-0,95	0,7-1,3	?	-
Swelling index (Sc)	0,15-0,22	?	?	-
Friction angle (Φ)	22-25	?	22	?
pre-consolidation pressure (pc)	140-270	?	?	-
(undrained) Shear strength kN/m2	45-70	45-70	11-30	24-36 (after soil improv.)
Natural warer content [%]	52-64	60-85	15-25 ; 20-40 (sand, clay respectively)	-
Grain size diameter [mm]	<0,0002	<0,0002	0,0002-4	0,63 (upper foreshore) - 0,76 (lower foreshore)
initial void ratio (e0)	1,373-1,669	1,8-2,2	?	-
Unit weight[kN/m3]		16	20,3	-
slope gradient	-	-	-	1:8-1:10
Specific density [kg/m3]	2630	2630	2600-2700	2650
Dry bed density [kg/m3]	?	?	?	?
Initial sediment layer thickness at bed [m]	<15	<25	1,35 ; 9 (avg, max respecively)	?
Settling velocity / fall velocity [m/s]	0.0001 - 0.001	0.0001 - 0.001	0,137	0,087
Critical bed shear stress for sedimentation [N/m2]	?	?	?	?
Critical bed shear stress for erosion [N/m2]	0,118	0,115	0,560	0,300
Median sediment diameter / D50 [m]	?	?	?	0,00063

Settling velocities of sand and sand-mud mixture particles were determined using Van Rijn formulas (de Vriend H.J. et al., 2010). Calculating the single clay particle settling velocity is not applicable in this case due to fact that cohesive sediment flocculates resulting in a typical fall velocity of 0.1-1 mm/s.

$$w_s = \frac{\Delta g D^2}{18\nu}$$

$$w_s = \frac{10\nu}{D}\left(\sqrt{1 + \frac{0{,}01 g D^3}{\nu^2}} - 1\right)$$

$$w_s = 1{,}1\sqrt{\Delta g D}$$

$$\psi_c = \frac{\tau_c}{(\rho_s - \rho_w) g D}$$

Critical shear stresses were determined using Shields formula for non-cohesive materials (Schiereck, 2004), the formula for critical shear stress of cohesive particles (Taki, 2001) and sand-mud mixture (Ahmad et al., 2011).

$$\tau_c = 0{,}05 + \beta\left(\frac{1}{\sqrt[3]{\{(\pi/6)(1 + sW)\} - 1}}\right)^2$$

$$\tau_{sm} = e^{\beta\left(1-\frac{1}{P_s}\right)}\tau_{e,s} + (1 - P_s)\tau_{e,m}$$

E.2 SITE INVESTIGATION

Visual site investigation conducted on the 30th of August 2011 supports information found in the literature about sea bottom soil conditions. In the Figure 0.22 it is noticeable that soil collected offshore has a similar size to the one present near the coastline. Figure 0.23 presents typical grain size of sand used during reclamation. Lack of fine sand particles indicates that they were washed away during the last 30 years. Typical clayey structure (Figure 0.24) confirms that marine clay founds the bottom of the eastern part of ECP.

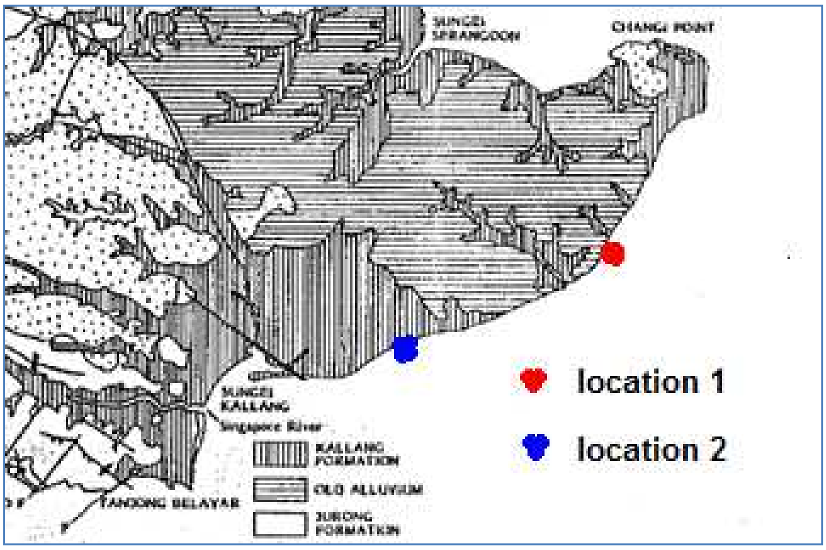


Figure 0.21 | Locations of soil samples collection

Figure 0.22 | Sample collected at location 1, about 150 m offshore

Figure 0.23 | Sample collected at location 2, about 6-8 m offshore

Figure 0.24 | Sample collected at location 2, about 15 m offshore

APPENDIX F RISK ANALYSIS

The risk analysis was carried out by organizing a brainstorm meeting with the project group. The likelihood of the risk and impact of its consequences leads to assigning a risk estimate, which is normative in the evaluation of each risk. Table 21 presents the matrix used for this purpose. The remainder of this appendix contains tables which describe the consequences, impact, likelihood, risk estimate and mitigation measures for every risk.

Table 21 | Risk estimate matrix (Australian Government, 2005)

RISK ESTIMATE MATRIX					
LIKELIHOOD	Highly likely	Low	Moderate	High	High
	Likely	Negligible	Low	High	High
	Unlikely	Negligible	Low	Moderate	High
	Highly unlikely	Negligible	Negligible	Low	Moderate
		Marginal	Minor	Intermediate	Major
		CONSEQUENCES			

	Risk	Consequences decription	Impact	Likelihood	Risk Estimate	Mitigation measures
	FEASIBILITY STUDY					
1	Public expectations regarding ECP utility are not met	- People will not visit new ECP area, facilities will not generate income, which leads to desertification of bussines	*minor*	*unlikely*	***Low***	- survey the public about their requirements and expectations - involving public paricipants in the feasibility study phase
2	Problems with acquiring landfill material	- The design will not be completed as designed. - Costs are raising	*intermediate*	*likely*	***High***	-investigating possibilities for landfill material purchase - investigating possibilities of alternative material usage
3	Hydrodynamic conditions do not allow the desired habitat to develop	- Erosion of coast / scouring of the bed due to insufficient protection - Less public intrest (income for bussines) due to unattractive area	*intermediate*	*unlikely*	***Moderate***	- redesigning shape, alignment etc. of the islands -design of extra breakwaters, groins and screens
4	Problems with acquiring permits for construction	- Implementation of the design does not take place (project ends on the paper)	*major*	*highly unlikely*	***Moderate***	- detailed inquiry about requirements of legislation / environmental agencies - making the design accoring to interational standards and norms
5	Costs of construction too high for client (government)	- Implementation of the design does not take place (project ends on the paper)	*major*	*highly unlikely*	***Moderate***	- applying low budget solutions (i.e. eco coast defences, reusable land fill material)
6	Governmental agencies are not interested in the project (purposes Ecoshape ≠ government)	- Implementation of the design does not take place (project ends on the paper)	*major*	*unlikely*	***High***	-lobbying among governmental agencies for eco-friendly design of reclaimed land
7	Design not ready in time	- competitive design implemented (waste of money on feasibility study and conceptual planning)	*minor*	*unlikely*	***Low***	- extra manpower required - deadlines for results of scientific researches

	DESIGN PHASE					
15	Insufficient / inaccurate wave data	- inappropriate conditions for habitats to grow - higher maintenance costs / too conservative design	*intermediate*	*unlikely*	***Moderate***	-purchasing historical wave data from specific location - involving parties possessing sufficient information about soil conditions
16	Insufficient / inaccurate soil conditions data	- land subsidance, therfore higher maintenance costs	*marginal*	*unlikely*	***Neglible***	- accurate and detailed soil investigation - involving parties possessing sufficient information about soil conditions
17	Insufficient / inaccurate sediment concentration data	- inappropriate conditions for habitats to grow - undesired erosion / accretion of coast	*intermediate*	*likely*	***High***	- accurate and detailed sediment measurements - investigating sources of sediments and sediment transport along ECP
18	Incorrect analysis of ECP coast development	- undesired erosion / accretion of coast	*minor*	*unlikely*	***Low***	- extra expetise on ECP coast development by organizations possessing required knowledge
19	Incorrect information regarding habitat requirement	- habitats do not establish which leads to erosion /scouring of coast / seabed	*intermediate*	*unlikely*	***Moderate***	- meticulus reserches on habitat requirements - applying similair rules as in successful reference projects
21	Model not accurate enough to evaluate designs (coarse reslution)	- insufficient info to design appropriate ecosystems - insufficient information to design appropriate coastal defence systems (cost of maintenance increase)	*intermediate*	*highly likely*	***High***	- conducting physical models

	Risk	Consequences decription	Impact	Likelihood	Risk Estimate	Mitigation measures
8	Not enough time to include ecology (habitats requirements not known)	- competitive design implemented (waste of money on feasibility study and conceptual planning)	*minor*	*unlikely*	***Low***	- extra manpower required - deadlines for results of scientific researches
9	Change of government	- Implementation of design does not take place (project ends on the paper)	*major*	*highly unlikely*	***Moderate***	-lobbying among new governmental agancies for eco-friendly design of reclaimed land
10	Soil conditions not suitable	- increase of costs due to soil improvments	*minor*	*unlikely*	***Low***	- applying soil improvement methods - implementing different construction method (island on piles, floating island)
11	Pollutants in water / soil	- bad conditions for the habitats to establish - erosion and scouring problems related to habitats	*intermediate*	*highly unlikely*	***Low***	- accurate and detailed soil and water measurements in terms of pollutants
12	No more need for space / recreation	- Implementation of design does not take place (project ends on the paper)	*major*	*highly unlikely*	***Moderate***	- ROI and feasability study
13	Connection to inland infrastructure is not possible	- improper accesibility for people results in a less public interst - increase of coast due to construction of untypical passages (tunnels)	*minor*	*highly unlikely*	***Neglible***	- design of untypical passages (tunnels, ferries, cable cars etc.)
14	MPA blocks the project due to influence on marine traffic	- Implementation of design does not take place (project ends on the paper) - new design of smaller islands reuslts in longer ROI	*major*	*likely*	***High***	- decreasing the size of reclaimed land - applying solutions that lead to reduction of area (i.e. steep slopes, quay wals)

	Risk	Consequences decription	Impact	Likelihood	Risk Estimate	Mitigation measures
22	Model does not produce reliable results	- inappropriate design resulting in erosion / scour (higher maintenance costs) - habitats do not establish	*intermediate*	*unlikely*	***Moderate***	- conducting longterm measurments in order to calibrate model
23	Insufficient time / manpower to complete design	- delay in delivery of final design - competitive design chosen - goverment postpones or reject decisions about construction	*major*	*highly unlikely*	***Moderate***	-involving more and / or more experienced staff - meeting the deadlines
24	Failure of information management (files lost / deleted)	- delay in delivery of final design - competitive design chosen - goverment postpones or reject decision about construction	*major*	*highly unlikely*	***Moderate***	- making periodical backups - using servers instead of personal data carriers to store files
25	Unpredictible sea level rise	- extinction of habitats - higher probability of damage during less severe weather conditions	*intermediate*	*highly unlikely*	***Low***	- considering conservative sea level rise predictions
26	Not enough space (critical mass) /slopes too steep for ecology	- change of requirements regarding function of island - preparation of new design (extra cost and time)	*marginal*	*highly unlikely*	***Neglible***	- designing smaller designs - applying different methods for implementation of ecosystems (terraces, floating mangroves / corals)
27	inappropriate type of mangroves / sea grass / corals / applied in the design	- habitats do not establish which leads to erosion of the coast / seabed	*intermediate*	*highly unlikely*	***Low***	- extra expertise of experienced personel - additional research on habitats
28	oocurance of stagnant water areas	- danger for newly implemented habitats to extinct - unattractive recreation conditions resulting in lesser interst of public (less income for business) - extra costs for implementing solution methods	*intermediate*	*unlikely*	***Moderate***	-design of constructions improving water flow and circulation

	Risk	Consequences decription	Impact	Likelihood	Risk Estimate	Mitigation measures
	CONSTRUCTION PHASE					
29	Bankrupcy of a contractor	- delays in construction - extra costs related with a new tender procedure	*marginal*	*highly unlikely*	***Neglible***	- choosing joint venture companies as contructors
30	Unexpected settlements	- extra cost of landfill material - extra costs of construction - in case of implementing ground improvements extra time costs involved	*minor*	*unlikely*	***Low***	- soil improvments (i.e. vertical drains, deep mixing) - rising and leveling the land
31	Too high current velocities	- extra costs related to counter active measures and new construction techniques - bed scouring	*marginal*	*likely*	***Neglible***	- construction of temporary screens for diverting or slowing currents - using heavier construction material or different construction methods
32	Ship collision	-delays in construction	*marginal*	*highly unlikely*	***Neglible***	- taking extra precautions
34	Delays due to weather conditions, earthquake tremors (liquefaction)	- delays in construction	*marginal*	*unlikely*	***Neglible***	- taking weather conditions into the planning and considering in the critical path
35	Project becomes too expensive due to unexpected events	- cease of construction and redesigning the original plan	*intermediate*	*unlikely*	***Moderate***	- conservative estimation of risks and costs of the project
36	Shortage of construction materials (e.g. landfill)	- cease of construction and redesigning the original plan	*intermediate*	*likely*	***High***	-purchasing material from different sources - using alternative materials
37	Public opposes the project during construction (permits withdrawn)	- cease of construction and redesigning the original plan	*intermediate*	*highly unlikely*	***Low***	- conducting construction with agreement of the public

	Risk	Consequences decription	Impact	Likelihood	Risk Estimate	Mitigation measures
38	Construction stopped by the MPA due to effect on marine traffic / mooring	- redesigning the original plan	*marginal*	*likely*	***Neglible***	- careful operation of dredging / construction activities in regard to marine traffic - negaotiations with the MPA about usa of marine /mooring routs and areas
39	Work stop due to problems with equipment and spare parts	- delays in construction	*marginal*	*highly unlikely*	***Neglible***	- choosing reliable and recognized contractors
40	Rare animal species living in the area of design, archelogocial / bomb findings	- cease / delay of construction - extra costc and time related to removal of bombs / archeological excavation	*intermediate*	*highly unlikely*	***Low***	- inspection of construction area - in case of detection hiring profesional experienced companies to make the excavations efficiently
41	Changes of governmetal plans	- cease of construction and redesigning the original plan - Implementation of design does not take place (project ends on the paper)	*major*	*highly unlikely*	***Moderate***	- lobbying among governmental agencies for soundness of land reclamation
42	High turbidity doesn't allow to implement ecology	- redesigning the original plan (extra costs and time) - changes in zone (land use) planning - no more area for ecological research	*minor*	*unlikely*	***Low***	- applying low-spillage construction techniques i.e. hydraulic pumping in the cofferdam, pumping onshore

	REALIZATION					
	Risk	**Consequences decription**	**Impact**	**Likelihood**	**Risk Estimate**	**Mitigation measures**
43	Erosion problems	- extra maintenance costs (beach nourishment), decrease of number of habitats	*intermediate*	*highly unlikely*	***Low***	- beach nourishment - construction of extra bed and coastal protection - planting and maintenance of habitats
44	Plague of insects / bacteria destroy ecology	- danger of habitats to extinct - erosion and scouring problems related to habitats extinction	*intermediate*	*highly unlikely*	***Low***	- periodical examination of ecosystems and surrounding waters for detection of hostile species
45	New area does not attract people	- People will not visit new ECP area, facilities will not generate income which leads to desertification of bussines	*minor*	*highly unlikely*	***Moderate***	- inculding public opinion on land use facilities development - advertisment of "new ECP"
46	Ecology will not establish	- erosion and scouring problems related to habitats extinction	*intermediate*	*likely*	***High***	- extra research on habitat requirements and its implementation
47	Islands swept away /severely damaged by extreme weather conditions	- extra maintenance costs - reinvestment in facilities and infrastructure (longer ROI period)	*major*	*highly unlikely*	***Moderate***	- conservative design during "feasibility study" and "design phase"
48	Contamination due to oil spill from tankers	- extinction or significant decrease of habitats and species in the ecosystem - erosion and scouring problems related to habitats extinction	*intermediate*	*highly unlikely*	***Low***	Cleanup utilities nearby and protective area for ecology

APPENDIX G SURVEY ECP

The survey is shown in paragraph G.1. The plots summarizing the results of the survey are given in paragraph.

G.1 SURVEY ECP

1. Are you a regular visitor of East Coast Park (more than 5 visits a year)?

    No
    Yes

2. Why do you come to East Coast Park?

    For the beach
    For leisure
    For the view
    For Fishing /Angling
    For nature
    For sports
    For BBQ-ing
    Other ....

3. Do you go swimming at East Coast Park?

    Yes
    No

4. What would be the best East Coast Park extension?

    A large island in front of the coast
    Multiple small islands in front of the coast
    Extension of the current coastline
    A combination of the above

    Any reason why?
    ....

5. What view do you prefer on the waterfront?

    Nature, like mangrove forests or botanical gardens
    Beaches
    Other ....

6. What is your opinion about a bio-diverse island with ecology, like a mangrove park with native species, sea grass meadows, coral reefs at East Coast Park?

    Not interested in, I would prefer other land use.
    Interesting, but I wouldn't like to pay extra for visiting such an area
    Interesting, I am willing to pay more for visiting such an area

7. What would be the best location for an East Coast Park extension?

    On the west side of East Coast Park
    On the east side of East Coast Park
    In the middle of East Coast Park

8. Have you heard of "Building with nature" as a strategy for coastal development?

    Yes
    No

G.2 RESULTS SURVEY ECP

The results of the survey are visualized in the figures in this section.

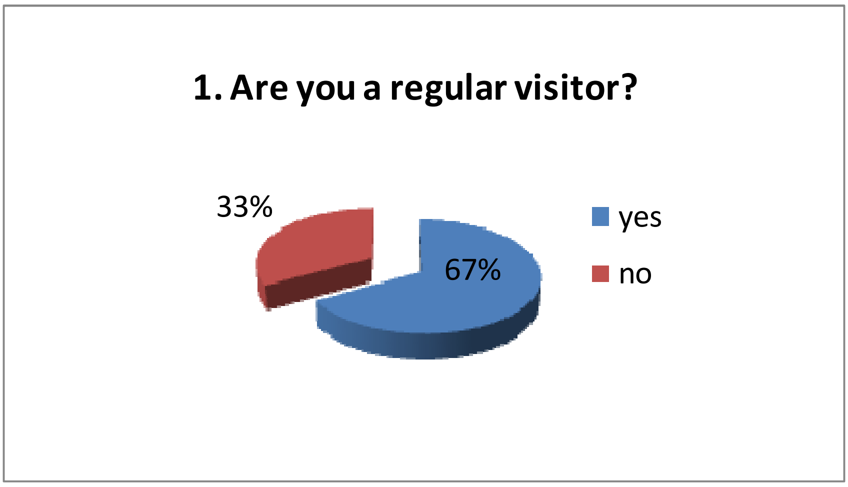


Figure 0.25 | Question 1

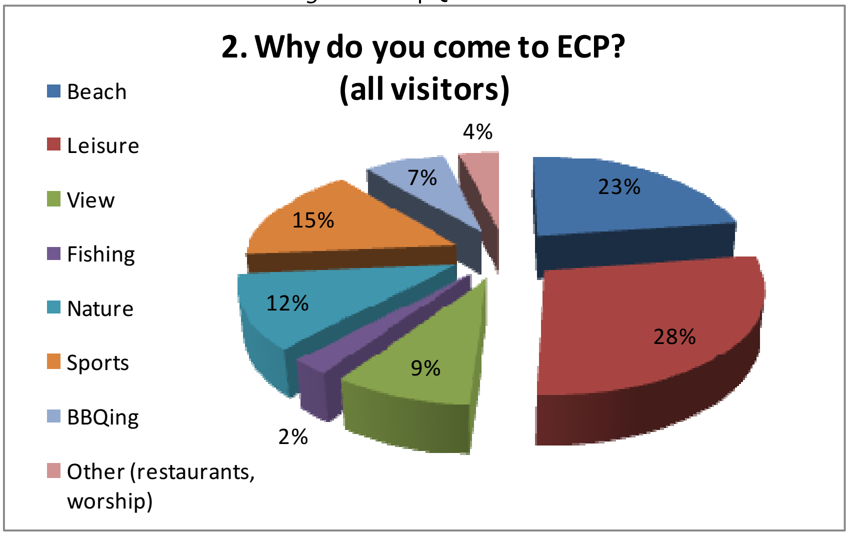


Figure 0.26 | Question 2 (all visitors)

The percentages in question 2 are based on the number of boxes checked as checking multiple boxes was possible.

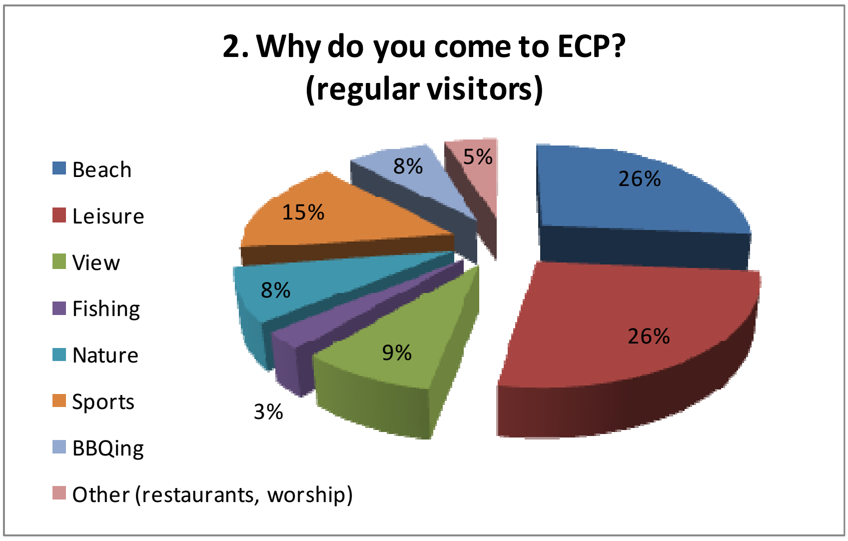


Figure 0.27 | Question 2 (regular visitors)

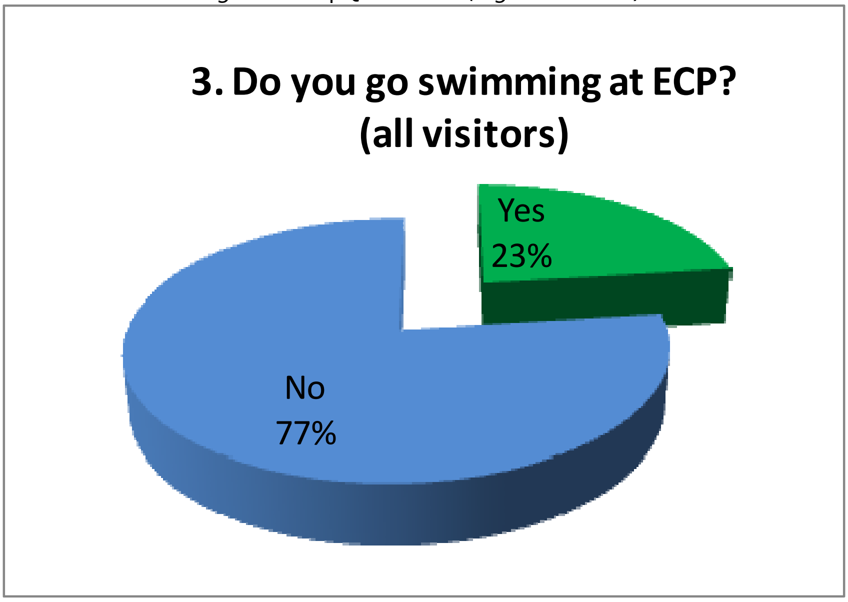


Figure 0.28 | Question 3

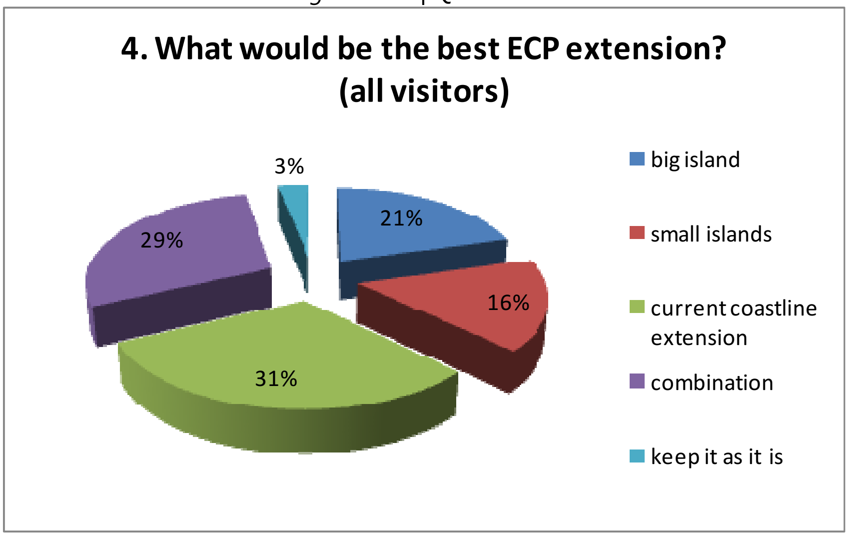


Figure 0.29 | Question 4

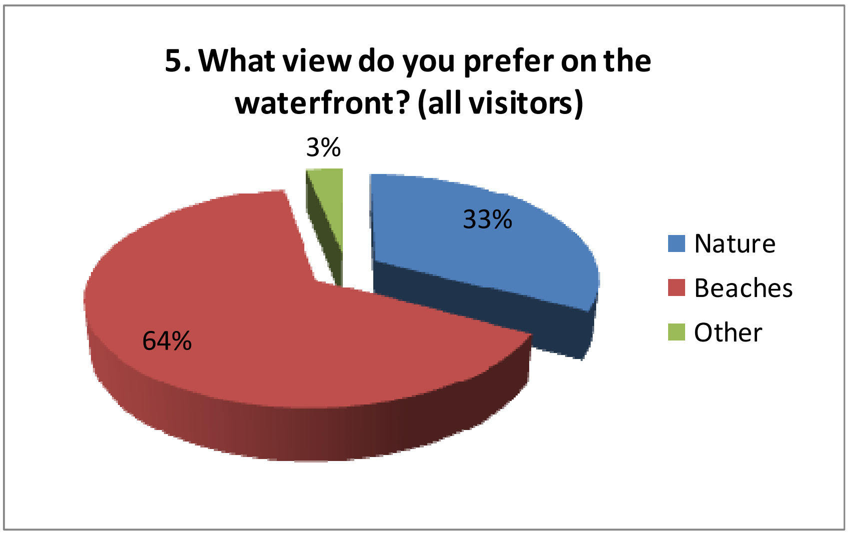


Figure 0.30 | Question 5 (all visitors)

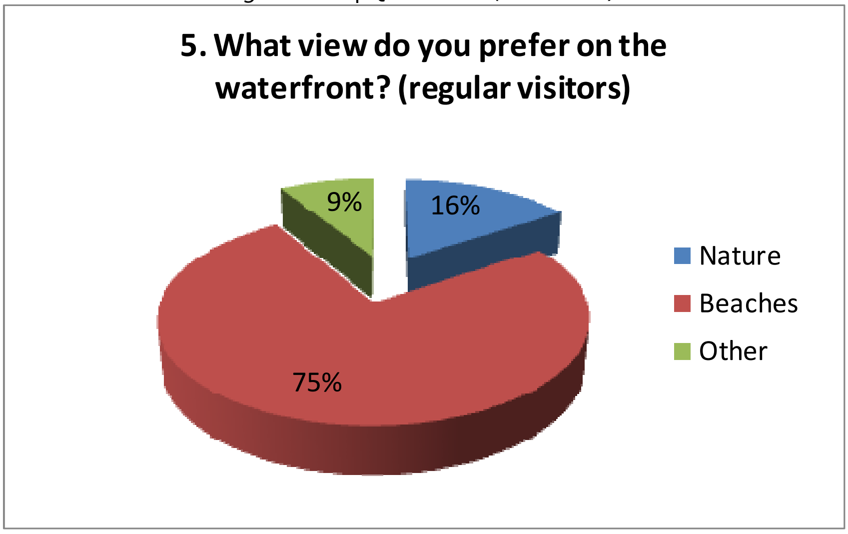


Figure 0.31 | Question5 (regular visitors)

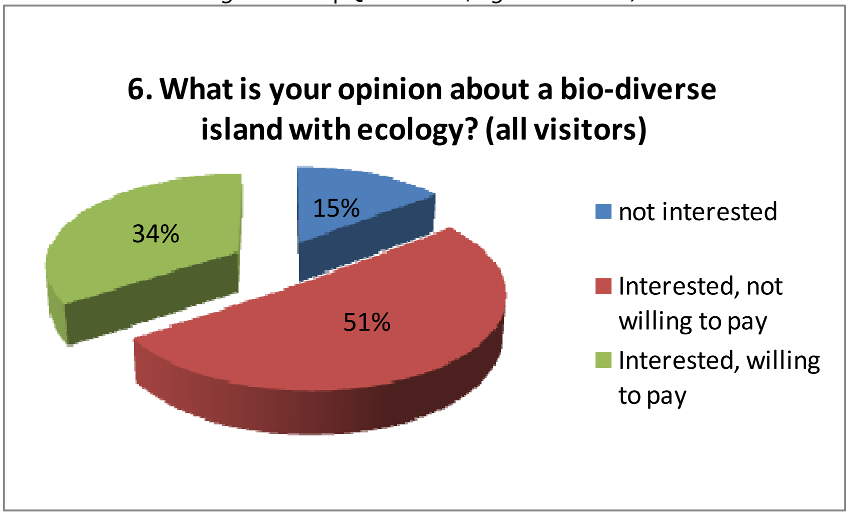


Figure 0.32 | Question 6

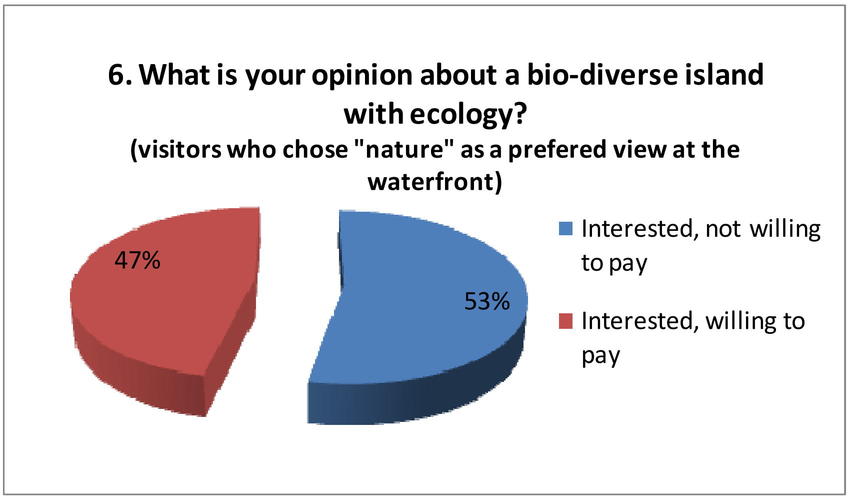


Figure 0.33 | Question 6 (filtered with question 5)

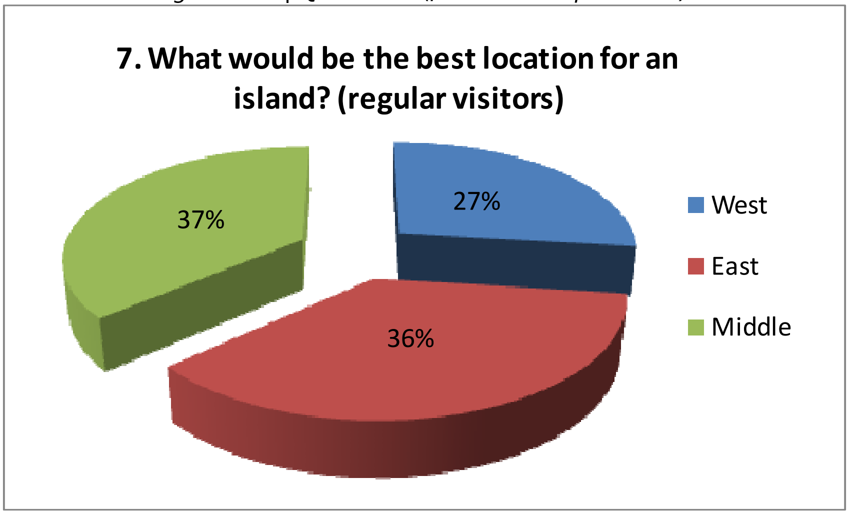


Figure 0.34 | Question7

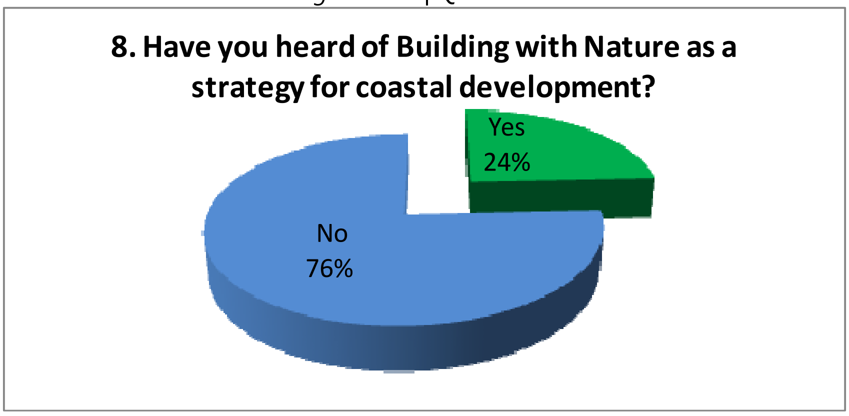


Figure 0.35 | Question 8

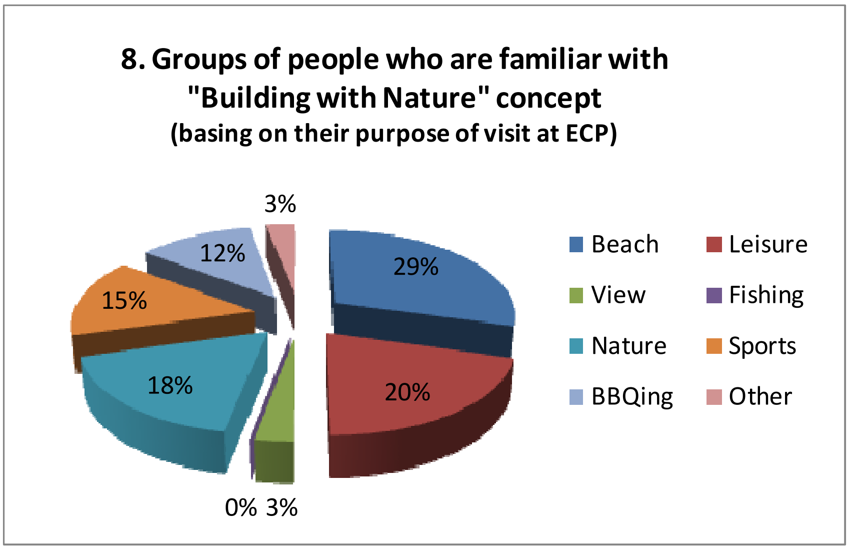


Figure 0.36 | Question 2 (filtered with question 8)

APPENDIX H DESIGN DRAWINGS

This appendix gives an overview of the sketches and drawings made of the preliminary designs.

H.1 THE FIRST SKETCHES

Figure 0.37 presents the first design sketches.

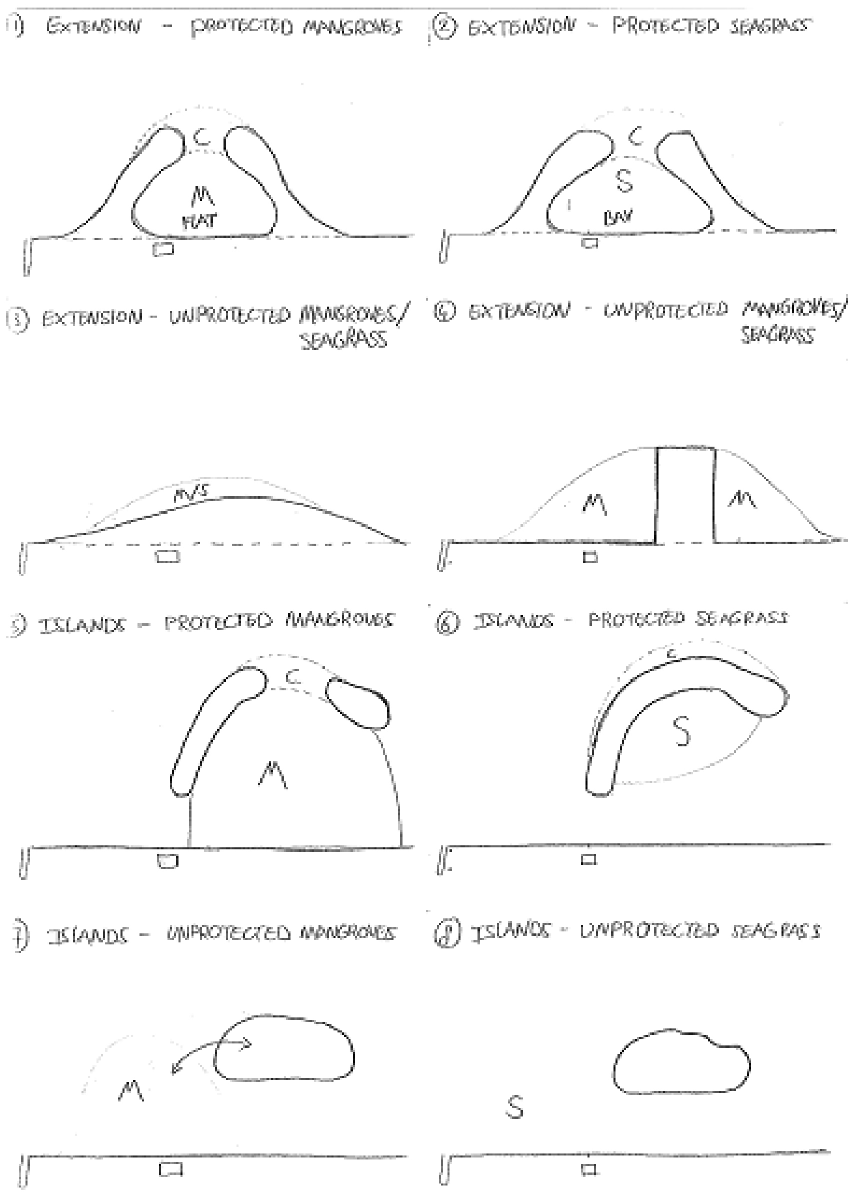


Figure 0.37 | The first sketches of the preliminary designs

H.2 TOP VIEWS PRELIMINARY DESIGNS

The preliminary designs are visualized in the drawings in the remainder of this section.

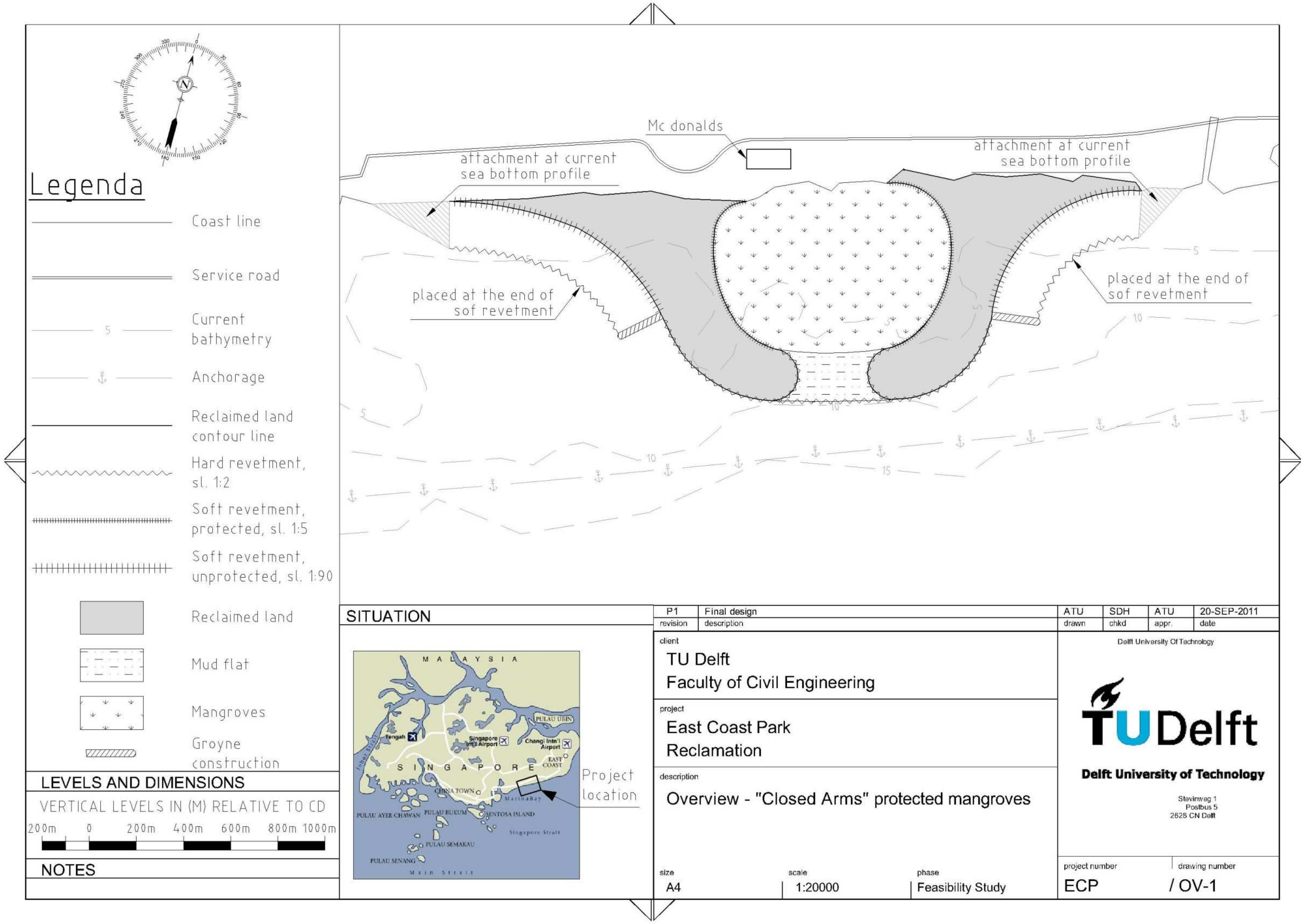


Figure 0.38 | Overview closed arms protected mangroves (design 1)

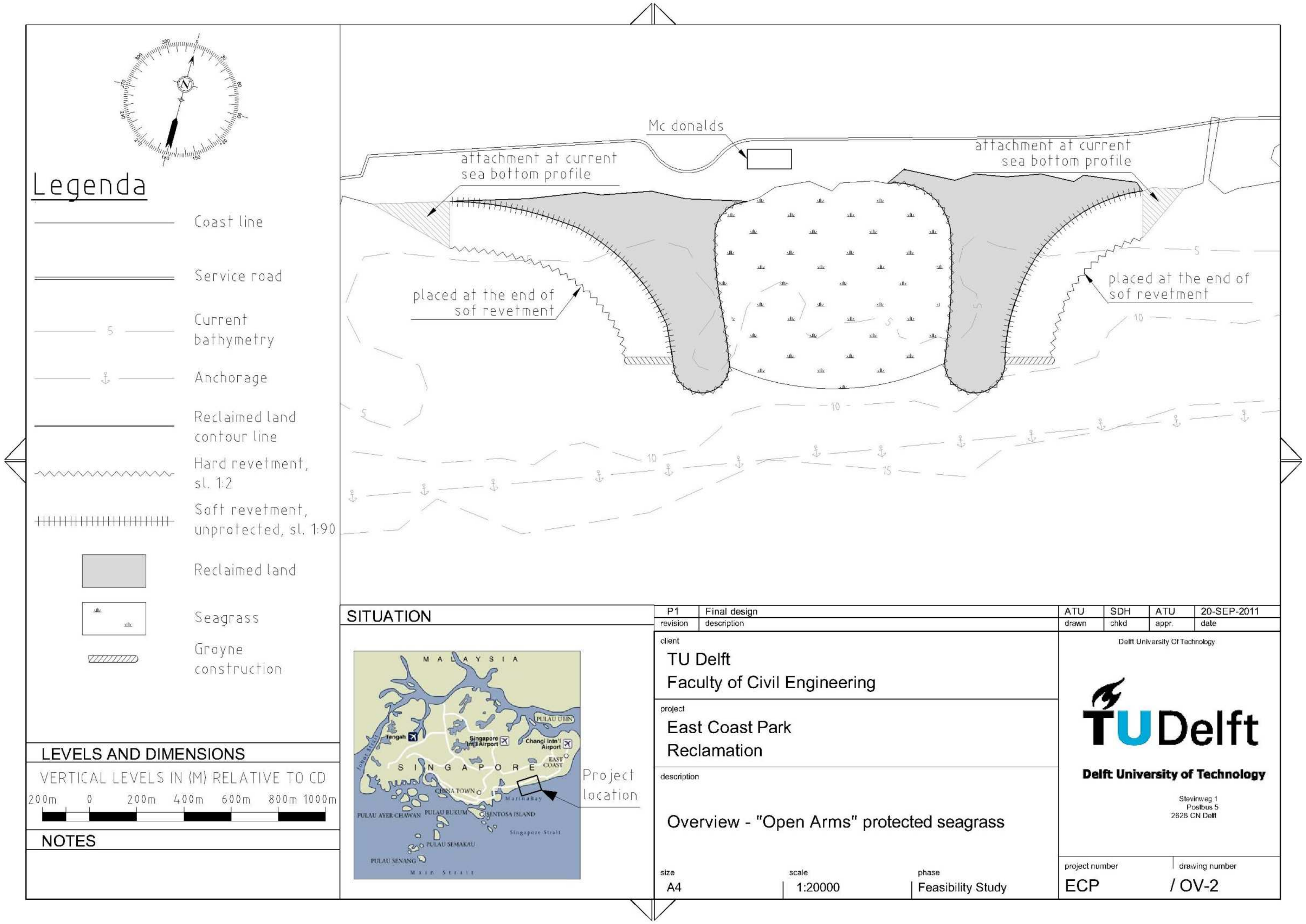


Figure 0.39 | Overview design 2 – "Open Arms" protected seagrass

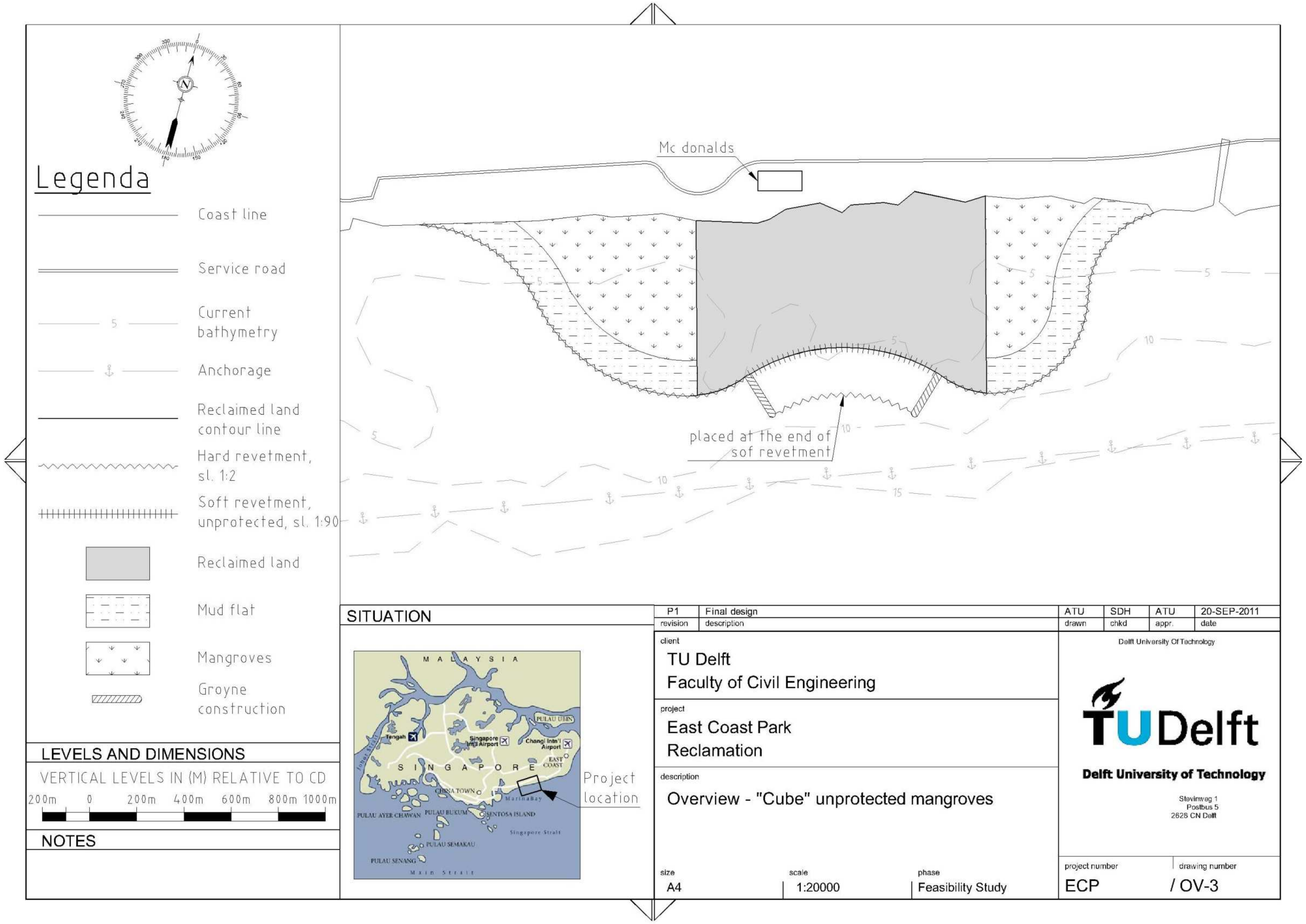


Figure 0.40 | Overview design 3 – "Cube" unprotected mangroves

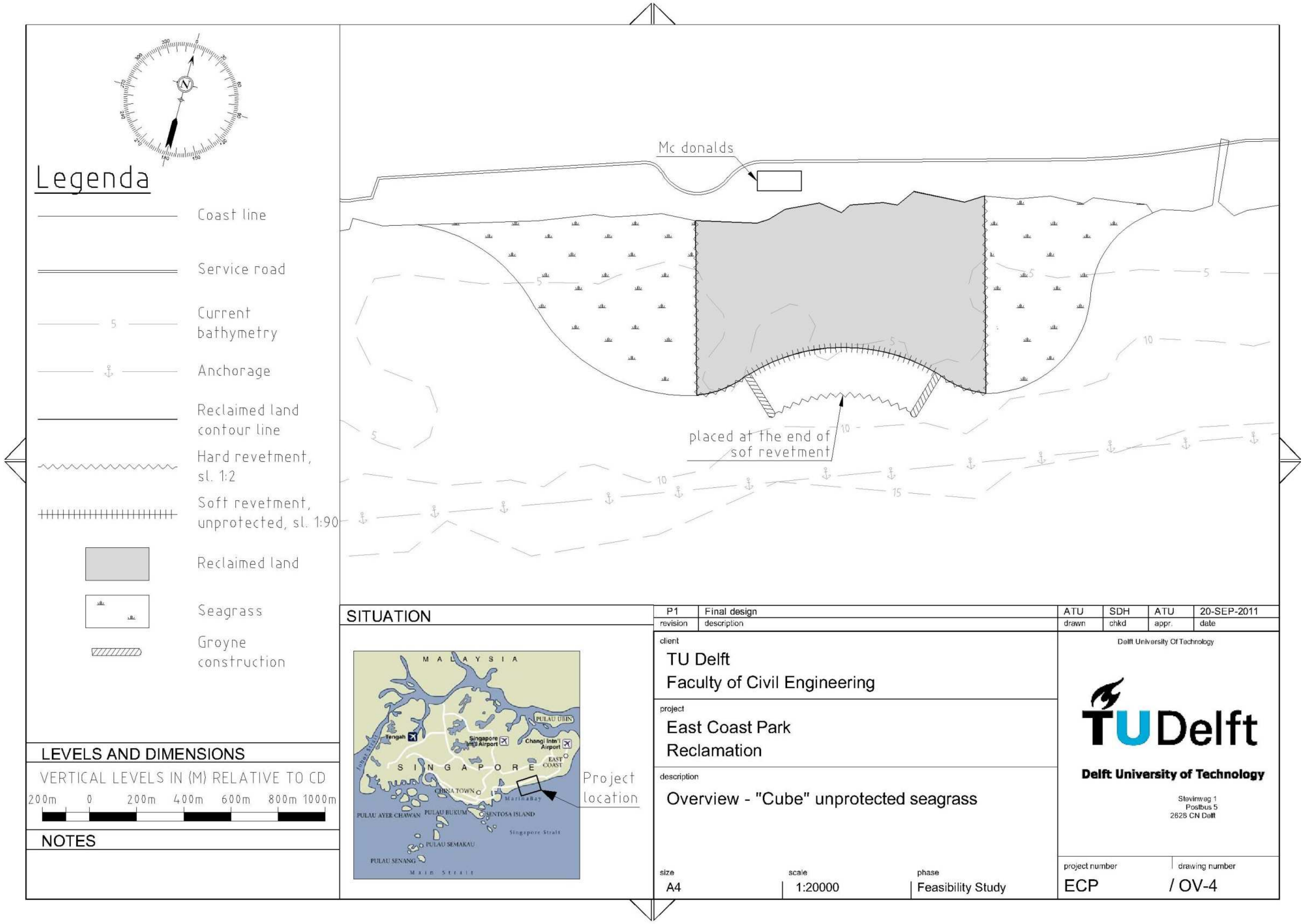


Figure 0.41 | Overview design 4 – "Cube" unprotected seagrass

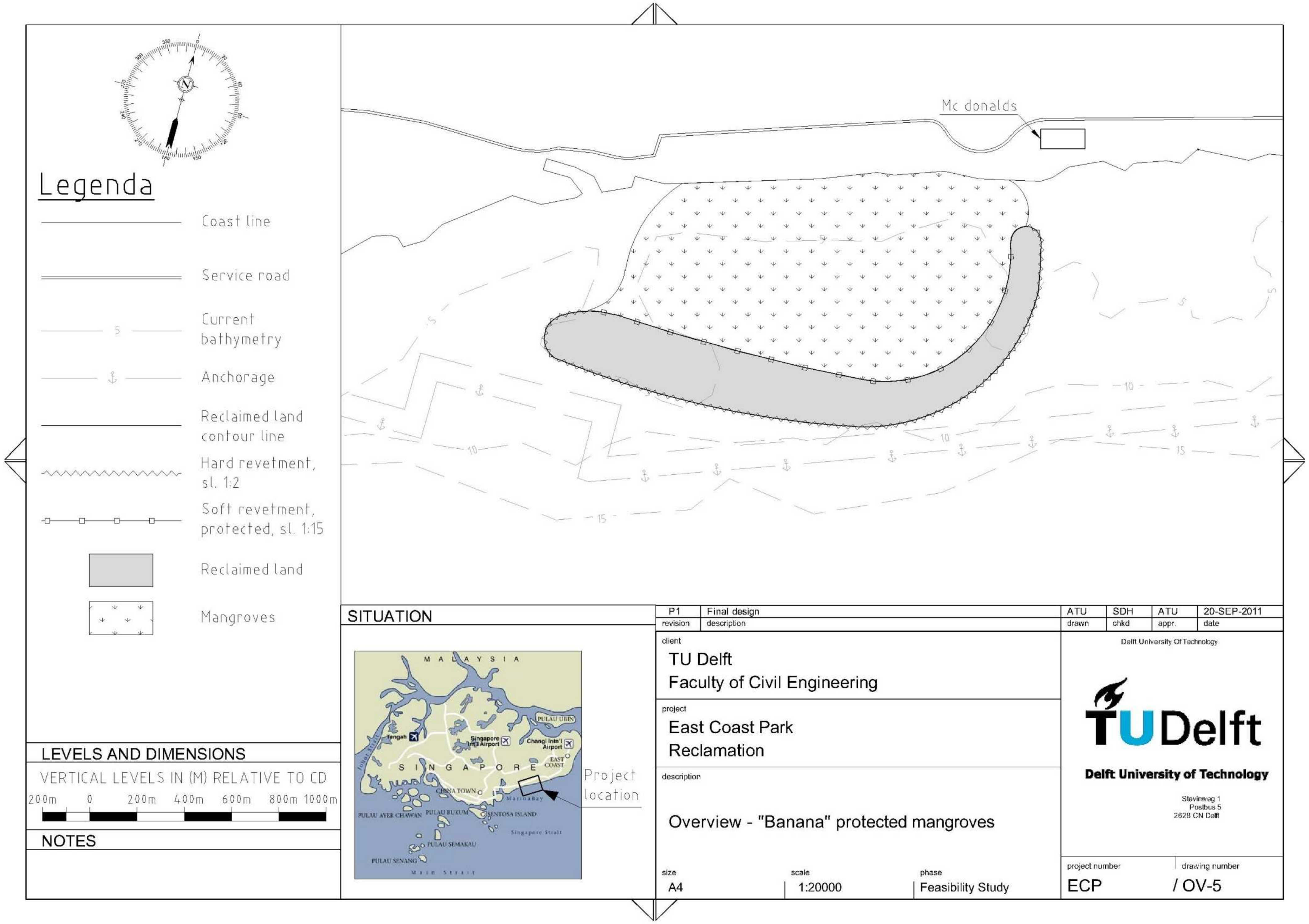


Figure 0.42 | Overview design 5 – "Banana" protected mangroves

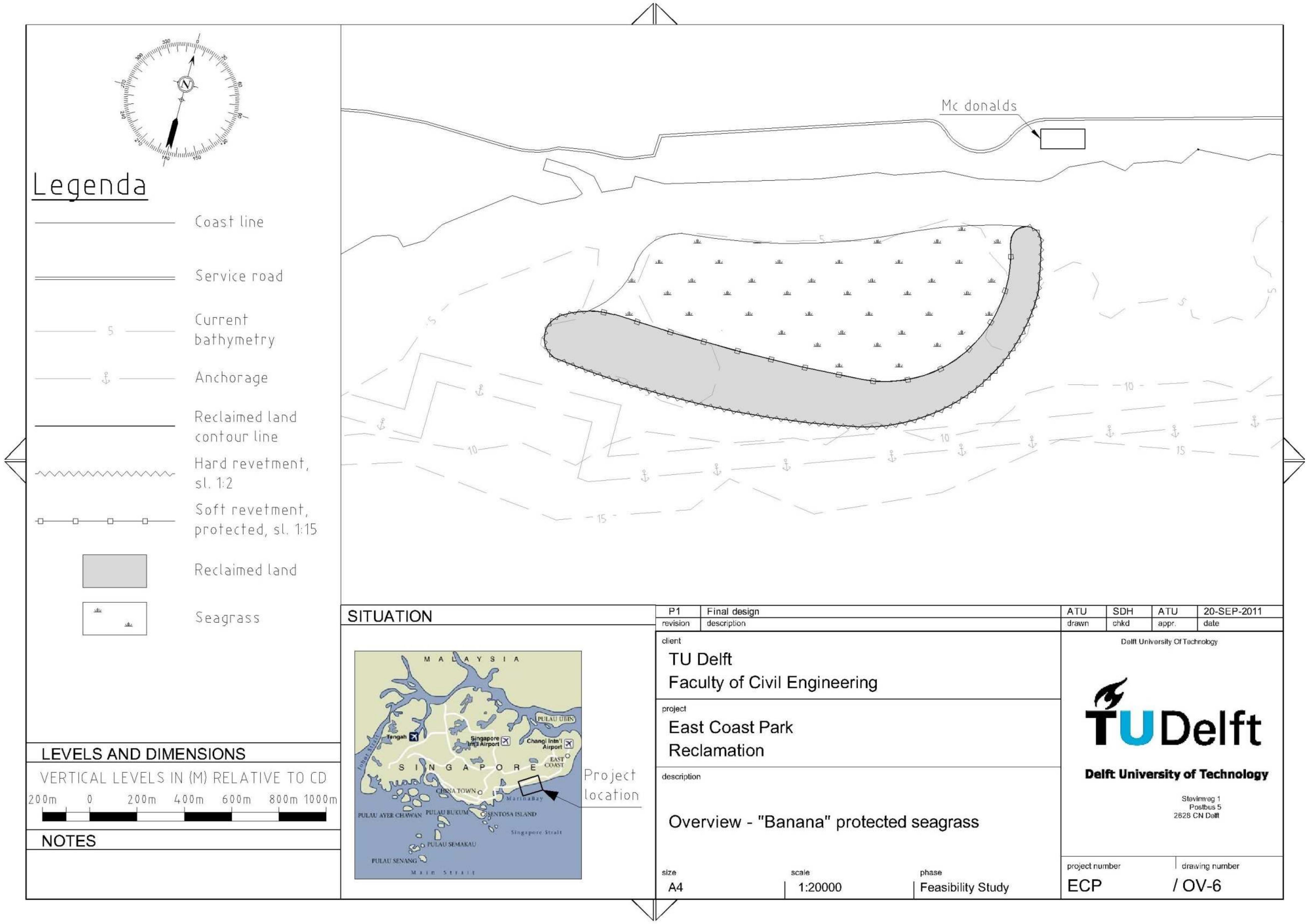


Figure 0.43 | Overview design 6 – "Closed Arms" protected seagrass

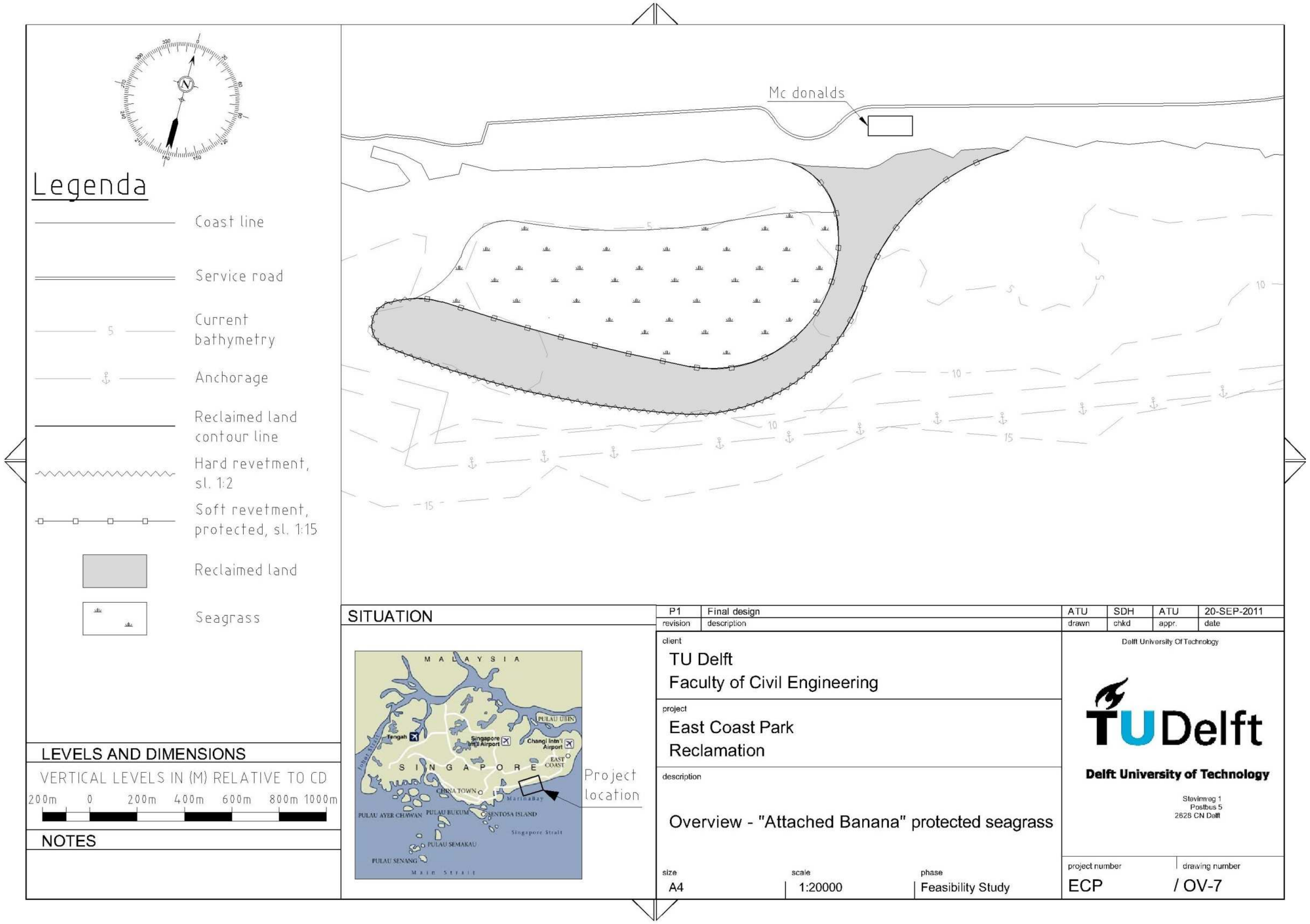


Figure 0.44 | Overview design 7 – "Attached banana" protected seagrass

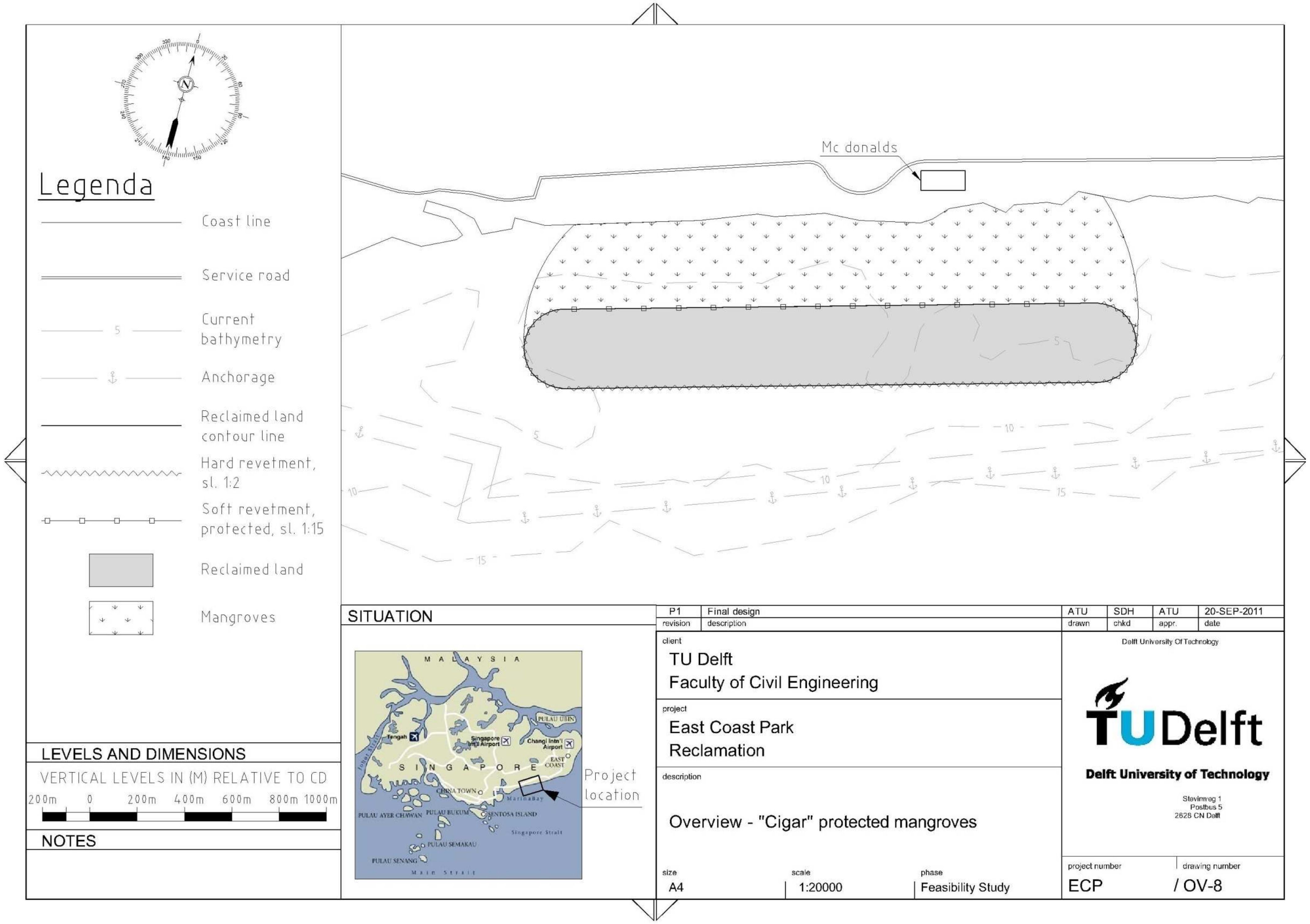


Figure 0.45 | Overview design 8 – "Cigar" protected mangroves

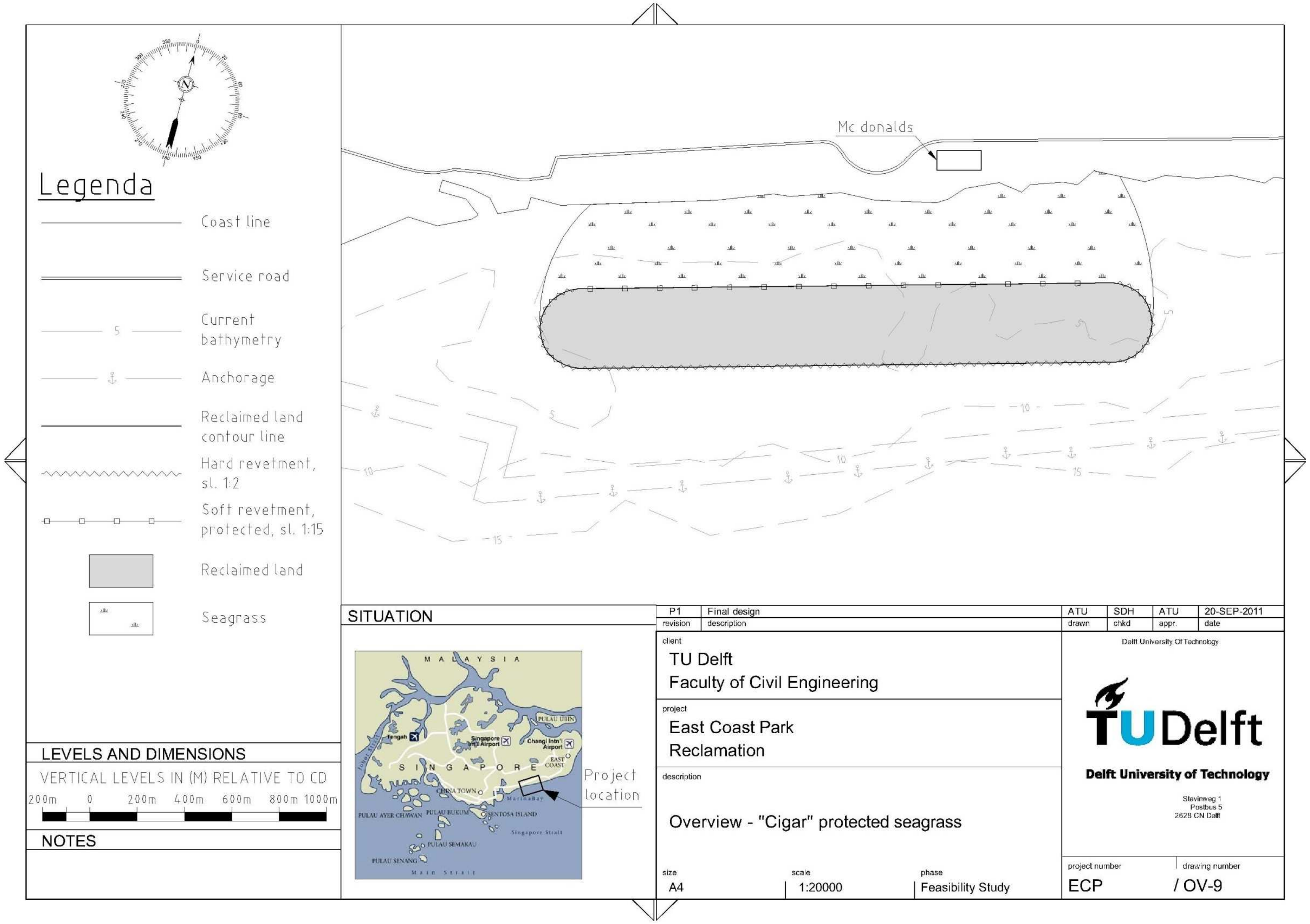


Figure 0.46 | Overview design 9 – "Cigar" protected seagrass

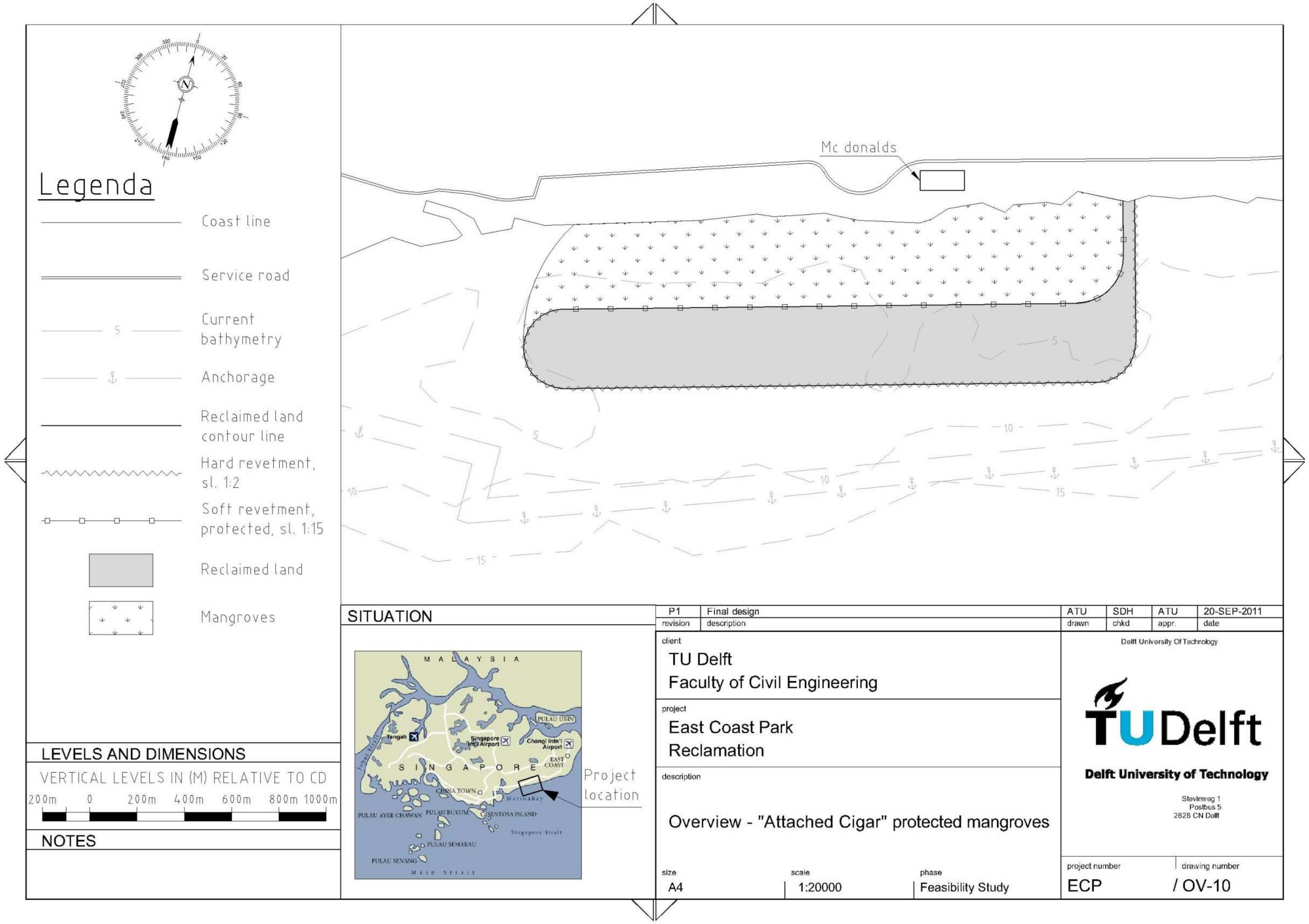


Figure 0.47 | Overview design 10 – "Attached Cigar" protected mangroves

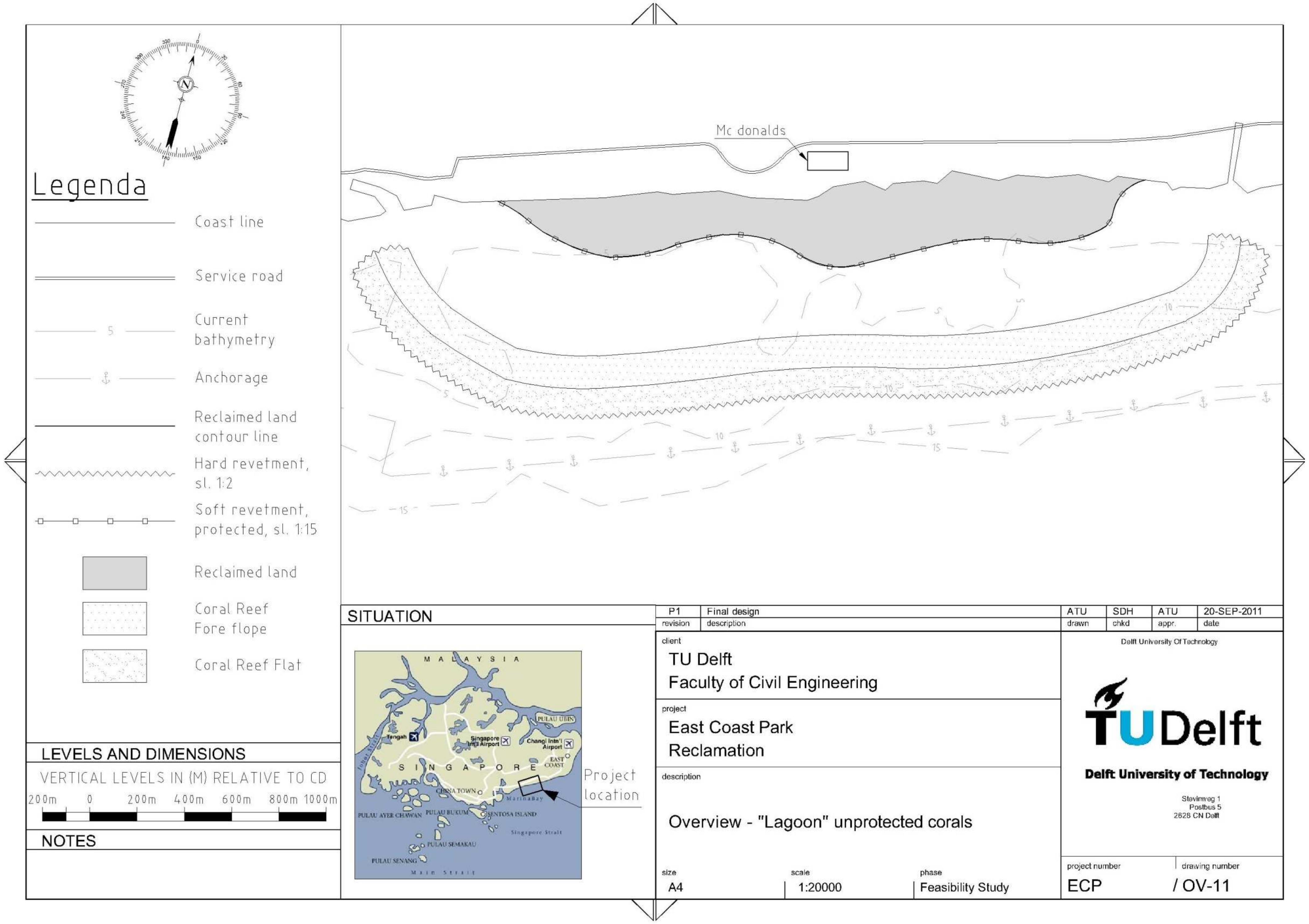


Figure 0.48 | Overview design 11 – "Lagoon" unprotected corals

H.3 CHARACTERISTIC CROSS SECTION

Before the designs of layouts of the additional land were prepared, all-the cross-sections were designed as the conceptual sections. During the design of these cross-sections, the ideas of incorporating habitats on the slopes were investigated in terms of meeting their requirements of i.e. time of inundation, maximum depth and area. After designing the overviews of the islands and considering the design boundary conditions such as bathymetry and area available for reclamation, only 6 out of 8 conceptual sections were elaborated and worked out as the design cross sections (CC-1 until CC-6). Ecological slopes in the cross sections CC-7 and CC-8 cannot be implemented in front of ECP. This is mainly due to the large distance required for the mudflats situated just in front of mangrove forest.

In the design cross-sections, the slopes of the soft as well as the hard revetments were engineered in order to meet the requirements concerning constructability, utility, ecology , "Building with Nature" and constrictions in the width. Equilibrium coastal profiles of 1:90 were needed for the slopes of beaches, while the cross-shore offshore distance available for the slopes is limited. Steep hard slopes had to be constructed in order to overcome this constriction. The steep slopes can be made with "Eco Xblocs" implies that the revetment will reflect waves. However, this kind of revetment also dissipates wave energy whereby it reduces the reflection of waves which is favorable for navigation.

Due to the scope of this feasibility study, the construction details of each revetment type were not elaborated in-depth. Hard revetments consist of geo-textile, filter layers and an armor layer. Soft revetments are entirely built from the landfill material.

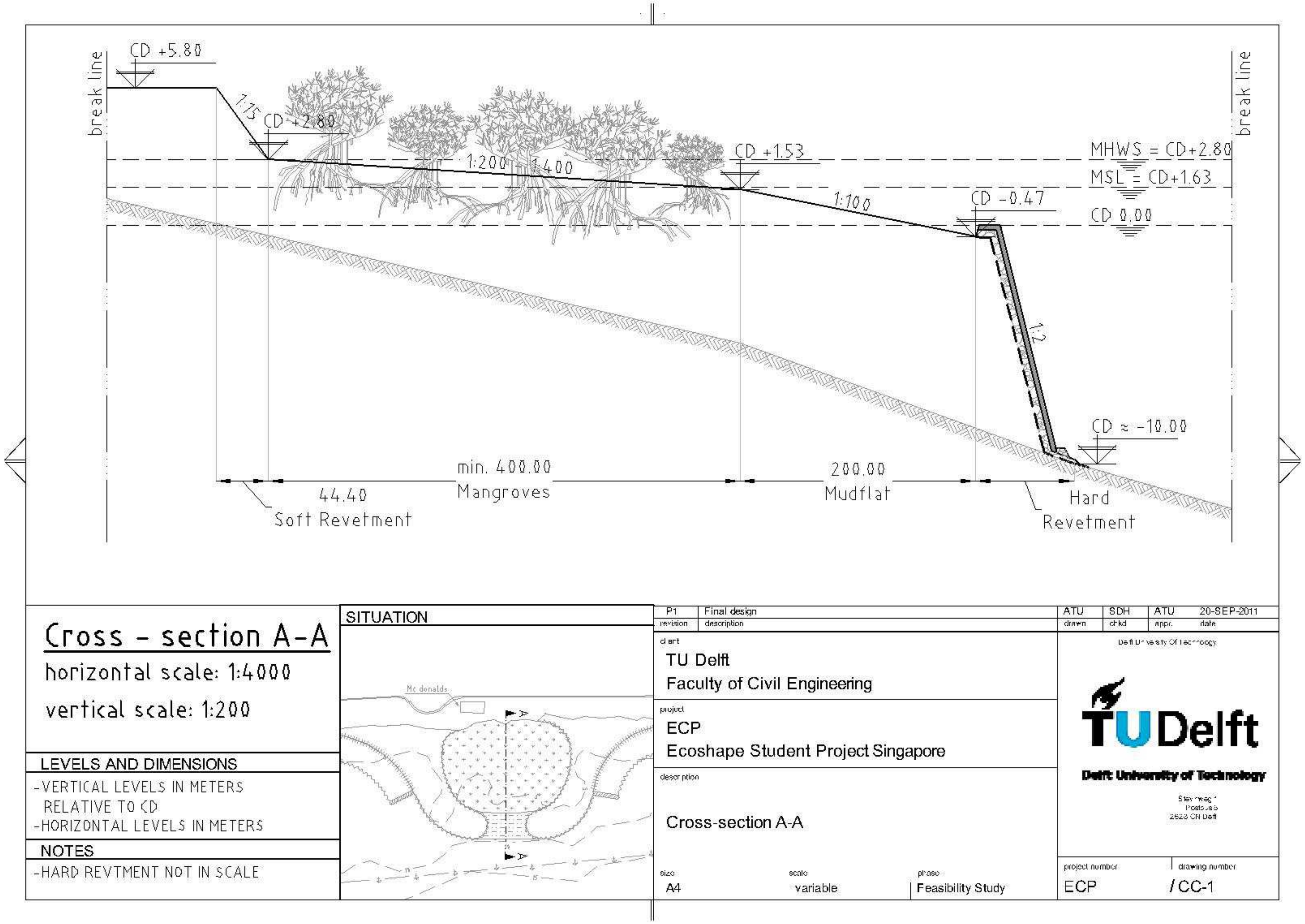


Figure 0.49 | Design cross-section A-A

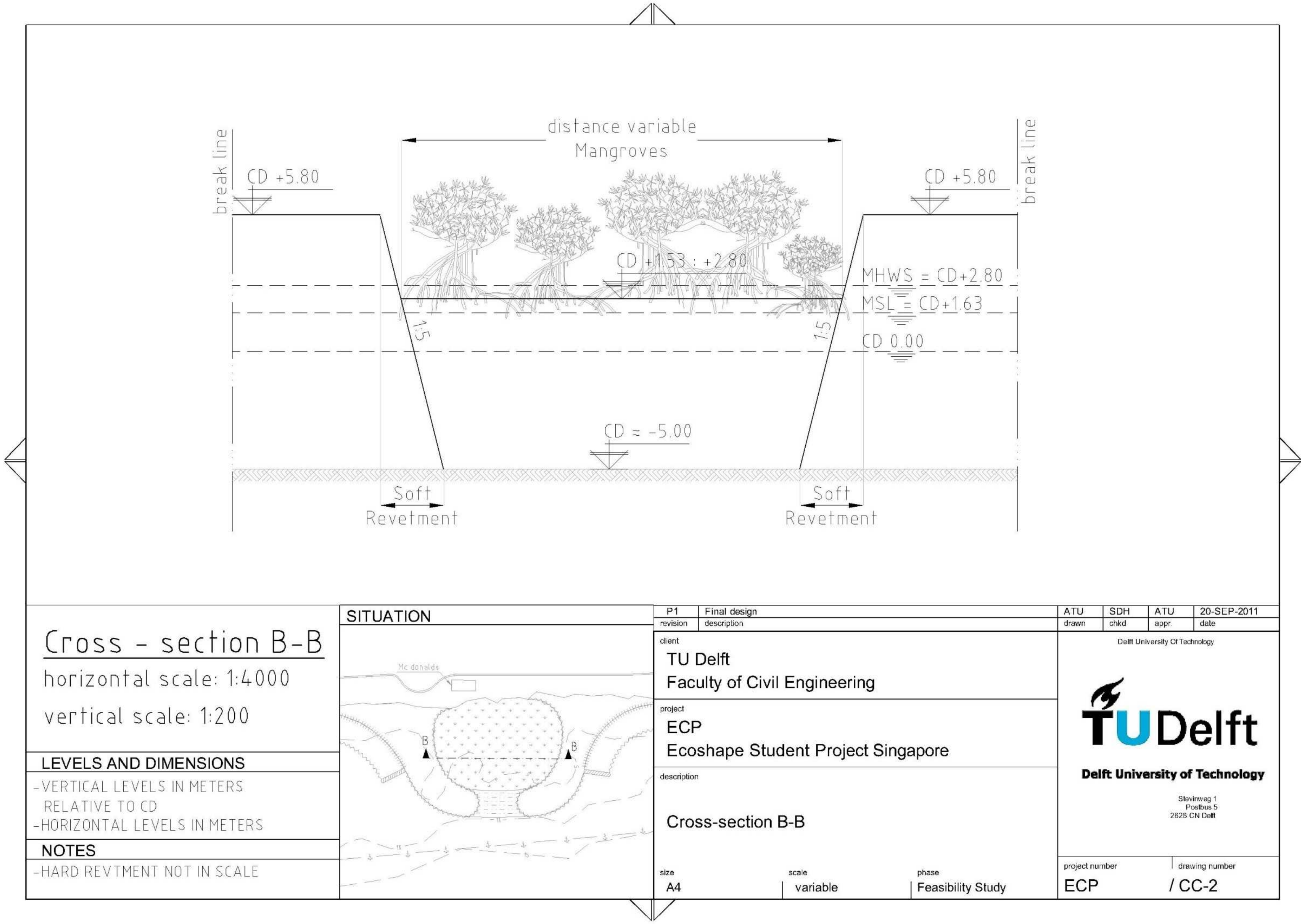


Figure 0.50 | Design cross-section B-B

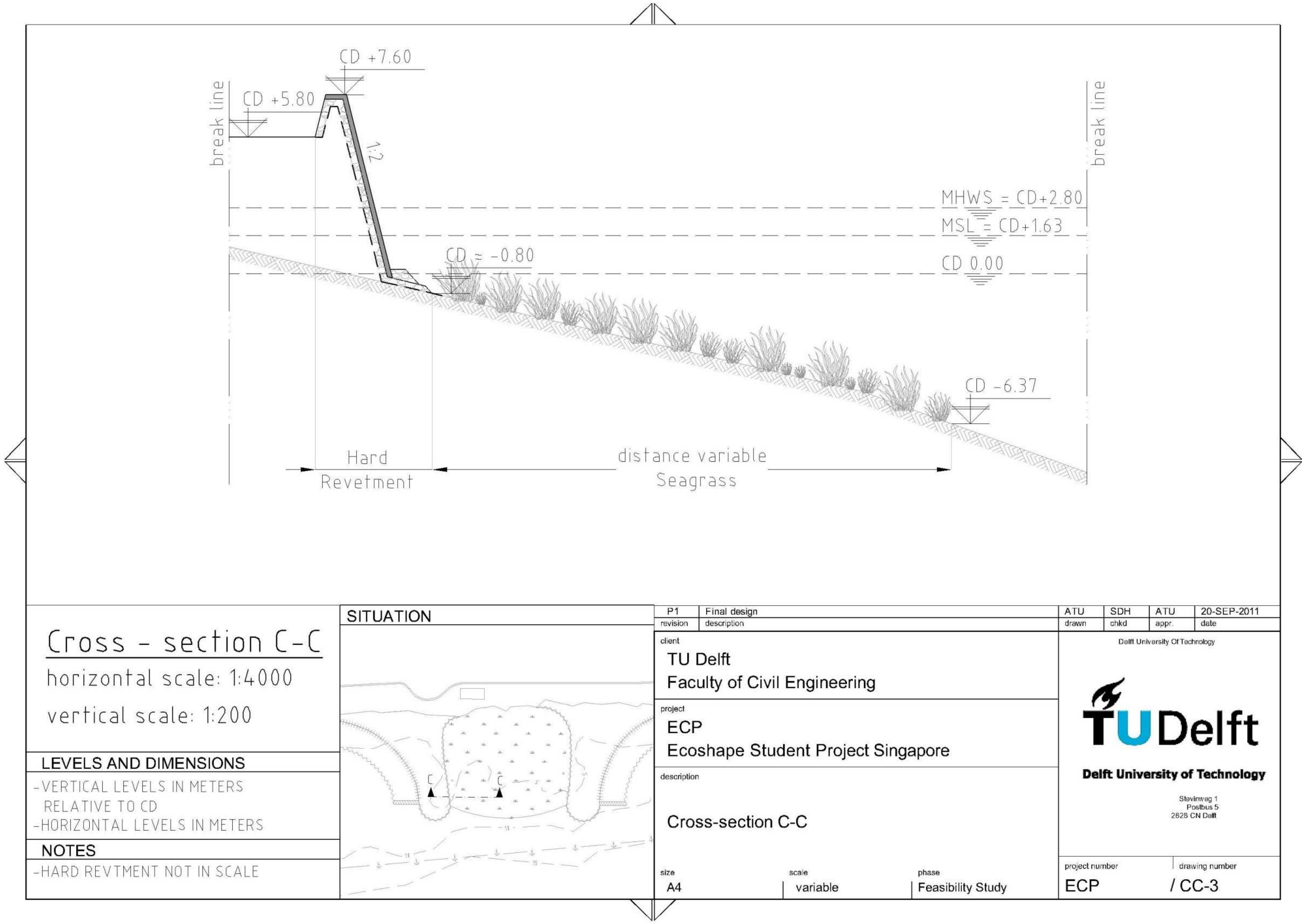


Figure 0.51 | Design cross-section C-C

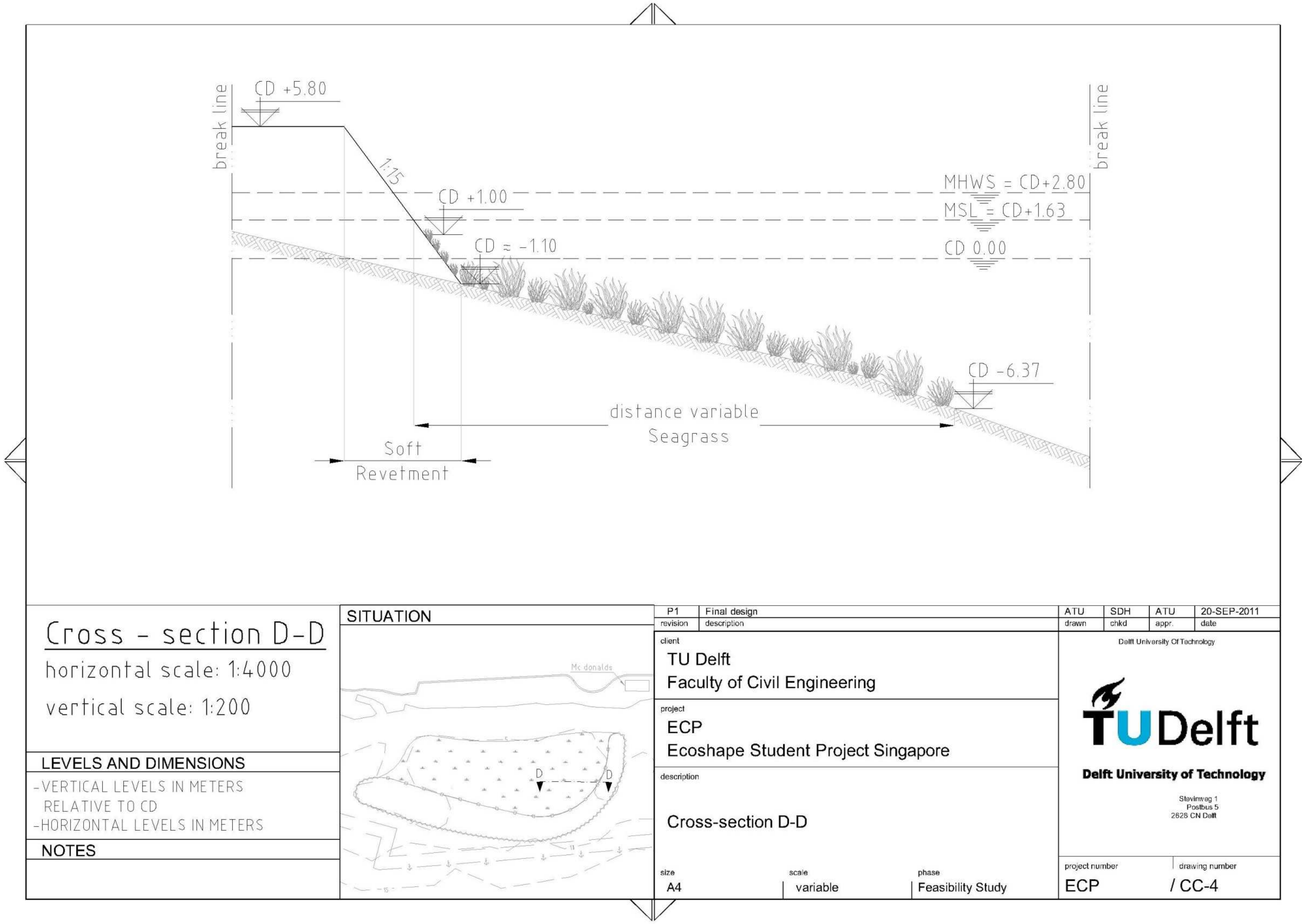


Figure 0.52 | Design cross-section D-D

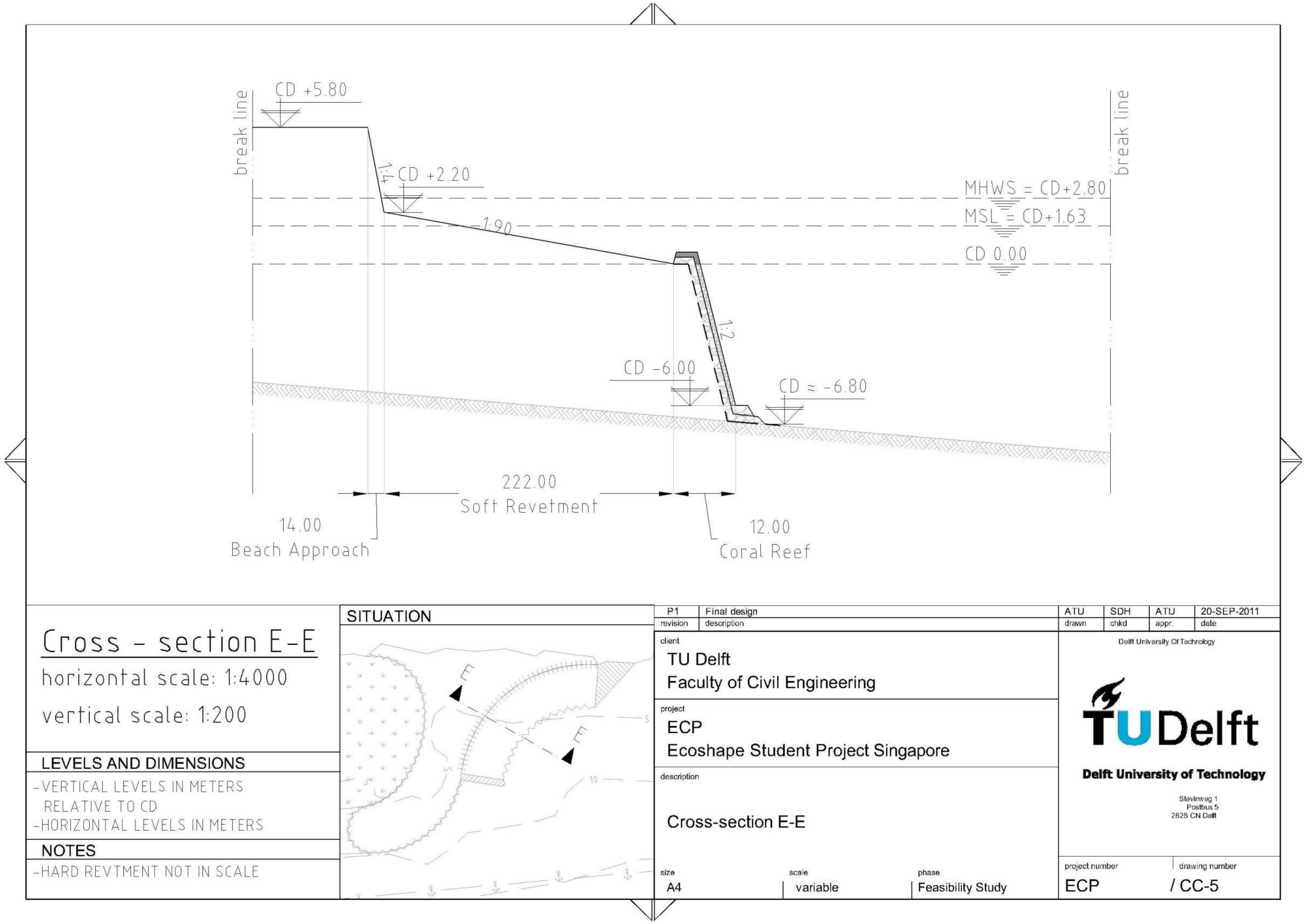


Figure 0.53 | Design cross-section E-E

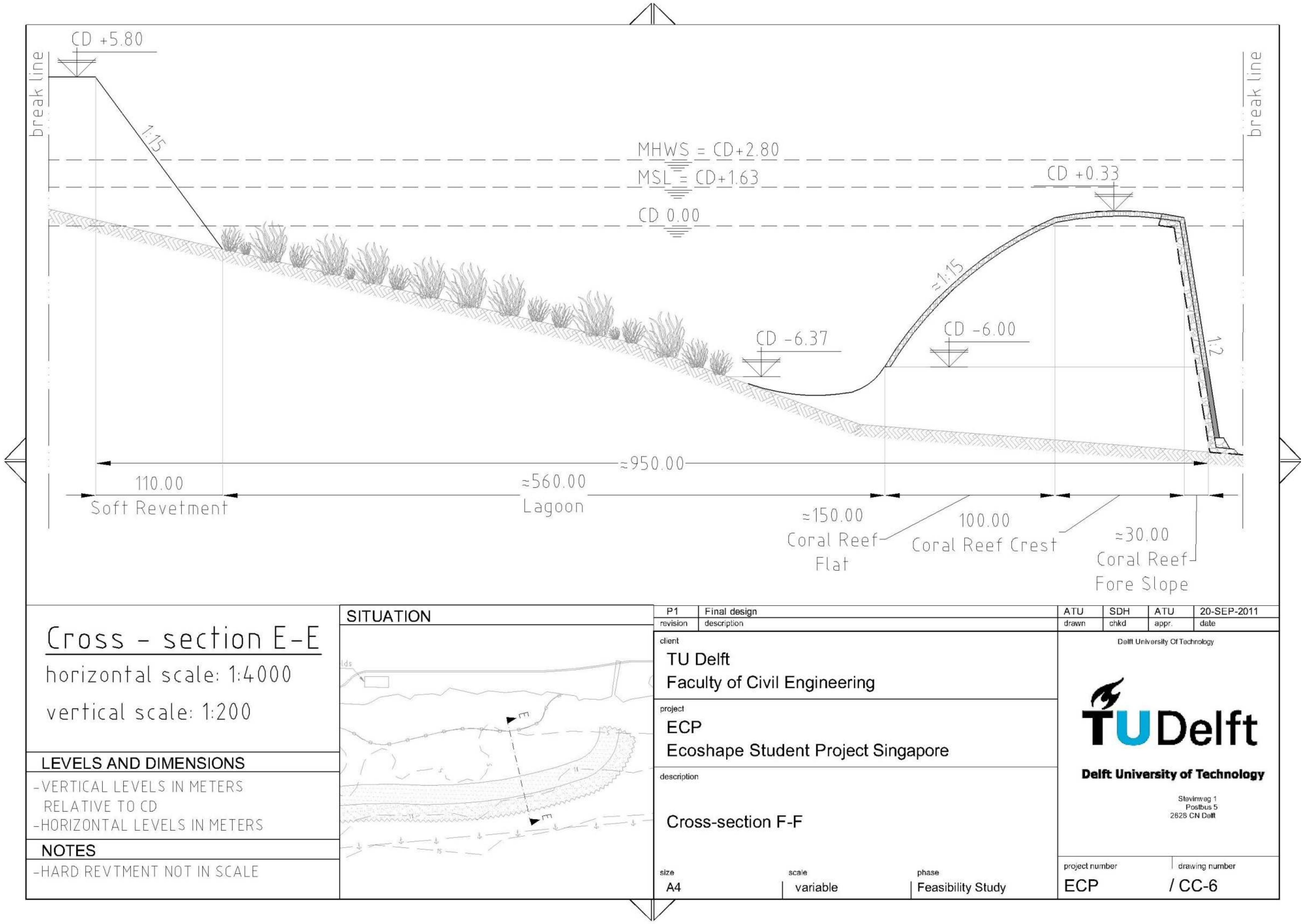


Figure 0.54 | Design cross-section F-F

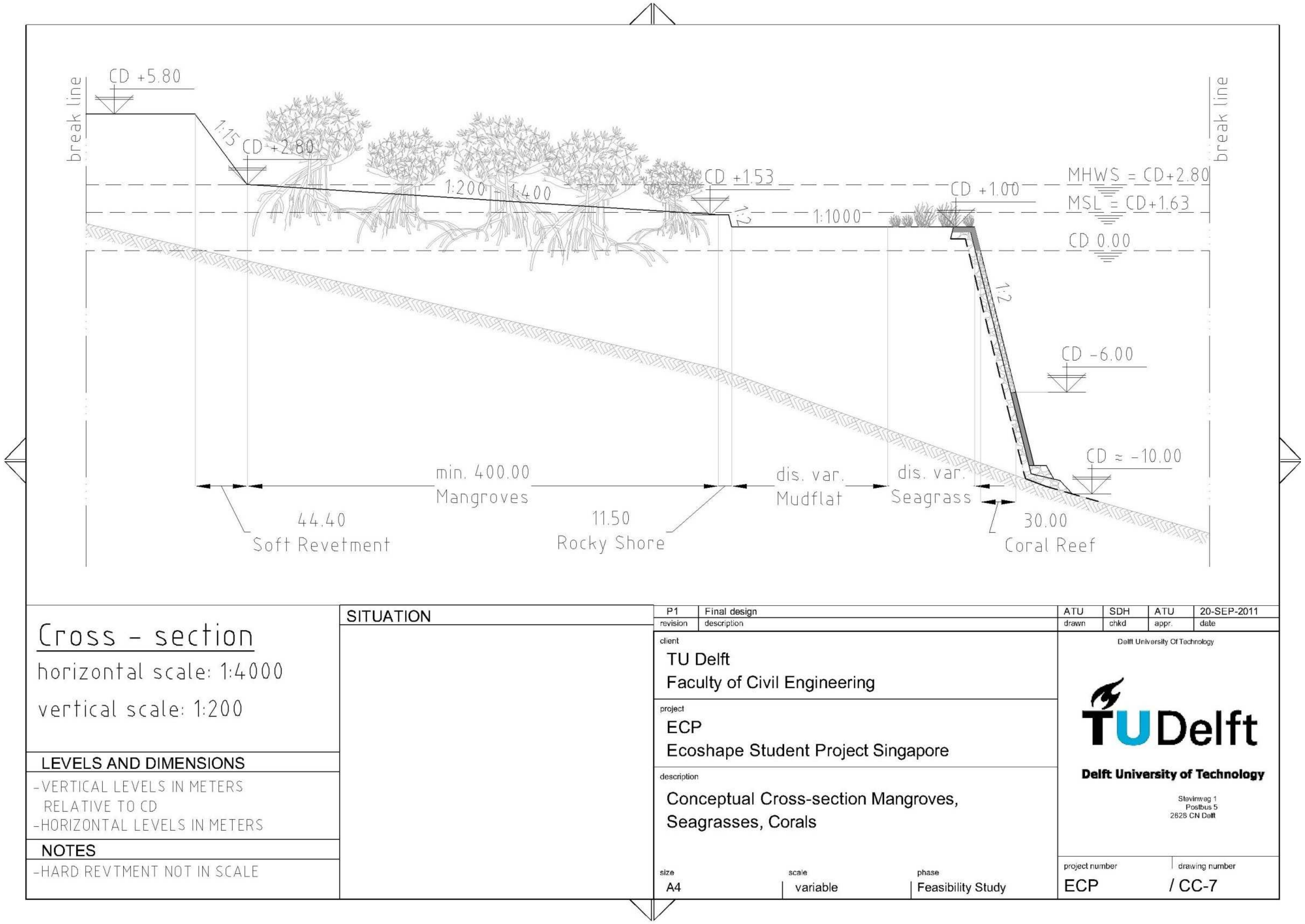


Figure 0.55 | Conceptual cross-section mangroves, seagrasses, corals

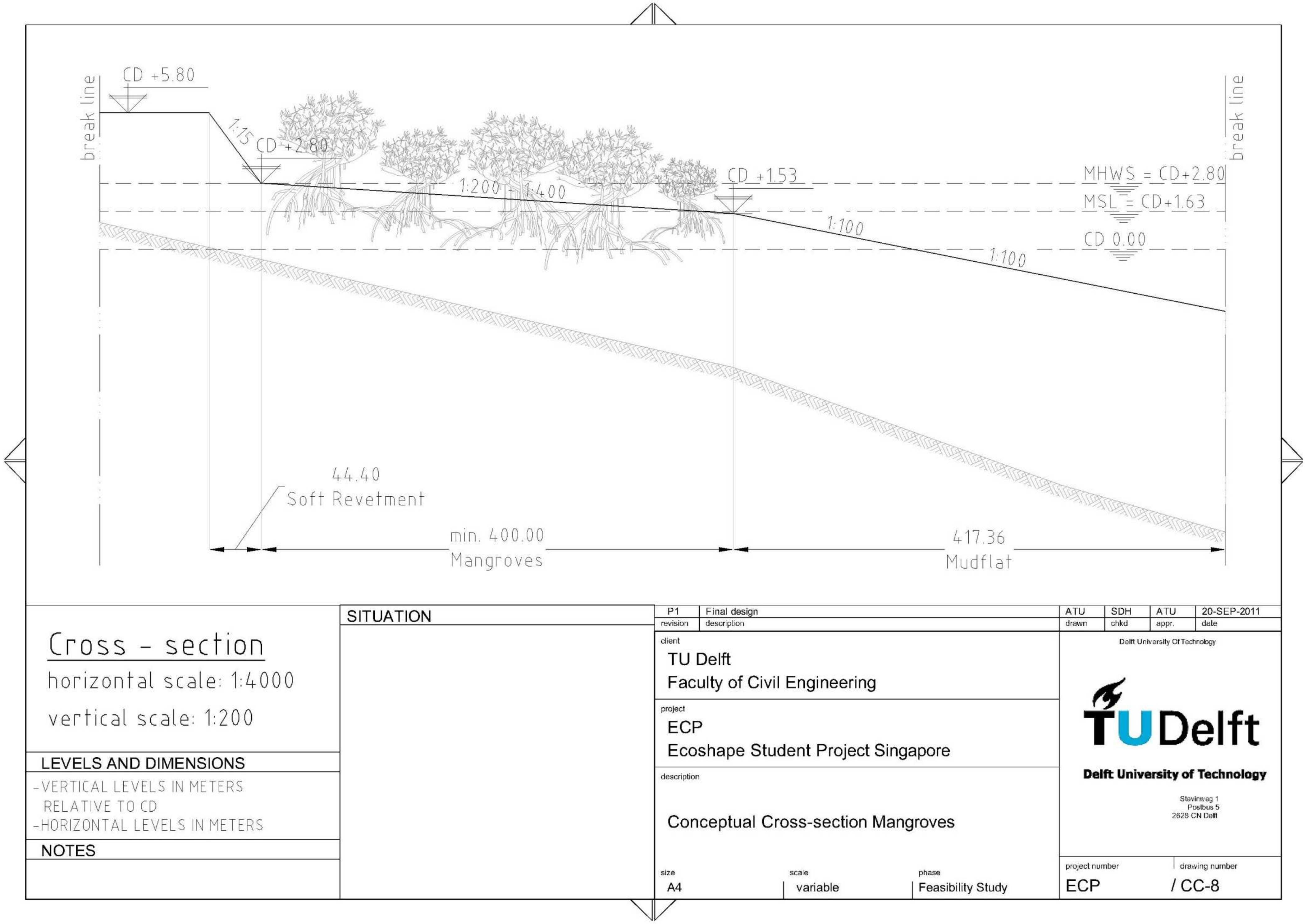


Figure 0.56 | Conceptual cross-section mangroves

APPENDIX I CALCULATION OF INUNDATION TIMES

The maximum and minimum inundation times are part of the habitat requirements and are dependent on the tidal regime. The inundation time determines up to what depth coral and seagrass can grow and what the minimum water depth for mangroves is. The inundation times are calculated using the Delft3D SRM water levels of 2004.

Coral and seagrass can grow up to a depth with an exposure time of 4 hours a day, this corresponds to an inundation time of 20 hours a day and a water level of 1.0 m above Chart Datum, see Table 22. Mangroves cannot be inundated for more than 800 min/day, which corresponds to a water level of 1,557 m above Chart Datum.

Table 22 | Relation between the inundation time and water levels

Water level	24 h/day	20 h/day	800 min/day
Water level [m + Delft3D 0 meter]	-1.527	-0.55	0.03
Water level [m + MSL]	-1,637	-0.66	-0.08
Water level [m + CD]	0	0.977	1.557

APPENDIX J DEVELOPMENT OF A NESTED MODEL IN DELFT3D

J.1 PURPOSE OF THE MODEL

J.1.1 WHY DO WE BUILD A MODEL?

There are many types of models in the world, but all of them have one thing in common; they try to reproduce (a part of) reality. For this project a numerical model has been developed in order to reproduce the natural coastal processes in our area of interest, East Coast Park.

The two main reasons to build a model for this project are:

3. To assess the influence of the designs on the hydrodynamic and morphological conditions and vice versa
4. To check whether the habitat requirements for ecology are met in the designs

From the two main reasons follow questions that are to be answered by the nested model:

- What are the present hydrodynamic and morphological conditions at ECP?
- How do the designs influence the hydrodynamic and morphological conditions and vice versa?
- Are the habitat requirements for ecology met in the designs?

These main questions can further be divided into sub questions:

- What are the present hydraulic conditions at ECP (currents, water levels and bed shear stresses)?
- What is the influence of the designs on the currents?
- What is the influence of the designs on the bed shear stresses?
- What are the sediment transport rates at ECP?
- What is the influence of the designs on the transport rates?
- Where are the present accretion spots for fines at ECP?
- What is the influence of the designs on the accretion of fines?

J.1.2 THE SINGAPORE REGIONAL MODEL

A collaboration of Deltares and the Singapore Delft Water alliance has led to the development of the Singapore Regional Model (SRM) (refer Figure 0.57).

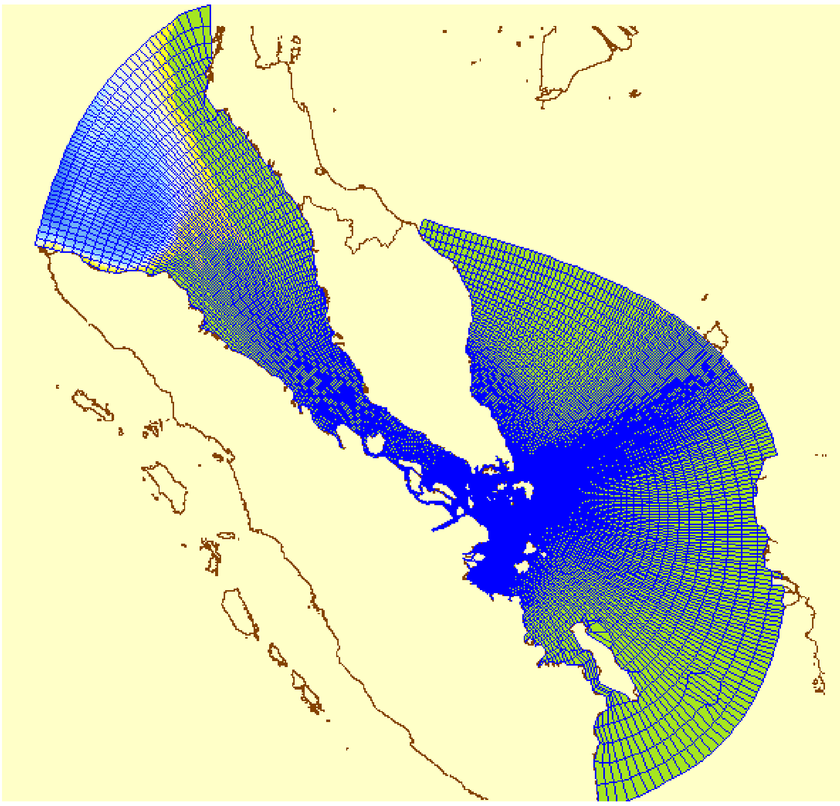


Figure 0.57 | The Singapore regional model

This model covers parts of the South China Sea in the northeast, part of the Java Sea in the south and a part of the Andaman Sea and the Malacca Strait in the North.

J.1.3 WHY DO WE NEST A MODEL?

A nested model is a small model embedded in a larger overall model. In this case, the overall model used is the Singapore Regional Model.

There are several reasons to nest a model inside an existing model. Firstly, nesting in an existing model saves a lot of work. The overall model has already been calibrated and validated. Secondly, models are nested to decrease the grid size in the area of interest; the whole area might be included in just a few gridcells in the overall model. Finally, models are nested to decrease the amount of computational time needed to run the model. Because of nesting, as little gridcells as possible are located in areas other than the one of interest. Especially in a desk study such as this one, computational time should be kept at a minimum.

Introduction to the nesting of a model using NESTHD 1 & 2

When a grid is nested in a bigger overall grid, the procedure of nesting develops specific time series on the boundaries of the smaller nested grid. The types of boundaries that can be developed in this way by the NESTHD tool in Delft3D are of the water level or perpendicular velocity type (Deltares, Delft3D - FLOW User Manual, 2011).

To be able to create the required time series, the boundary conditions of the nested grid have to be specified first. A boundary segment can range from 2 to multiple gridcells and is specified as an open boundary on the edges of the grid that is to be nested. The required amount of boundary segments needed is determined by the difference in gridcell size between the nested and overall model. In an ideal situation, each boundary segment coincides exactly with the length or width of a gridcell of the overall model to lose as little information as possible.

The nesting sequence is a two step procedure. First, using the boundary specifications of the nested model, a range of observation points is created around these boundaries in the overall model. Secondly, the overall model is run with these observation points. Using the output files of this run, the required time series on the boundaries of the nested model are now created.

J.1.4 USE OF THE NESTED MODEL

The most important function of the nested model is to assess the hydrodynamics of the system with and without additional land forms.

Furthermore, this model will be used to perform a sensitivity analysis for sediments and thus no full morphodynamic calculations will be made. Firstly, there are big gaps in the input data needed to perform the calculations (bottom composition silt vs. sand, sediment concentrations in water and on boundaries, dredge and dump areas). Secondly, there is no measured data to compare these calculations with sediment transport rates, erosion and accretion spots, coastline retreat and advance.

Finally, the model will be used in a desk study during this project, which implies that computational times should be kept at a minimum (max overnight run).

J.1.5 PARAMETERS TO BE QUANTIFIED BY THE NESTED MODEL

The parameters that have to be quantified by the nested model follow from the purpose and the use of the model. An overview of these parameters is presented in Table 23.

Table 23 | Parameters to be quantified

What to judge	Which quantities?	Which quantities?
Tides and currents		
	Base run	*Design runs*
Current	Maximum current velocities	Maximum current velocities
	Direction velocity vectors	Direction velocity vectors
	Difference in maximum current velocities	
	Difference directions of velocity vectors	
Tide	-	Inundation frequencies and -times
Bed shear stresses	Maximum bed shear stresses	Maximum bed shear stresses
	Difference in maximum bed shear stresses	
Sediment		
	Base run	*Design runs*
Transport rates	Longshore transport rates	Longshore transport rates
	Difference in longshore transport rates	
Concentrations	Sediment concentrations	Sediment concentrations in sheltered area's
Accretion and erosion	Accretion of fine sediments	Accretion of fine sediments
	Difference in accretion of fine sediments	
Waves		
	Base run	*Design runs*
Waves	Mean and significant wave heights	Mean and significant wave heights in sheltered area's
	Difference in wave heights	
	Refracted wave directions	Refracted wave directions
	Difference in refracted wave directions	

J.1.6 REQUIRED RESOLUTION OF GRID

So far, it has become clear why which parameters are to be quantified by the nested model. From these specifications follow the required resolution of the nested models grid (Ooi, 2011), (Maren, 2011):

- Gridcells cannot be smaller than 30 x 30 m to prevent the occurrence of numerical problems.
- To prevent the creation of artificial roughness, at least five cells should be located in between possible land reclamations (also between islands and coast)
    - o The islands must be located as close as possible to the shoreline for both economical and infrastructural reasons i.e. the access road should be short and less landfill is needed close to the shore.
    - o To be able to judge the influence of the offshore distance of the islands on the hydrodynamics, the gridcells dimensions near the coast should be as small as possible. The minimum offshore distance is determined by the absolute minimum gridcell size and the minimum required number of gridcells in between two land forms. These two restrictions provide a minimum offshore distance of 150 m (5 x 30 m).
- Enough gridcells should be present in the intertidal zone.
- The ecosystems should be located in more than one gridcell.
- Elevation drops of more than 1 m per gridcell are considered coarse. Considering the slope of a mangrove forest (avg. 1:300) and the minimum required width (400 m), this implies a minimum of three gridcells for the mangrove forest.
- Assuming a minimum of three gridcells per ecosystem, a restriction on the maximum allowed gridcell dimension follows from the minimum required ecosystem patch size:

- Mangroves (minimum patch size: 400 x 400 m) → 135 x 135 m
- Seagrass (no minimum patch size) → -
- Corals (very large minimum patch size) → >> 135 x 135 m

- To minimize the influence of the shape of an island on the orthogonality of the gridcells when cutting the design into the grid (refer J.5.1), gridcells should be as small as possible.
- Outside the area of interest, gridcell dimensions should preferably equal the gridcell dimensions of the overall model. This way, no information of the overall model is lost during nesting.
- After the first 800 m the number of gridcells should be kept at a minimum to decrease the computational time as much as possible.

J.1.7 REQUIRED ACCURACY OF RESULTS NESTED MODEL

Finally, after it has become clear why which parameters are to be quantified by the nested model and what resolution is needed to obtain these results, the specifications for the accuracy of the nested models results follow (Ooi, 2011), (Maren, 2011):

For engineering purposes, the nested modelling results should be within an accuracy range of 3-5% compared to the overall models results (SRM). Compared to the mean quantities, the following allowed errors follow from this restriction:

- The error of the water levels of the nested model < 0.03 m compared to overall models results (SRM).
- The error of the velocity magnitudes of the nested model < 0.025 m compared to overall models results (SRM)
- The error of the velocity directions of the nested model < 5° compared to overall models results (SRM)

J.2 BUILDING A FINE GRID IN THE AREA OF INTEREST

J.2.1 THE AREA OF INTEREST

The sieve analysis in paragraph 3.3 determined all the possible locations where the designs can be located.

J.2.2 LOCATION AND SPECIFICATIONS OF OPEN BOUNDARIES

Multiple restrictions on the location of the open boundaries of the nested grid have been taken into account. An overview of these restrictions is given below (Ooi, 2011) (Maren, Tides and residual flows, 2011):

- The grid should be as small as possible because of constraints on computational power of this desk study.
- The western boundary should be located east of Marina barrage.
- The open boundaries should be as perpendicular to the flow in the channel as possible, otherwise mass might be lost from the system.
- The open boundaries should cut through high velocities preferably.
- The open boundaries should cut across deep water, giving Delft3D more room to correct for mass continuity.
- The cross section over the boundary with regards to the depth profile should be as smooth as possible. The western boundary should therefore be located as far to the east of the deep water near Sentosa Island as possible. If a large gradient in the depth profile is inevitable, enough gridcells should be available to assure a smooth transition from shallow to deep water.
- The open boundaries should not be located near dry points.
- When a region with water is cut off by the boundary, the local depth of the boundary at this point should be increased to compensate for the loss of volume.
- The open boundaries should be located far enough from the area of interest to ensure that these open boundaries have as little influence on the model as possible. Furthermore, if this is the case, it is possible to alter the bathymetry near the boundaries without influencing the physics of the model (Kurniawan, 2011).

J.2.3 SPLINES

The final splines used in this study are shown in Figure 0.58, incorporating as much of the specifications as laid down in paragraph J.2.1 as possible:

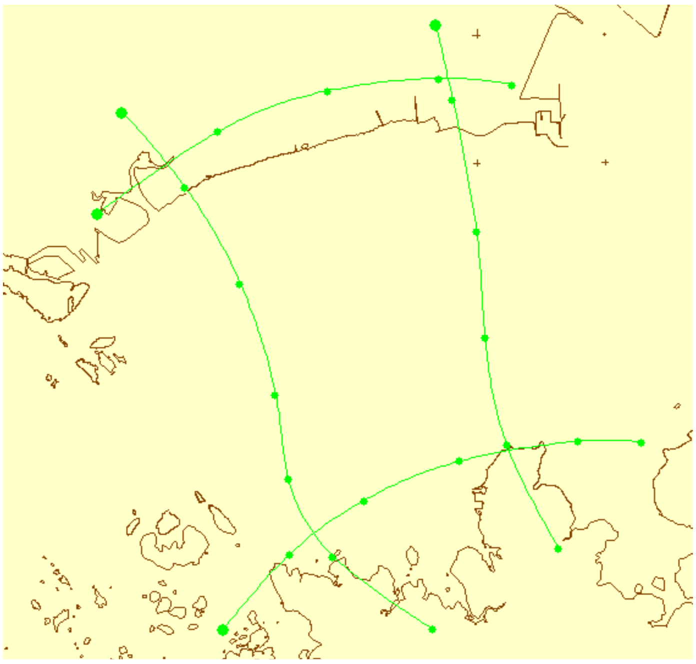


Figure 0.58 | Final set of splines used

J.2.4 REQUIREMENTS FOR GRID PROPERTIES

The requirements that are met in the grid designs are presented below:

Table 24 | Requirements for grid design (Deltares, Delft3D - RGFGRID User Manual, 2011)

Property	Requirement
Orthogonality	< 0.02 - 0.04
M - smoothness	< 1.20
N - smoothness	< 1.20

When a grid is orthogonal, less numerical diffusion occurs and less computational time is needed. The same holds for the M- and N – smoothness of the grid. The grid meets these requirements everywhere, except at the land boundary, where the gridcells have been attached to the land boundary.

J.3 CALIBRATION PROCESS OF THE NESTED MODEL

J.3.1 QUANTITIES THAT HAVE BEEN COMPARED

The three quantities that have been compared are:

- Water levels in observation points
- Velocity vector magnitude and direction from map files and in observation points
- Discharges in observation points

The discharge has only been checked close to the coast. The gridcells in the area of interest near the coast are very small. This influences the results in these cells, making it difficult to compare these results with the results from the SRM. Furthermore, the grid has been snapped to the land boundary in the nested grid, creating alternate flow patterns because of these boundaries.

In order to still cross check the results close to the coast, the discharge through the cells has to be taken into account. $Q = v * A$ should be a constant similar value in both models. The discharge in the larger gridcells of the SRM should be equal to the sum of the individual discharges from the smaller gridcells in the nested model that are encompassed by the bigger gridcell (refer Figure 0.65).

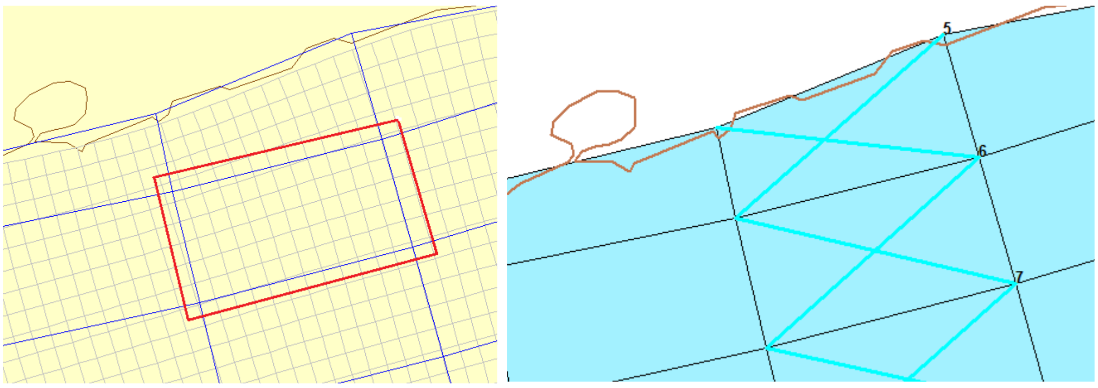


Figure 0.59 | Left: overview of number of gridcells of nested grid in one gridcell of the overall model; Right: gridcell corresponds to observation point 6 of the SRM

J.3.2 METHODS USED TO ASSESS THE QUANTITIES

Mean error

The mean error represents the mean of all the errors between the actual values and the estimators.

$$mean\ error = MSE(\hat{\theta}) = E[\hat{\theta} - \theta]$$

To get a better feeling for the magnitude of the ME, this value has also been divided by the absolute mean of the results of the SRM.

(Root) mean squared error

The mean squared error is a way of defining the difference between actual values and the estimation of these values. It shows the average of the squared difference between the true and the estimated value.

$$mean\ squared\ error = MSE(\hat{\theta}) = E\left[(\hat{\theta} - \theta)^2\right]$$

The root mean squared error (RMSE) draws the root of the mean squared error. The RMSE has the same units as the actual values and is therefore directly easily comparable with these values.

$$root\ mean\ squared\ error = \sqrt{MSE(\hat{\theta})} = E\left[(\hat{\theta} - \theta)^2\right]$$

To get a better feeling for the magnitude of the (R)MSE, these values have also been divided by the absolute mean of the results of the SRM.

Mean relative error

The mean relative error expresses the error of the numerical model in terms of the actual size of the modeled value:

$$MRE = \frac{\sum_0^n \frac{(\hat{\theta} - \theta)}{\theta}}{n}$$

The relative error can be very big when the actual number is very small. Cases like this can increase the mean relative error dramatically.

J.3.3 OBSERVATION POINTS IN BOTH THE SRM AND THE NESTED MODEL

To be able to compare the results of the simulations of the nested grids with the base run of the SRM model, observation points have been chosen in different areas; relatively far offshore, nearshore and in between these two locations.

The offshore locations should give the best match with the results of the SRM, since the size of the gridcells will be close to that of the SRM's cells. Furthermore, the boundaries are prescribed with time series that have been created by the SRM. On the boundaries, the results should therefore be an exact match.

Near the land boundary, the effects of the land boundary on the results become noticeable. The SRM does not follow the land boundary as well as the nested grid. The effect of the land boundary on the flow in the nested model creates a discrepancy between the results of the nested model and the SRM. More differences will arise because of the difference in gridcell sizes; the results from the much smaller cells near the coast will differ from those of the SRM.

As a consequence, gridcells 13, 14, 16, 17, 19 and 20 in the middle of the computational domain have been chosen to calibrate the results. The gridcells have a size similar to the gridcells of the SRM and are located far away from the shore and boundaries.

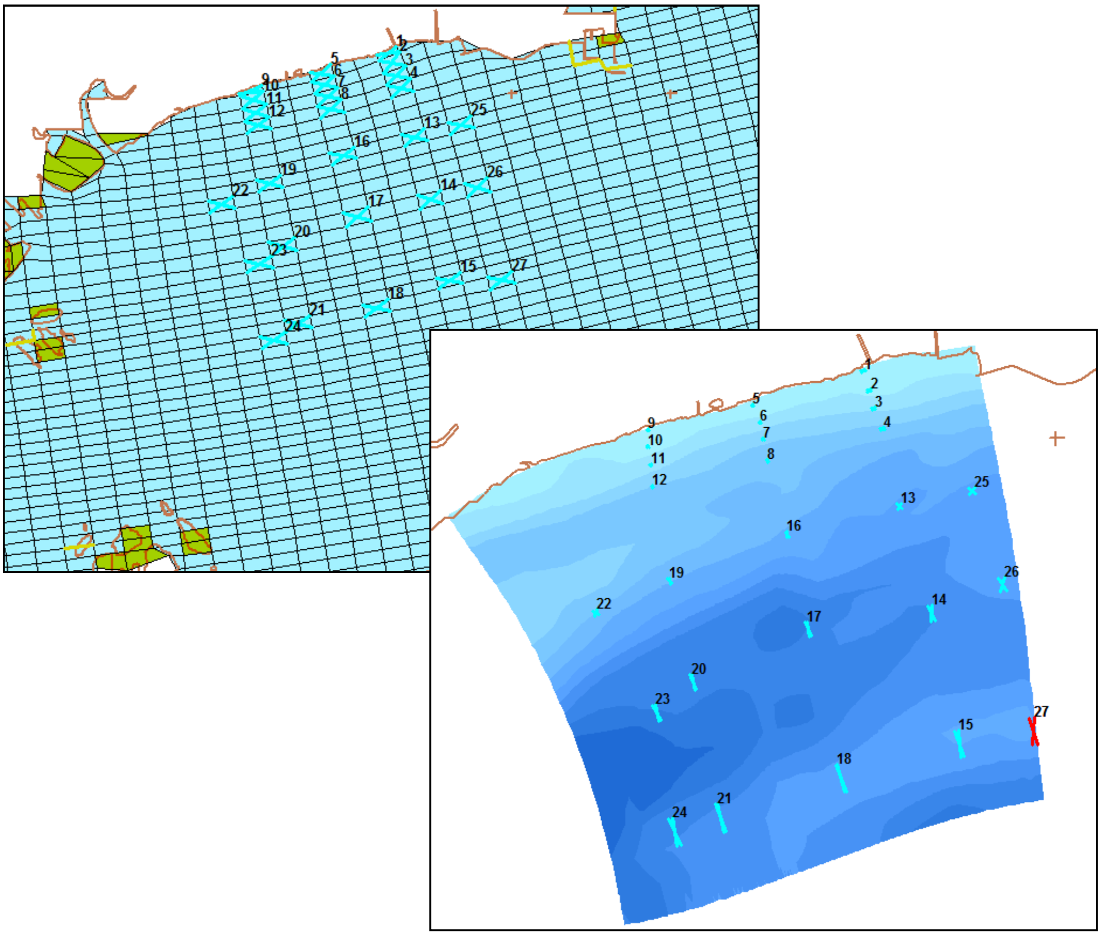


Figure 0.60 | Observation points in the SRM (left) and the nested grid (right) in front of East Coast Park

The observation points in the nested grid are located in the centre of the larger cells that have been chosen as observation points in the overall model.

J.3.4 SETTINGS OF DELFT3D FOR BASE RUN OF THE SRM

Table 25 | Settings parameters Delft3Dfor the baserun of the SRM

Delft3D section	Delft3D subsection	Input parameter	Value in Delft3D
Domain	Grid	Grid	m31
		Grid enclosure	m31
		Number of layers	1
	Bathymetry		m31
	Dry points		Multiple
	Thin dams		Multiple
Time frame		Simulation start time	01 01 2004 00 00 00
		Simulation stop time	21 01 2004 00 00 00
		Time step	4 min
		Local time zone (LTZ)	8
Processess	Constituents	Salinity	
	Physical	-	
Initial conditions	Uniform values	Water level	0 m
		Salinity	31 ppt *[1]*
Boundaries	Flow conditions	Type, Forcing	Water level, astronomic
		Reflection parameter alpha	75 s2
	Transport conditions	Salinity	31 ppt *[1]*
Physical paramterers	Constants	Gravity	9.81 m/s2
		Water density	1000 kg/m3
		Temperature	30 C *[1]*
	Roughness	Bottom roughness	Manning, uniform 0.022
		Wall roughness	Free slip conditions
	Viscosity	Turbulence model	Not applicable
		Horizontal eddy viscosity	1
		Horizontal eddy diffusivity	1
Numerical parameters		Drying and flooding check at	Grid cell centres and faces
		Depth specified at	Grid cell corners
		Depth at grid cell centres	Mean
		Depth at grid cell faces	Min
		Threshold depth	0.1 m
		Marginal depth	- 999 meter
		Smoothing time	60 min
		Advection scheme for momentum	Cyclic
		Advection scheme for transport	Cyclic
		Forester filter	On
Output	Storage	Interval	120 min
		History interval	60 min
		Restart interval	1440 min

[1] (Robinson R. A., 1953), (Tkalich et al., 2004)

Simulation start and stop time

All simulations have been run for three weeks, but only the time steps of the last two weeks have been used in the comparison of the results. The results of the first week have been omitted because this coincides with the spin up of the SRM, which is exactly one week (Kurniawan, 2011). To make sure that the spin up is completely gone from the system, 2 extra days of results have been omitted, which means that all results used in the calibration range from the 10th of January 2004 to the 21st of January 2004.

General remarks on parameters settings

The effect of the monsoon has been incorporated in the SRM. This can be done in two ways; by means of a BCR file or incorporated in the tidal constituents. A BCR file is a way to lift the mean around which the tidal constituents vary. This way, effects of wind and monsoon can be implemented. In the SRM and our model however, the monsoon effects have been described by tidal constituents in order to keep the BCR file empty. It is therefore possible to add other wind induced effects on top of the monsoon, for instance the effect of a storm surge. The problem with a BCR file is that it can not be used across years. If a multiple year simulation is required, including morphology, a restart file would have to be used. With the monsoon being described by tidal constituents however, a cross year simulation is possible.

J.3.5 OVERVIEW OF DIFFERENT GRIDS USED

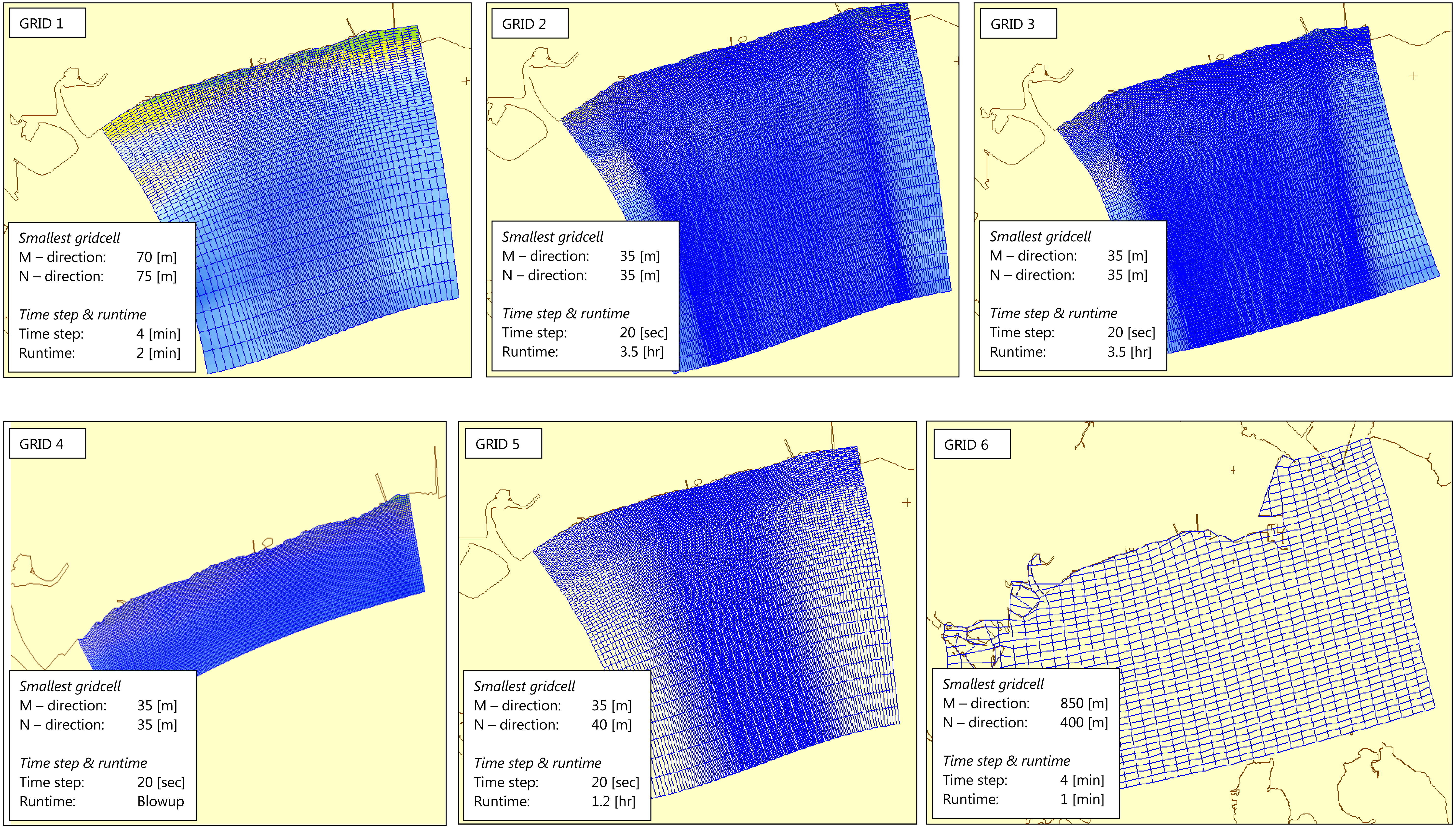


Figure 0.61 | Overview of grids used in the calibration process

J.3.6 PARAMETERS ALTERED IN THE CALIBRATION PROCESS

This paragraph tries to give an overview of all the parameters that have been altered and adjusted during the calibration process.

Table 26 | Parameters that have been adjusted in the calibration process

Nested in	Type of open boundary	Location of boundary	Boundary segments	Grid
derefined SRM	water level	north	1	1
'normal' SRM	current	east	multiple	2
	Riemann	south		3
		west		4
				5
				6

Time step	Bathymetry	Reflection parameter α	Time interval nesting
7,5 [min]	Uniform 10 [m]	0	1 [hr]
4 [min]	SRM	50	20 [min]
2 [min]	SRM smoothed	75	
1 [min]	ENC	100	
0.5 [min]	SRM smoothed + ENC		
0.3 [min]			

Overall model for nesting

There are two versions of the Singapore regional model; the derefined SRM and the 'normal' SRM. The derefined SRM has only one third of the gridcells of the normal SRM, which dramatically reduces the runtime of this model. Although both models have been used for nesting, it soon became clear that the derefined model was not accurate enough for the purposes of this study. The normal SRM has therefore been used for nesting in the majority of the simulations.

Type and locations of open boundaries

When a nested grid is located in the open water, open boundaries have to be prescribed on these boundaries. There are three types of boundaries that have been varied on these open boundaries; water level, current and Riemann boundaries. These types have been varied in different locations and configurations (north, east, south and west).

Although many boundary configurations have been applied, only one setup has proven to produce realistic and accurate results; water levels on the southern and currents on the eastern and western boundaries.

One of the reasons that water level boundaries alone do not produce sufficient or even realistic results is the fact that the flows in the area of interest have a diurnal character, while the water levels have a semi diurnal character (Maren, Tides and residual flows, 2011). Furthermore, much of the flow patterns are created by the bathymetry and shape of the computational domain of the SRM. With the computational domain greatly decreased in the nested model, it is impossible to re-create these flow patterns with only water levels forcing the boundaries.

Boundary segments

The open boundaries in the north, east, south or west encompass more than one gridcell of the nested model. Therefore, segments have to be prescribed which divide these open boundaries into multiple sections. During the calibration, the number and sizes of these segments have been varied. Ideally, each boundary segment of the nested grid corresponds to the size of a gridcell of the overall model. In that case, all the information from the nested model is transferred to the nested model.

Grids used in the calibration

The specifications for the locations of the open boundaries as laid down in paragraph J.2.2 led to the development of the first grid. It has originated from the final set of splines but has been cut off in the south to decrease the amount of gridcells in areas that are not in the area of interest.

The runtimes of this grid are low and the results are relatively accurate. The only problem with this grid is the resolution of the gridcells in the area of interest, which is not fine enough according to the specifications as laid down in paragraph J.1.6 on the required resolution of the grid.

The second grid has been developed to overcome the resolution problems of the first grid. The gridcells in the entire area of interest, starting just east of Marina barrage up to the Tanah Merah ferry terminal and extending 1500 meters off shore, are all dimensioned to be 30 by 30 meters. The big advantage of this grid, the increase in resolution, in return also brings forth one of its biggest problems; it has a very long runtime. More importantly, the results of this grid are not accurate.

In an attempt to improve the results of the refined grid, a third grid has been developed. The spacing near the edges of the grid has been increased to dampen out numerical disturbances entering the grid from the boundaries. The results from Figure 0.62 however show that this attempt has failed. The spacing should probably have been much wider in order for it to dampen out the numerical errors. Furthermore, this grid also has a very long runtime.

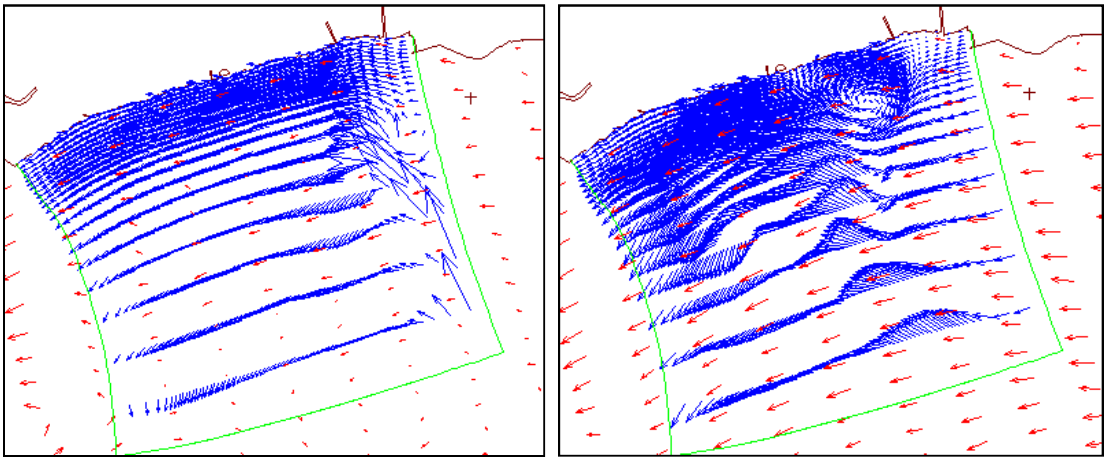


Figure 0.62 | Typical example of numerical disturbances from two consecutive time steps; the blue arrows represent the velocity vectors of the nested grid. The red arrows are the velocity vectors of the overall model (normal SRM). The green line embodies the open boundaries of the nested model

As a final effort to maintain the very fine resolution in our area of interest, grid 4 has been developed. Grid 4 has been cut short and has been nested in grid 1, combining the best of both worlds; a fine resolution and a short runtime. The setup looked promising, but all the attempted runs with this grid have blown up.

Grid 5 is a consensus between fine resolution on the one and little computational time on the other hand. It is not as fine as grid 2, but finer than grid 1, allowing for a fine enough resolution in the area of interest. The results of this grid however are not accurate enough. Most probable, the spacing near the edges is not big enough, which again generated numerical disturbances near the edges.

Grid 6 has been developed to assess the influence of enhancing the domain of the grid. Although not many runs have been made with this grid, all attempts have blown up. Causes for this blowup are most probably found in grid spacing and the smoothness of the bathymetry. Efforts to improve this grid have been stopped because of time constraints.

Concluding, only gird one has proven to produce both accurate results while maintaining a relatively short runtime.

Time steps

In the process of calibration, time steps varying between 7.5 [min] and 20 [sec] have been applied. To determine which time step belonged to each grid, a time step investigation has been carried out. The time step was halved up to the point where the results did not change anymore. The time steps and their corresponding run times as shown in Figure 0.61 are the results of these time step investigations.

The time step has to be decreased when nesting with a finer grid because of the Courant number $\frac{u\Delta x}{\Delta t}$, which should be a similar constant value in both grids and always smaller then $4\sqrt{2}$. Assuming the velocities in the SRM and the nested model are equal to each other, the ratio $\frac{\Delta x}{\Delta t}$ determines the time step needed when the grid size decreases.

Bathymetry

Three different types of bathymetry have been applied in the calibration process; a uniform depth of 10 [m], the original bathymetry of the SRM and the bathymetry of the electronic navigational charts (ENC) (refer Figure 0.1in Appendix A).

To improve the nested models results, the bathymetry has been smoothed out on both the western, eastern and southern boundaries. To avoid numerical disturbances, large gradients in the bathymetry underneath the boundaries should be prevented. Deep holes or relatively shallow areas on the boundaries have therefore been erased manually in QUICKIN.

To obtain more realistic results, more detailed bathymetric information from the electronic navigational charts has been implemented in the grids. To save time, the calibrated bathymetrical data from the SRM has been combined with the ENC depth contour data. The detailed ENC data has been implemented near the coast, while the rest of the grid uses the original SRM data.

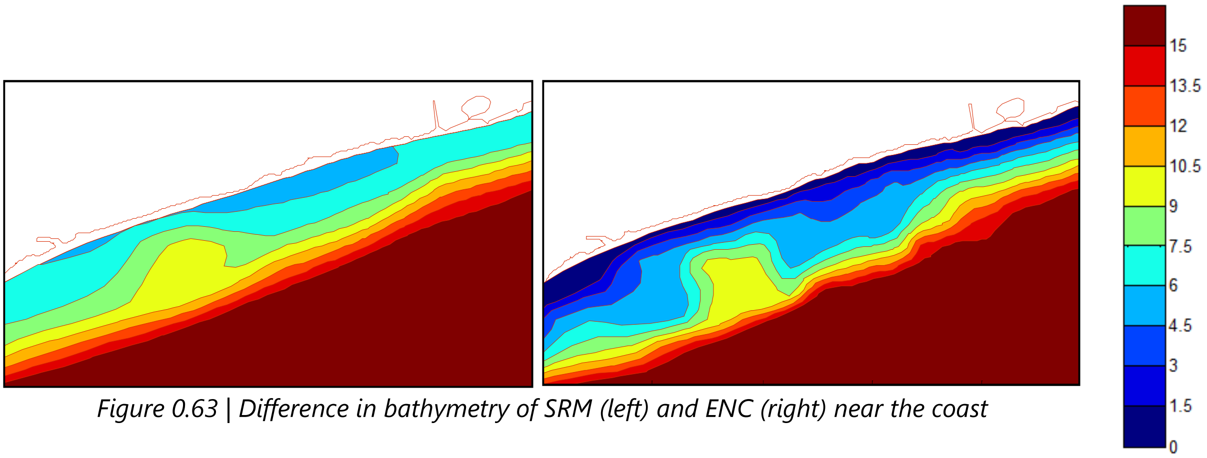


Figure 0.63 | Difference in bathymetry of SRM (left) and ENC (right) near the coast

Reflection parameter alpha

Adjusting the reflection parameter alpha allows waves to partly travel out of the domain, which can dampen out numerical errors travelling through the domain. It is a way of implementing boundary conditions that are similar to the Riemann type. When applying such a weakly reflective boundary, the reflection parameter alpha is adjusted to a nonzero value. Recommended values are between 50 [s^2] and 100 [s^2] (Deltares, Delft3D - FLOW User Manual, 2011).

Time interval nested grids

In an attempt to improve the results of the nested grids, the time interval of the time series on the boundaries has been decreased from 1 hour to 20 minutes. Reasoning behind this is that processes that take place in a time scale smaller than 1 hour cannot be reproduced correctly if the information is fed to the nested model only once every hour.

J.4 SPECIFICATIONS AND PERFORMANCE OF FINAL MODEL

J.4.1 SPECIFICATIONS FINAL MODEL

The specifications presented in Table 27 have shown to give the most accurate results during the calibration process.

Table 27 | Specifications final model

Nested in	Grid	Location of boundary	Type of open boundary	Boundary segments
'normal' SRM	1	east	current	multiple
		south	water level	
		west	current	
Time step	**Bathymetry**	**Reflection parameter α**	**Time interval nesting**	
0.5 [min]	SRM smoothed + ENC	0	20 [min]	

J.4.2 TIME DOMAIN IN WHICH THE MODEL WILL BE USED

The time during which the nested model will be run is determined by the desired use of the model. The nested model has been build to investigate the effects of the designs on the hydrodynamics and vice versa and to perform a sensitivity analysis for sediments. This implies that no full morphodynamic calculations will be performed which in return implies that the effect of the monsoon does not have to be taken into account. Furthermore, as this is a desk study, the computational time should be kept at a minimum. As a consequence, a two week fortnightly run will suffice to be able to evaluate the different designs.

The fortnightly period should incorporate the most severe conditions during the year, incorporating the highest flow velocities. After careful inspection of the figures below, it was found that this period is found between 7-Dec-2004 00-00-00 up to 21-Dec-2004 00-00-00. This coincides with the period of the northeast monsoon (December to February).

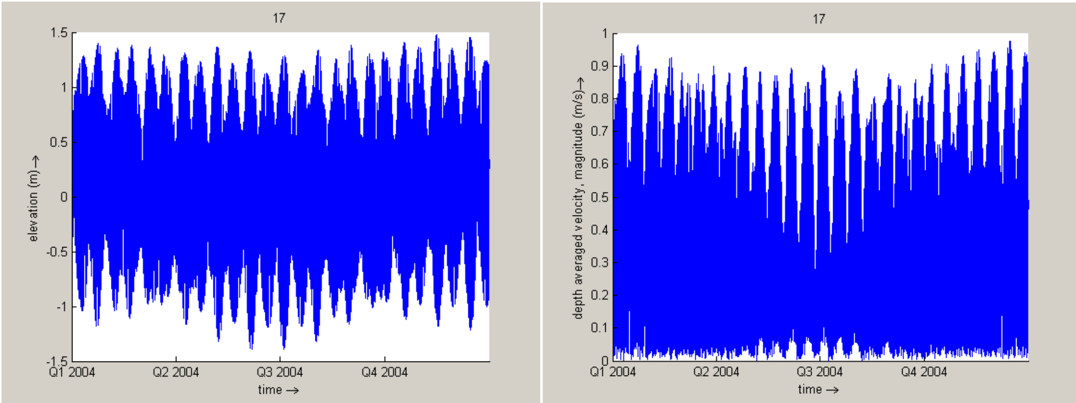


Figure 0.64 | Water levels (left) and magnitude of velocity vectors (right) during a full year cycle

J.4.3 PERFORMANCE OF THE NESTED MODEL

The performance of the nested model is judged by means of five different graphs, which are presented in Figure 0.65.

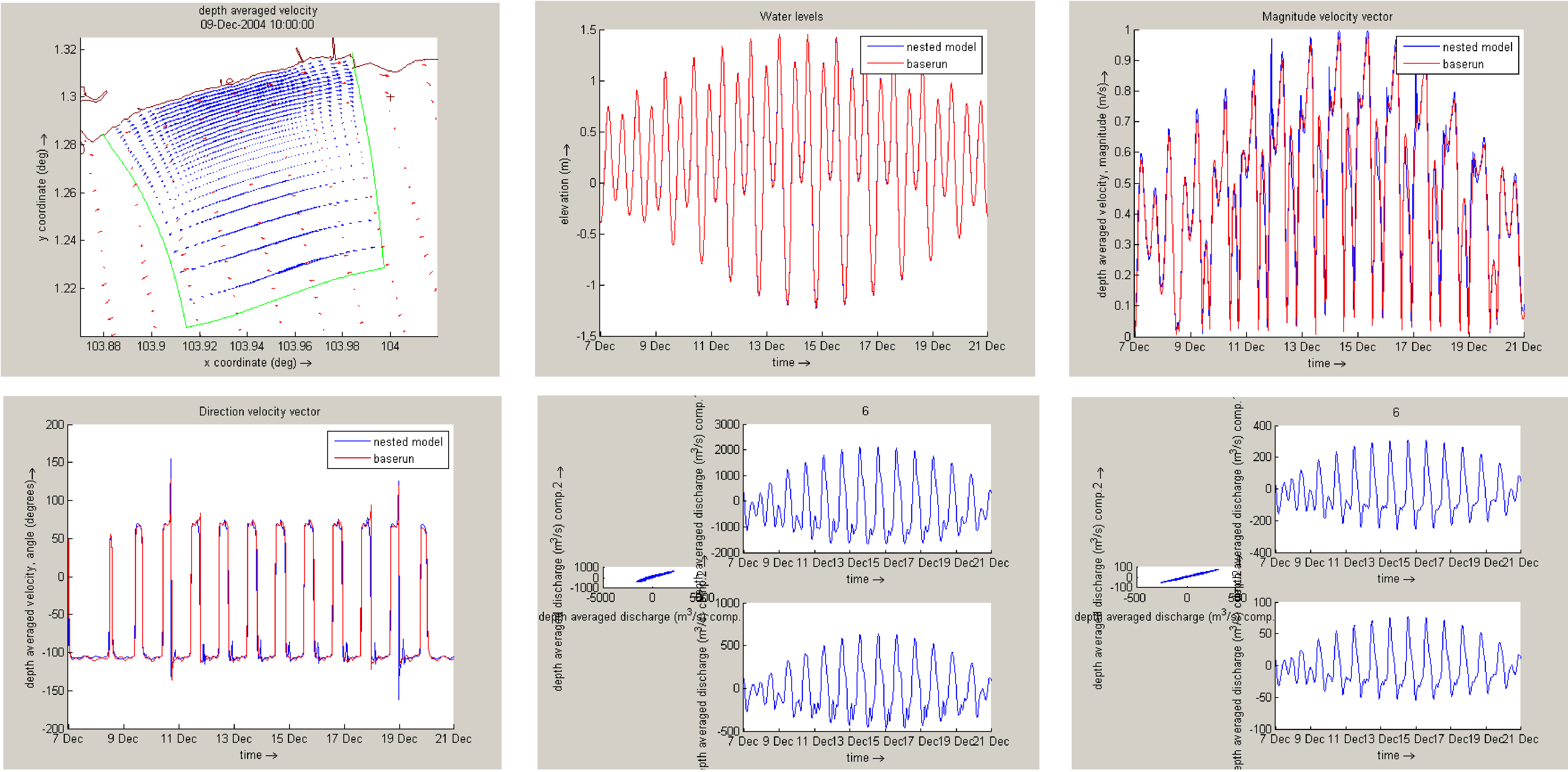


Figure 0.65 | Comparison between the nested model and the SRM; from top left to bottom right:
(1) velocity vector field in observation point 17 (blue =nested model, red = baserun, green = open boundaries nested model),
(2) water level in observation point 17,
(3) magnitude velocity vector in observation point 17,
(4) direction velocity vector in observation point 17,
(5) discharge in observation point 6 (SRM),
(6) discharge in observation point 6 (nested grid)

Error calculations

The graphs of Figure 0.65 only show the comparison of the results in observation point 17. Table 28 presents an overview of the error calculations for observation points 13, 14, 16, 17, 18, 19 and 20.

Table 28 | Overview of error calculations for different observation points

	Parameter	13	14	16	17	19	20	Average
Water level	*Mean error (ME)*	0,006	0,005	0,005	0,004	0,005	0,004	0,005
	Mean squared error (MSE)	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	Root mean squared error (RMSE)	0,008	0,006	0,006	0,006	0,006	0,005	0,006
	Mean relative error (MRE)	7,274	9,656	8,540	7,452	9,190	7,299	8,235
	ME / absolute mean SRM	1,072	0,909	0,877	0,782	0,817	0,709	0,861
	RMSE / absolute mean SRM	1,378	1,191	1,150	1,053	1,140	0,969	1,147
Velocity	*Mean error (ME)*	0,026	0,024	0,042	0,033	0,068	0,028	0,037
	Mean squared error (MSE)	0,002	0,002	0,005	0,002	0,013	0,001	0,004
	Root mean squared error (RMSE)	0,042	0,041	0,073	0,049	0,113	0,039	0,060
	Mean relative error (MRE)	16,996	11,062	19,229	13,100	19,981	13,678	15,674
	ME / absolute mean SRM	5,874	4,645	9,804	6,772	16,027	5,848	8,162
	RMSE / absolute mean SRM	9,653	8,163	16,877	10,076	26,725	7,958	13,242
Direction	*Mean error (ME)*	6,388	5,795	10,134	5,268	8,373	5,212	6,862
	Mean squared error (MSE)	406,129	255,380	864,998	345,007	538,338	226,890	439,457
	Root mean squared error (RMSE)	20,153	15,981	29,411	18,574	23,202	15,063	20,397
	Mean relative error (MRE)	8,847	9,525	116,936	15,039	138,366	18,205	51,153
	ME / absolute mean SRM	6,842	6,264	10,268	5,548	8,903	5,258	7,181
	RMSE / absolute mean SRM	21,584	17,274	29,800	19,562	24,670	15,194	21,347

J.4.4 CONCLUSIONS ON THE ACCURACY OF THE NESTED MODEL

Table 29 repeats the required accuracy of the modeled results from paragraph J.1.7. These numbers follow from the fact that the results should be within a range of accuracy of 5%.

Table 29 | Required accuracy of modelled results

Parameter	Error
Water level	<0.03 m
Velocity vector magnitude	<0.025 m
Velocity vector direction	<5 °

The water levels in all the observation points easily meet the accuracy demands. They are almost an exact match with the original water levels. The reason for the relatively high mean error is found in the fact that this error can become very large if the original number is very small.

The errors found in the magnitude of the velocity vectors are too big. Although the averaged ME and RMSE are close (0.037, 0.060), the mean relative errors are well above 10%. The shape of the graphs however are a good match, which combined with the relatively small ME and RMSE leads to believe that the results are accurate enough to be used.

The accuracy of the direction of the velocity vectors is the lowest. The ME however are very close to the required accuracy. The reason for the relatively big RMSE errors can be found in the fact that very big errors can arise when the two time series are subtracted from each other; e.g. when the real value is 359° and the simulated value is 1°, the results almost are an exact match, but the error is 358°. Furthermore, because of a phase lag, very big differences can be found. The shape of the graphs however is a good match. Combined with the relatively small ME's, the results of the nested model are sufficient.

J.5 SETUP MODEL FOR DESIGN RUNS

J.5.1 IMPLEMENTING THE DESIGNS IN THE GRID

The shape of the designs has been cut into the grid. The gridcells have been smoothed in the corners to prevent staircase boundaries near the edges.

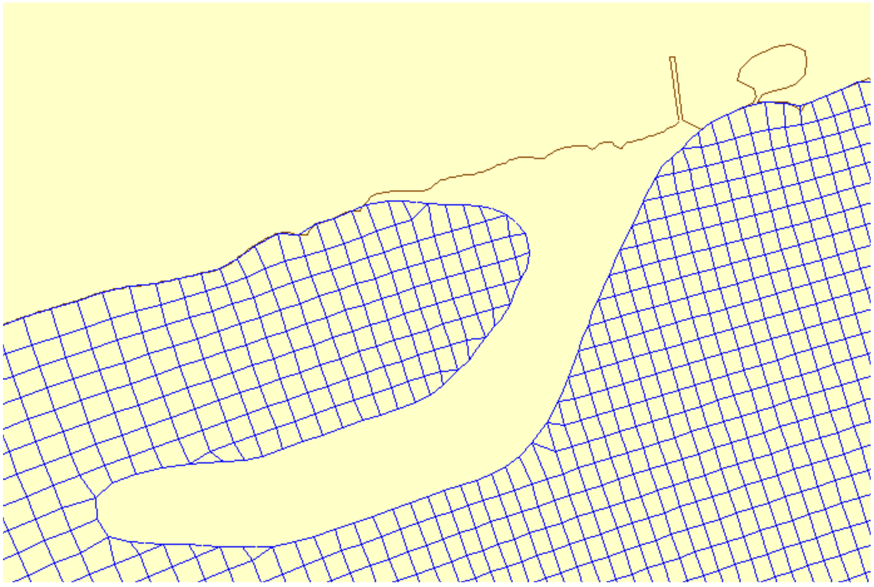


Figure 0.66 | Overview of implemented design in grid

J.5.2 SETUP OF THE NESTED MODEL

The nested model will be used to evaluate the influence of the designs on the hydrodynamics and vice versa. Furthermore, fine sediments will be added to the system, both on the boundaries and as an initial condition sediment concentration. The initial sediment layer thickness will be set at 0, which implies that only accretion of fine sediments will be taken into account.

Table 30 gives an full overview of the settings of Delft3D for the design runs:

Table 30 | Settings Delft3D for design runs

Delft3D section	Delft3D subsection	Input parameter	Value in Delft3D
Domain	Grid	Grid	design [...] grid
		Grid enclosure	design [...] grid
		Number of layers	1
	Bathymetry		Original SRM + ENC
	Dry points		
	Thin dams		
Time frame		Simulation start time	07 01 2004 00 00 00
		Simulation stop time	21 01 2004 00 00 00
		Time step	0.5 min
		Local time zone (LTZ)	8
Processess	Constituents	Salinity, Sediments	
	Physical	-	
Initial conditions		Water level	0 m
		Salinity	31 ppt
		Concentration SedimentCoh	0.01 kg/m3
Boundaries	Boundary conditions	Water level, astronomic	Water level, astronomic
		Reflection parameter alpha	0 s2
	Transport conditions	Salinity	31 ppt
		Concentration SedimentCoh	0.01 kg/m3
Physical paramterers	Constants	Temperature	30 C
		Water density	1000 kg/m3
	Roughness	Bottom roughness	Manning, uniform 0.022
		Wall roughness	Free slip conditions
	Viscosity	Turbulence model	Not applicable
		Horizontal eddy viscosity	10
		Horizontal eddy diffusivity	10
		Vertical eddy viscosity	Not applicable
		Vertical eddy diffusivity	Not applicable
	Sediments	Reference density for hindered settling	1600 kg/m3
	Sediments (SedimentCoh)	Specific density	2650 kg/m3
		Dry bed density	500
		Settling velocity	0.1 mm/s
		Critical bed shear stress for sedimentation	1000 N/m2
		Critical bed shear stress for erosion	0.11 N/m2
		Erosion parameter	0.0001 kg/m2/s
		Initial sediment layer thickness at bed	0 m
	Morphology	Update bathymetry during FLOW simulation	yes
		Include effect of sediment on fluid density	no
		Morphological scale factor	1
		Spin-up interval before morphological changes	0 min
		Minimum depth for sediment calculation	0,1
Numerical parameters		Drying and flooding check at	Grid cell centres and faces
		Depth specified at	Grid cell corners
		Depth at grid cell centres	Mean
		Depth at grid cell faces	Mor
		Threshold depth	0.1 m
		Marginal depth	-999 meter
		Smoothing time	60 min
		Advection scheme for momentum	Cyclic
		Advection scheme for transport	Cyclic
Output	Storage	Interval	120 min
		History interval	20 min
		Restart interval	1440 min

J.6 LIMITATIONS

The resolution of the final grid does not meet the demands as laid down in paragraph *J.1.6 required resolution of the grid*; the size of the gridcells in the area of interest is too big. The possibility of placing the island close to the shore generates the biggest restriction on the gird cell sizes; as small as possible. The models results however have shown that the flow velocities increase to unacceptable values when the islands are placed to close to shore (<200 m). This observation raises the question whether such a fine resolution really is needed.

The tidal forcing has been omitted from the models. The reason for omitting the forcing is a software conflict. The SRM has been setup in an older version of Delft3D than the version of Delft3D used in this report (version 4.00.00). This however is not a big problem because the effect of the tidal forcing would be in the range of centimeters (Kurniawan, 2011). The simulations of the SRM that have been used to compare results have also been run without tidal forcing. The effect is thus not noticeable when comparing results, but the results that have been used to compare with are off by a few centimeters.

The mud flats on which the mangroves grow have been modelled at mean sea level in the different designs. In reality, these flats will have a slope in the order of 1:200. As a consequence, the flats in the designs are inundated for a shorter period of time than would be the case in reality. The nested model however is not used to determine the inundation times. Furthermore, higher flow velocities are found near the edges of the flats because there is no smooth transition between the mud flat and the water level at MSL.

It is not possible to include land masses above MSL in Delft3D, which could influence the hydro- and morphodynamics of the mud flats of the mangrove forests (e.g. not possible to assess accretion of fines above MSL).

The SRM bathymetry is very course near the coast. The time series that are prescribed on the boundaries are generated by the SRM. As the area of the nested model is relatively small, this could imply that wrong information is fed to the model. The area of the nested model should be chosen much larger to make sure that the information on the boundaries does not have a significant effect on the nested models results anymore.

It is not possible to perform a full morphodynamic calculation with the current model setup for multiple reasons:

- As the model is only run for a fortnightly period of two weeks, the monsoon is not included in the runs. This implies that the influence of the monsoon on the longshore sediment transport rates cannot be evaluated
- The area of the model is too small, which implies that the boundaries have an influence on the models results (sediment can leave the system)
- Current velocities and directions have to be reproduced more accurately to incorporate asymmetrical aspects of the flow
- There is a lack of necessary input data; sediment concentrations in the water and on the boundaries, location and influence of dredge and dump areas, sediment compositions and locations (sand vs. silt / clay).

Waves have not been included in the design runs.

J.7 RECOMMENDATIONS

In an attempt to improve the nested models results further, flux instead of velocity boundaries can be described on the boundaries of the small nested grid.

Another boundary setup that needs further research is the water level east, water level west and Riemann south configuration. Special attention should be given to the corners of the grid, where the different boundary types meet. In these corners, the information provided by the boundaries should coincide.

Ways of improving the model and to make it fit for full morphodynamic calculations are:

- The models area should be enlarged. The boundaries should be located far away from the area of interest to reduce the effect of the boundaries on the models results.
- The spacing of the grid near the boundaries should be as large as possible to dampen out numerical disturbances.
- With the area of the nested grid enlarged, the type of boundaries to be used should be investigated again. Using boundaries of the water level type on all open boundaries could prove to be successful in this case.
- The resolution of the grid should be in the order of 30 x 30 m in the area of interest.
- The open boundaries should be chosen such that they do not cross complicated flow patterns such as large eddies.
- The model should be run for a full year to incorporate the monsoon.
- Waves should be added to the simulations to assess their influence on the hydro- and morphodynamics.
- A bcd file should be created to make the distinction between mud and sand on the bottom
- Layers should be added to the model to improve the accuracy of the modeled results

Before full morphodynamic calculations can be made, more information of the coastal system at ECP is needed; sediment transport rates, sediment concentrations, detailed locations of erosion and accretion spots, sediment compositions and locations (sand vs. silt / mud) and detailed information on dredging and dumping activities in the area.

J.8 MATLAB SCRIPT USED TO EVALUATE RESULTS

```
% -----Clearing memory and adding path-----

clear; close all; clc;
addpath('c:\Delft3D\w32\delft3d_matlab\')

% -----Invoking calculations from observation points with required scales-----

observation_points                              = 0;
vector_field_depth_averaged_velocity            = 0;
maximum_velocities                              = 0;
    minscale_vel = 0;
    maxscale_vel = 1;
maximum_bed_shear_stresses                      = 0;
    minscale_bed_design = 0;
    maxscale_bed_design = 1.5;
    minscale_bed_base = 0;
    maxscale_bed_base = 1.5;
cum_sedimentation_fines                         = 0;
    minscale_fines = 0;
    maxscale_fines = 0.001;
discharge                                       = 0;
    cross_section = 'West';
water_levels                                    = 0;
magnitude_velocity_vector                       = 0;
direction_velocity_vector                       = 0;
calculations_errors                             = 0;
    observation_point = '(27,49)';

% ----- Choice of period -----

time_step = 1:1009;

% ----- Choice of latitude and longitude of map plots -----

latlong = [103.895 103.935 1.285 1.310];

% ----- Observation points -----

if (observation_points == 1);

    d3d_qp('openfile','c:\Delft3D\sediment\cube seagrass\trih-run1.dat')
    d3d_qp('selectfield','location observation points')
    d3d_qp('allt',0)
    d3d_qp('alls',1)
    d3d_qp('presenttype','labels')
    d3d_qp('fontsize',9)
    d3d_qp('colour',[ 0 0 1 ])
    d3d_qp('quickview')

    d3d_qp('openfile','c:\Delft3D\sediment\cube seagrass\Singapore.ldb')
    d3d_qp('colour',[ 0.501961 0 0 ])
    d3d_qp('addtoplot')

    d3d_qp('openfile','c:\Delft3D\sediment\cube seagrass\trim-run1.dat')
    d3d_qp('selectfield','closed boundaries')
    d3d_qp('colour',[ 0.501961 0 0 ])
    d3d_qp('addtoplot')

    title('Observation points')
    axis('equal',latlong)

else display('no observation points');
end

%-----Vector field depth averaged velocity-----
```

```matlab
if (vector_field_depth_averaged_velocity == 1);

    d3d_qp('openfile','c:\Delft3D\sediment\cube seagrass\Singapore.ldb')
    d3d_qp('colour',[ 0.501961 0 0 ])
    d3d_qp('quickview')

    d3d_qp('openfile','c:\Delft3D\sediment\cube seagrass\trim-run1.dat')
    d3d_qp('selectfield','closed boundaries')
    d3d_qp('colour',[ 0.501961 0 0 ])
    d3d_qp('addtoplot')

    d3d_qp('openfile','c:\Delft3D\sediment\cube seagrass\trim-run1.dat')
    d3d_qp('selectfield','depth averaged velocity')
    d3d_qp('component','vector')
    d3d_qp('vecscalem','manual')
    d3d_qp('1vecunit',0.005)
    d3d_qp('thinfld','uniform')
    d3d_qp('thinfact',1)
    d3d_qp('colour',[ 0 0 1 ])
    d3d_qp('editt',100)
    d3d_qp('addtoplot')

    d3d_qp('openfile','c:\Delft3D\Base run 7 21 dec\trim-baserun_restart.dat')
    d3d_qp('selectfield','depth averaged velocity')
    d3d_qp('vecscalem','manual')
    d3d_qp('1vecunit',0.005)
    d3d_qp('thinfld','uniform')
    d3d_qp('thinfact',6)
    d3d_qp('colour',[ 1 0 0 ])
    d3d_qp('editt',100)
    d3d_qp('addtoplot')

    axis('equal',latlong)
    xlabel('Longitude [deg]','FontSize',10)
    ylabel('Latitude [deg]','FontSize',10)
    title('Vector field depth averaged velocity')

else display('no vector field depth averaged velocity')
end

% ----- Maximum velocities in grid points entire domain -----

if (maximum_velocities == 1);

    d3d_qp('openfile','c:\Delft3D\sediment\cube seagrass\trim-run1.dat')
    d3d_qp('selectfield','depth averaged velocity')
    d3d_qp('component','magnitude')
    d3d_qp('allt',1)
    d3d_qp('exportdata','c:\Delft3D\sediment\cube seagrass\velocities.mat')

    load velocities.mat
    velocity = data.Val;

    maxvel_3D = max(velocity(:,:,:));
    maxvel_2D = squeeze(maxvel_3D);

    d3d_qp('openfile','c:\Delft3D\sediment\cube seagrass\trim-run1.dat')
    d3d_qp('selectfield','depth averaged velocity')
    d3d_qp('allt',0)
    d3d_qp('editt',100)
    d3d_qp('exportdata','c:\Delft3D\sediment\cube seagrass\velocity_ts100.mat')

    load velocity_ts100.mat

    data.Val = maxvel_2D;

    save('maximum_velocities.mat','data')
```

```
d3d_qp('openfile','c:\Delft3D\sediment\cube seagrass\Singapore.ldb')
d3d_qp('colour',[ 0.501961 0 0 ])
d3d_qp('quickview')

d3d_qp('openfile','c:\Delft3D\sediment\cube seagrass\maximum_velocities.mat')
d3d_qp('presenttype','patches with lines')
d3d_qp('colour',[ 0 0 0 ])
d3d_qp('climmode','manual')
d3d_qp('climmin',minscale_vel)
d3d_qp('climmax',maxscale_vel)
d3d_qp('addtoplot')

axis('equal',latlong)
title('Maximum velocities from all time steps [m/s]')

%----- Reading base run results -----

d3d_qp('openfile','c:\Delft3D\Base run 7 21 dec\trim-baserun_restart.dat')
d3d_qp('selectfield','depth averaged velocity')
d3d_qp('component','magnitude')
d3d_qp('allt',1)
d3d_qp('exportdata','c:\Delft3D\Base run 7 21 dec\velocities_baserun.mat')

load 'c:\Delft3D\Base run 7 21 dec\velocities_baserun.mat'
velocity_baserun = data.Val;

maxvel_baserun_3D = max(velocity_baserun(:,:,:));
maxvel_baserun_2D = squeeze(maxvel_baserun_3D);

d3d_qp('openfile','c:\Delft3D\Base run 7 21 dec\trim-baserun_restart.dat')
d3d_qp('selectfield','depth averaged velocity')
d3d_qp('allt',0)
d3d_qp('editt',100)
d3d_qp('exportdata','c:\Delft3D\Base run 7 21 dec\velocity_baserun_ts100.mat')

load 'c:\Delft3D\Base run 7 21 dec\velocity_baserun_ts100.mat'

data.Val = maxvel_baserun_2D;

save('c:\Delft3D\Base run 7 21 dec\maximum_velocities_baserun.mat','data')

d3d_qp('openfile','c:\Delft3D\Base run 7 21 dec\Singapore.ldb')
d3d_qp('colour',[ 0.501961 0 0 ])
d3d_qp('quickview')

d3d_qp('openfile','c:\Delft3D\Base run 7 21
dec\maximum_velocities_baserun.mat')
d3d_qp('presenttype','patches with lines')
d3d_qp('colour',[ 0 0 0 ])
d3d_qp('climmode','manual')
d3d_qp('climmin',minscale_vel)
d3d_qp('climmax',maxscale_vel)
d3d_qp('addtoplot')

axis('equal',latlong)
title('Maximum velocities from all time steps base run [m/s]')

%----- Subtracting velocities base run from results designs -----

maxvel_difference = maxvel_baserun_2D - maxvel_2D;

load velocity_ts100.mat

data.Val = maxvel_difference * -1;

save('velocities_difference.mat','data')

d3d_qp('openfile','c:\Delft3D\sediment\cube seagrass\Singapore.ldb')
```

```
    d3d_qp('colour',[ 0.501961 0 0 ])
    d3d_qp('quickview')

    d3d_qp('openfile','c:\Delft3D\sediment\cube
seagrass\velocities_difference.mat')
    d3d_qp('presenttype','patches with lines')
    d3d_qp('colour',[ 0 0 0 ])
    d3d_qp('climmode','automatic')
    d3d_qp('addtoplot')

    axis('equal',latlong)
    title('Difference in maximum velocities compared to base run [m/s]')

else display('no maximum velocities')
end

% ----- Maximum bed shear stresses in entire domain -----

if (maximum_bed_shear_stresses == 1)

    d3d_qp('openfile','c:\Delft3D\sediment\cube seagrass\trim-run1.dat')
    d3d_qp('selectfield','maximum bed shear stress')
    d3d_qp('allt',1)
    d3d_qp('exportdata','c:\Delft3D\sediment\cube seagrass\bed_shear_stresses.mat')

    load bed_shear_stresses.mat
    bed_shear_stresses = data.Val;

    max_bed_shear_stresses_3D = max(bed_shear_stresses(:,:,:));
    max_bed_shear_stresses_2D = squeeze(max_bed_shear_stresses_3D);

    d3d_qp('openfile','c:\Delft3D\sediment\cube seagrass\trim-run1.dat')
    d3d_qp('selectfield','maximum bed shear stress')
    d3d_qp('allt',0)
    d3d_qp('editt',100)
    d3d_qp('exportdata','c:\Delft3D\sediment\cube
seagrass\bed_shear_stresses_ts100.mat')

    load bed_shear_stresses_ts100.mat

    data.Val = max_bed_shear_stresses_2D;

    save('maximum_bed_shear_stresses.mat','data')

    d3d_qp('openfile','c:\Delft3D\sediment\cube seagrass\Singapore.ldb')
    d3d_qp('colour',[ 0.501961 0 0 ])
    d3d_qp('quickview')

    d3d_qp('openfile','c:\Delft3D\sediment\cube
seagrass\maximum_bed_shear_stresses.mat')
    d3d_qp('presenttype','patches with lines')
    d3d_qp('colour',[ 0 0 0 ])
    d3d_qp('climmode','manual')
    d3d_qp('climmin',minscale_bed_design)
    d3d_qp('climmax',maxscale_bed_design)
    d3d_qp('addtoplot')

    axis('equal',latlong)
    title(texlabel('Maximum bed shear stresses from all time steps [N/m^2]'))

    %----- Reading base run maximum bed shear stresses -----

    d3d_qp('openfile','c:\Delft3D\Base run 7 21 dec\trim-baserun_restart.dat')
    d3d_qp('selectfield','maximum bed shear stress')
    d3d_qp('allt',1)
    d3d_qp('exportdata','c:\Delft3D\Base run 7 21
dec\bed_shear_stresses_baserun.mat')
```

```
    load 'c:\Delft3D\Base run 7 21 dec\bed_shear_stresses_baserun.mat'
    bed_shear_stresses_baserun = data.Val;

    max_bed_shear_stresses_baserun_3D = max(bed_shear_stresses_baserun(:,:,:));
    max_bed_shear_stresses_baserun_2D = squeeze(max_bed_shear_stresses_baserun_3D);

    d3d_qp('openfile','c:\Delft3D\Base run 7 21 dec\trim-baserun_restart.dat')
    d3d_qp('selectfield','maximum bed shear stress')
    d3d_qp('allt',0)
    d3d_qp('editt',100)
    d3d_qp('exportdata','c:\Delft3D\Base run 7 21
dec\bed_shear_stresses_baserun_ts100.mat')

    load 'c:\Delft3D\Base run 7 21 dec\bed_shear_stresses_baserun_ts100.mat'

    data.Val = max_bed_shear_stresses_baserun_2D;

    save('c:\Delft3D\Base run 7 21 dec\max_bed_shear_stresses_baserun.mat','data')

    d3d_qp('openfile','c:\Delft3D\Base run 7 21 dec\Singapore.ldb')
    d3d_qp('colour',[ 0.501961 0 0 ])
    d3d_qp('quickview')

    d3d_qp('openfile','c:\Delft3D\Base run 7 21
dec\max_bed_shear_stresses_baserun.mat')
    d3d_qp('presenttype','patches with lines')
    d3d_qp('colour',[ 0 0 0 ])
    d3d_qp('climmode','manual')
    d3d_qp('climmin',minscale_bed_base)
    d3d_qp('climmax',maxscale_bed_base)
    d3d_qp('addtoplot')

    axis('equal',latlong)
    title(texlabel('Maximum bed shear stresses from all time steps base run
[N/m^2]'))

    %----- Subtracting maximum shear stresses base run from results designs -----

    max_bed_shear_stresses_difference = max_bed_shear_stresses_baserun_2D -
max_bed_shear_stresses_2D;

    load bed_shear_stresses_ts100.mat

    data.Val = max_bed_shear_stresses_difference * -1;

    save('max_bed_shear_stresses_difference.mat','data')

    d3d_qp('openfile','c:\Delft3D\sediment\cube seagrass\Singapore.ldb')
    d3d_qp('colour',[ 0.501961 0 0 ])
    d3d_qp('quickview')

    d3d_qp('openfile','c:\Delft3D\sediment\cube
seagrass\max_bed_shear_stresses_difference.mat')
    d3d_qp('presenttype','patches with lines')
    d3d_qp('climmode','automatic')
    d3d_qp('addtoplot')

    axis('equal',latlong)
    title(texlabel('Diff. in maximum bed shear stresses compared to base run
[N/m^2]'));

else display ('no maximum bed shear stresses')
end

% ----- Cumulative sedimentation of fine sediment -----

if (cum_sedimentation_fines == 1);
```

```
    d3d_qp('openfile','c:\Delft3D\sediment\cube seagrass\Singapore.ldb')
    d3d_qp('colour',[ 0.501961 0 0 ])
    d3d_qp('quickview')

    d3d_qp('openfile','c:\Delft3D\sediment\cube seagrass\trim-run1.dat')
    d3d_qp('selectfield','cum. erosion/sedimentation')
    d3d_qp('presenttype','patches with lines')
    d3d_qp('colour',[ 0 0 0 ])
    d3d_qp('climmode','manual')
    d3d_qp('climmin',minscale_fines)
    d3d_qp('climmax',maxscale_fines)
    d3d_qp('editt',100)
    d3d_qp('addtoplot')

    axis('equal',latlong)
    title('Cumulative sedimentation of fines [m]')

else display('no sedimentation of fines')
end

% ----- Discharge -----

if (discharge == 1);

    d3d_qp('openfile','c:\Delft3D\sediment\cube seagrass\trih-run1.dat')
    d3d_qp('selectfield','instantaneous discharge')
    d3d_qp('station',cross_section)
    d3d_qp('allt',0)
    d3d_qp('colour',[ 0 0 1 ])
    d3d_qp('editt',time_step)
    d3d_qp('quickview')
    title('Instantaneous discharge')

    d3d_qp('openfile','c:\Delft3D\sediment\cube seagrass\trih-run1.dat')
    d3d_qp('selectfield','cumulative discharge')
    d3d_qp('station',cross_section)
    d3d_qp('allt',0)
    d3d_qp('colour',[ 0 0 1 ])
    d3d_qp('editt',time_step)
    d3d_qp('quickview')
    title('Cumulative discharge')

else display('no discharge')
end

% ----- Water levels in observation points -----

if (water_levels == 1);

    d3d_qp('openfile','c:\Delft3D\sediment\cube seagrass\trih-run1.dat')
    d3d_qp('selectfield','water level')
    d3d_qp('station',observation_point)
    d3d_qp('allt',0)
    d3d_qp('colour',[ 0 0 1 ])
    d3d_qp('editt',time_step)
    d3d_qp('quickview')
    title('Water level')
    d3d_qp('exportdata','c:\Delft3D\sediment\cube seagrass\WL_nested.mat')

    d3d_qp('openfile','c:\Delft3D\Base run 7 21 dec\trih-baserun_restart.dat')
    d3d_qp('selectfield','water level')
    d3d_qp('station',observation_point)
    d3d_qp('allt',0)
    d3d_qp('colour',[ 1 0 0 ])
    d3d_qp('editt',time_step)
    d3d_qp('addtoplot')
    d3d_qp('exportdata','c:\Delft3D\sediment\cube seagrass\WL_SRM.mat')
```

```
    legend('design','baserun')
    title('Water levels')

else display('no water levels')
end

% ----- Magnitude velocity vector in observation point -----

if (magnitude_velocity_vector == 1);

    d3d_qp('openfile','c:\Delft3D\sediment\cube seagrass\trih-run1.dat')
    d3d_qp('selectfield','depth averaged velocity')
    d3d_qp('station',observation_point)
    d3d_qp('allt',0)
    d3d_qp('colour',[ 0 0 1 ])
    d3d_qp('component','magnitude')
    d3d_qp('editt',time_step)
    d3d_qp('quickview')
    title('Magnitude vector')
    d3d_qp('exportdata','c:\Delft3D\sediment\cube seagrass\dav_nested.mat')

    d3d_qp('openfile','c:\Delft3D\Base run 7 21 dec\trih-baserun_restart.dat')
    d3d_qp('selectfield','depth averaged velocity')
    d3d_qp('station',observation_point)
    d3d_qp('allt',0)
    d3d_qp('colour',[ 1 0 0 ])
    d3d_qp('component','magnitude')
    d3d_qp('editt',time_step)
    d3d_qp('addtoplot')
    d3d_qp('exportdata','c:\Delft3D\sediment\cube seagrass\dav_SRM.mat')

    legend('design','baserun')
    title('Magnitude velocity vector')

else display('no magnitude velocity vector')
end

% ----- Direction velocity vector in observation point -----

if (direction_velocity_vector == 1);

    d3d_qp('openfile','c:\Delft3D\sediment\cube seagrass\trih-run1.dat')
    d3d_qp('selectfield','depth averaged velocity')
    d3d_qp('station',observation_point)
    d3d_qp('allt',0)
    d3d_qp('colour',[ 0 0 1 ])
    d3d_qp('component','angle (degrees)')
    d3d_qp('editt',time_step)
    d3d_qp('quickview')
    title('Angle vector')
    d3d_qp('exportdata','c:\Delft3D\sediment\cube seagrass\direction_nested.mat')

    d3d_qp('openfile','c:\Delft3D\Base run 7 21 dec\trih-baserun_restart.dat')
    d3d_qp('selectfield','depth averaged velocity')
    d3d_qp('station',observation_point)
    d3d_qp('allt',0)
    d3d_qp('colour',[ 1 0 0 ])
    d3d_qp('component','angle (degrees)')
    d3d_qp('editt',time_step)
    d3d_qp('addtoplot')
    d3d_qp('exportdata','c:\Delft3D\sediment\cube seagrass\direction_SRM.mat')

    legend('design','baserun')
    title('Direction velocity vector')

else display('no direction velocity vector')
end
```

```
%-----Calculation errors-----

if (calculations_errors == 1);

    %-----Water level errors-----

    load WL_nested.mat
    WL_nested = data.Val;

    load WL_SRM.mat
    WL_SRM = data.Val;

    error_WL = WL_nested - WL_SRM;
    ME_WL = mean(abs(error_WL));
    squarederror_WL = error_WL.^2;
    MSE_WL = mean(squarederror_WL);
    RMSE_WL = sqrt(MSE_WL);
    MRE_WL = (mean(abs((WL_nested - WL_SRM)./WL_SRM))) * 100;

    ME_percentage_WL = (ME_WL / mean(abs(WL_SRM))) * 100;
    RMSE_percentage_WL = (RMSE_WL / mean(abs(WL_SRM))) * 100;

    %-----Magnitude velocity vector-----

    load dav_nested.mat
    dav_nested = data.Val;

    load dav_SRM.mat
    dav_SRM = data.Val;

    error_vel = dav_nested - dav_SRM;
    ME_vel = mean(abs(error_vel));
    squarederror_vel = error_vel.^2;
    MSE_vel = mean(squarederror_vel);
    RMSE_vel = sqrt(MSE_vel);
    MRE_vel = (mean(abs((dav_nested - dav_SRM)./dav_SRM))) * 100;

    ME_percentage_vel = (ME_vel / mean(dav_SRM)) * 100;
    RMSE_percentage_vel = (RMSE_vel / mean(dav_SRM)) * 100;

    %-----Direction velocity vector-----

    load direction_nested.mat
    direction_nested = data.Val;

    load direction_SRM.mat
    direction_SRM = data.Val;

    error_dir = direction_nested - direction_SRM;
    ME_dir = mean(abs(error_dir));
    squarederror_dir = error_dir.^2;
    MSE_dir = mean(squarederror_dir);
    RMSE_dir = sqrt(MSE_dir);
    MRE_dir = (mean(abs((direction_nested - direction_SRM)./direction_SRM))) * 100;

    ME_percentage_dir = (ME_dir / mean(abs(direction_SRM))) * 100;
    RMSE_percentage_dir = (RMSE_dir / mean(abs(direction_SRM))) * 100;

    %-----Writing results to Excel-----

    results = zeros(18,1);

    results(1,1)=ME_WL;
    results(2,1)=MSE_WL;
    results(3,1)=RMSE_WL;
    results(4,1)=MRE_WL;
    results(5,1)=ME_percentage_WL;
    results(6,1)=RMSE_percentage_WL;
```

```
    results(7,1)=ME_vel;
    results(8,1)=MSE_vel;
    results(9,1)=RMSE_vel;
    results(10,1)=MRE_vel;
    results(11,1)=ME_percentage_vel;
    results(12,1)=RMSE_percentage_vel;

    results(13,1)=ME_dir;
    results(14,1)=MSE_dir;
    results(15,1)=RMSE_dir;
    results(16,1)=MRE_dir;
    results(17,1)=ME_percentage_dir;
    results(18,1)=RMSE_percentage_dir;

    disp(results)

    xlswrite('c:\Delft3D\sediment\cube seagrass\finalgrid.xls', results,
'Comparison', 'C2');

else display('no calculations errors')
end
```

APPENDIX K DELFT3D RESULTS

This appendix contains both the figures of the Delft3D results (section K.1) and the tables that were made based on the Delft3D results (section K.2).

K.1 FIGURES DELFT3D RESULTS

The following 11 paragraphs display figures of Delft3D results of each of the 11 designs.
The figures display following features:

- Depth average velocity and its direction
- Maximum velocities from all time steps
- Difference in maximum velocities compared to base run
- Maximum bed shear stresses from all time steps
- Cumulative sedimentation of fines
- Cumulative discharge at tips in between the arms (figures K.1.1, K.1.2 only)

K.1.1 CLOSED ARMS PROTECTED MANGROVES (DESIGN 1)

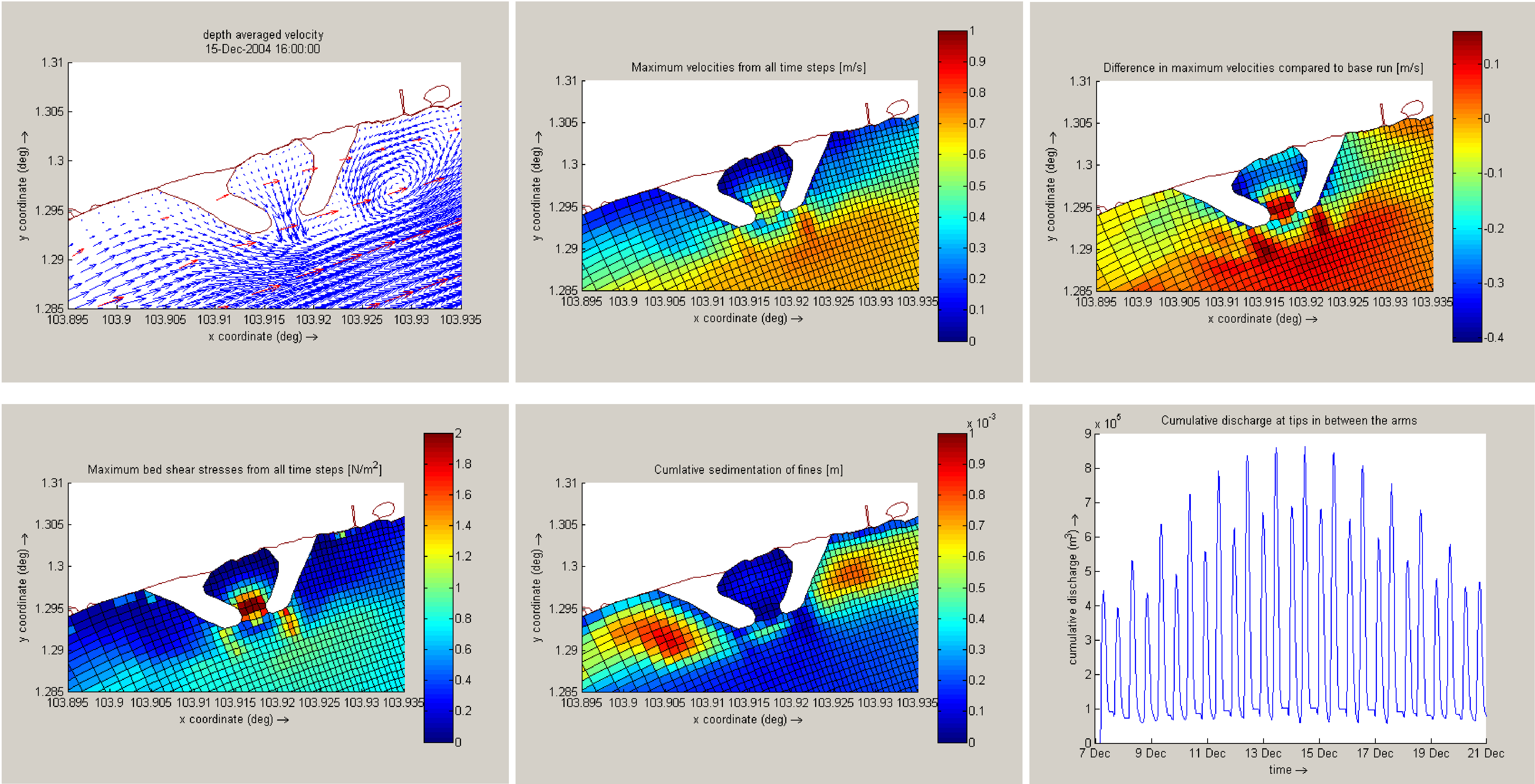


Figure 0.67 | Delft3D Results Closed Arms Protected Mangroves (Design 1)

K.1.2 OPEN ARMS PROTECTED SEAGRASS (DESIGN 2)

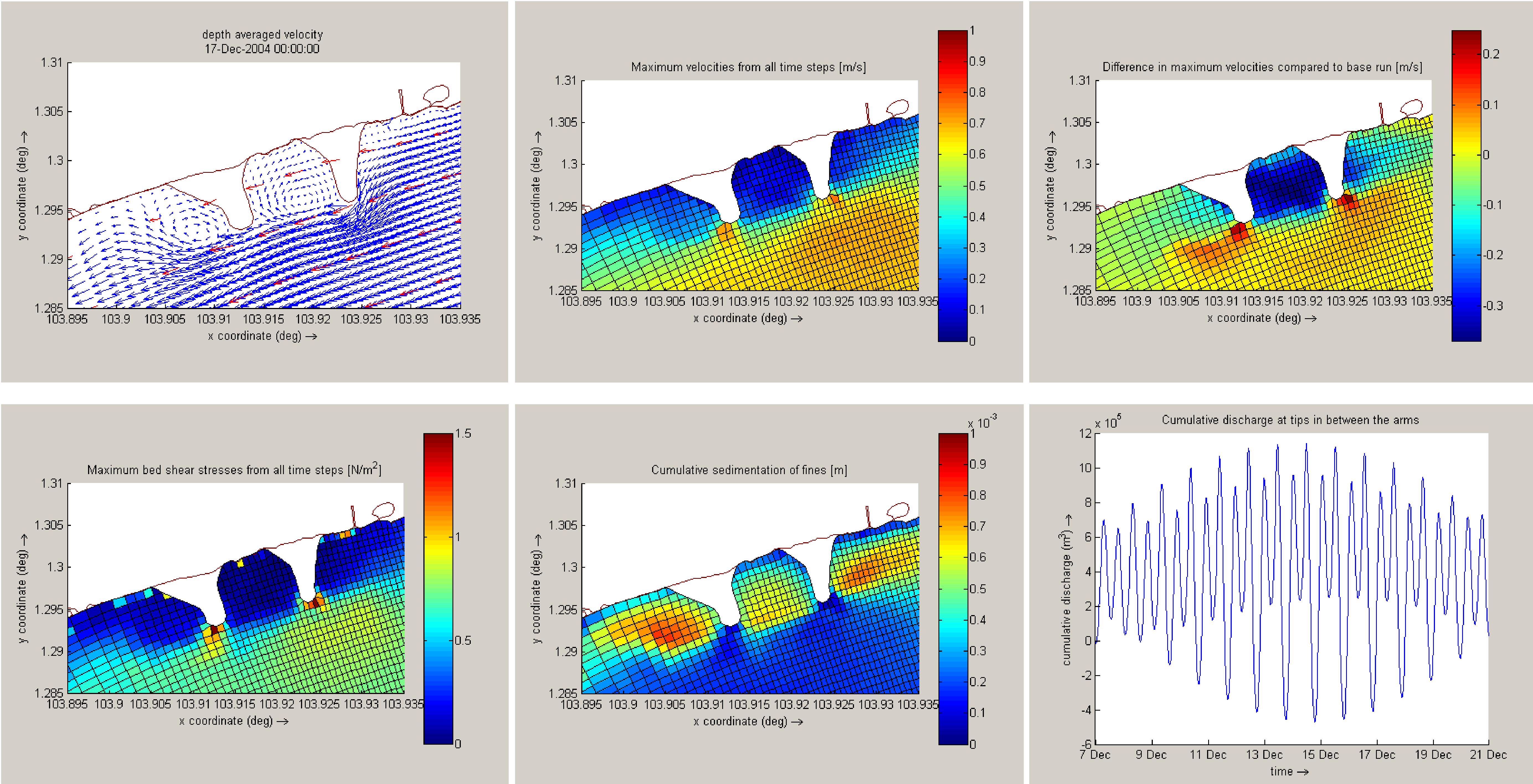


Figure 0.68 | Delft3D Results Open Arms Protected Seagrass (Design 2)

K.1.3 CUBE UNPROTECTED MANGROVES (DESIGN 3)

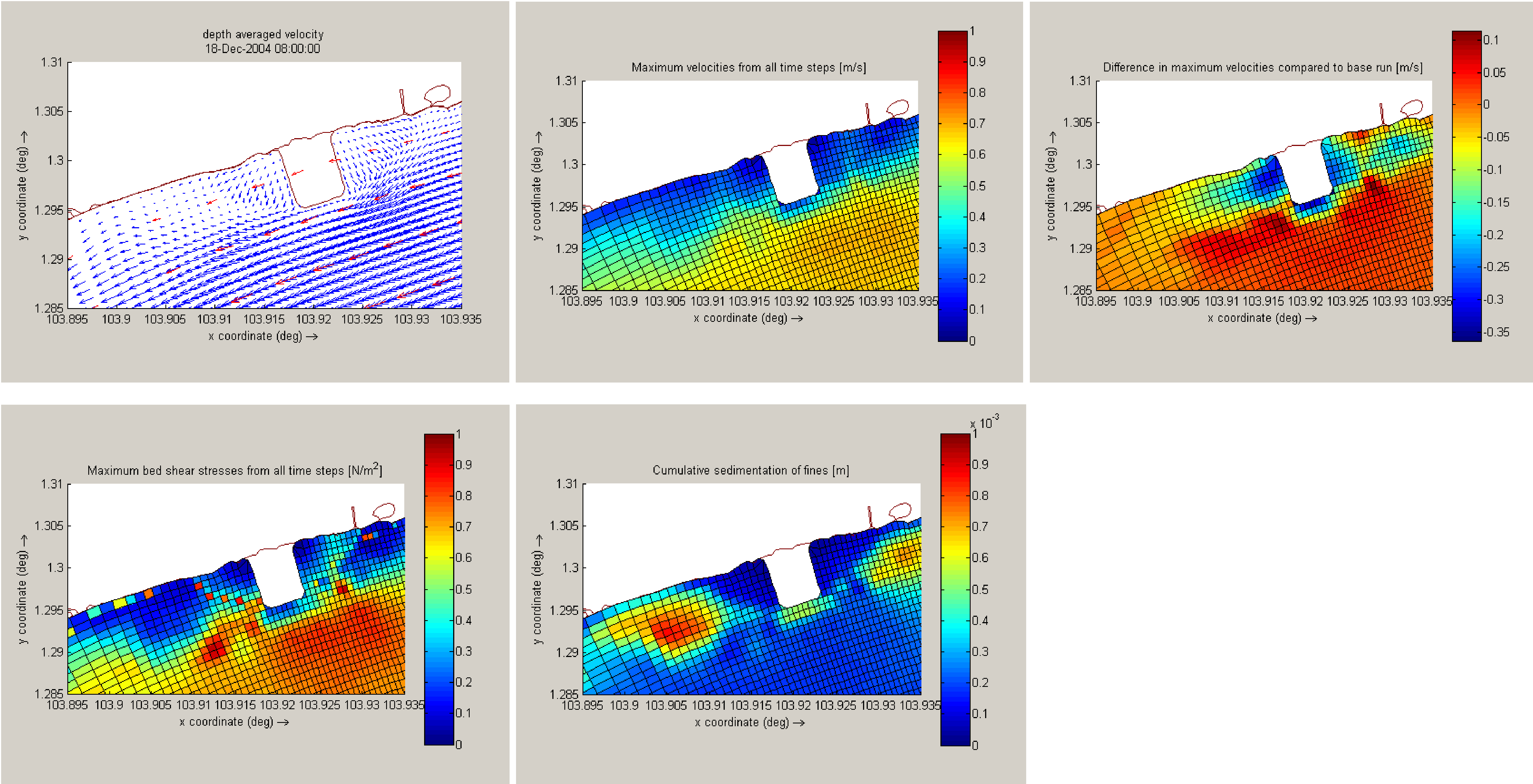


Figure 0.69 | Delft3D Results Cube Unprotected Mangroves (Design 3)

K.1.4 CUBE UNPROTECTED SEAGRASS (DESIGN 4)

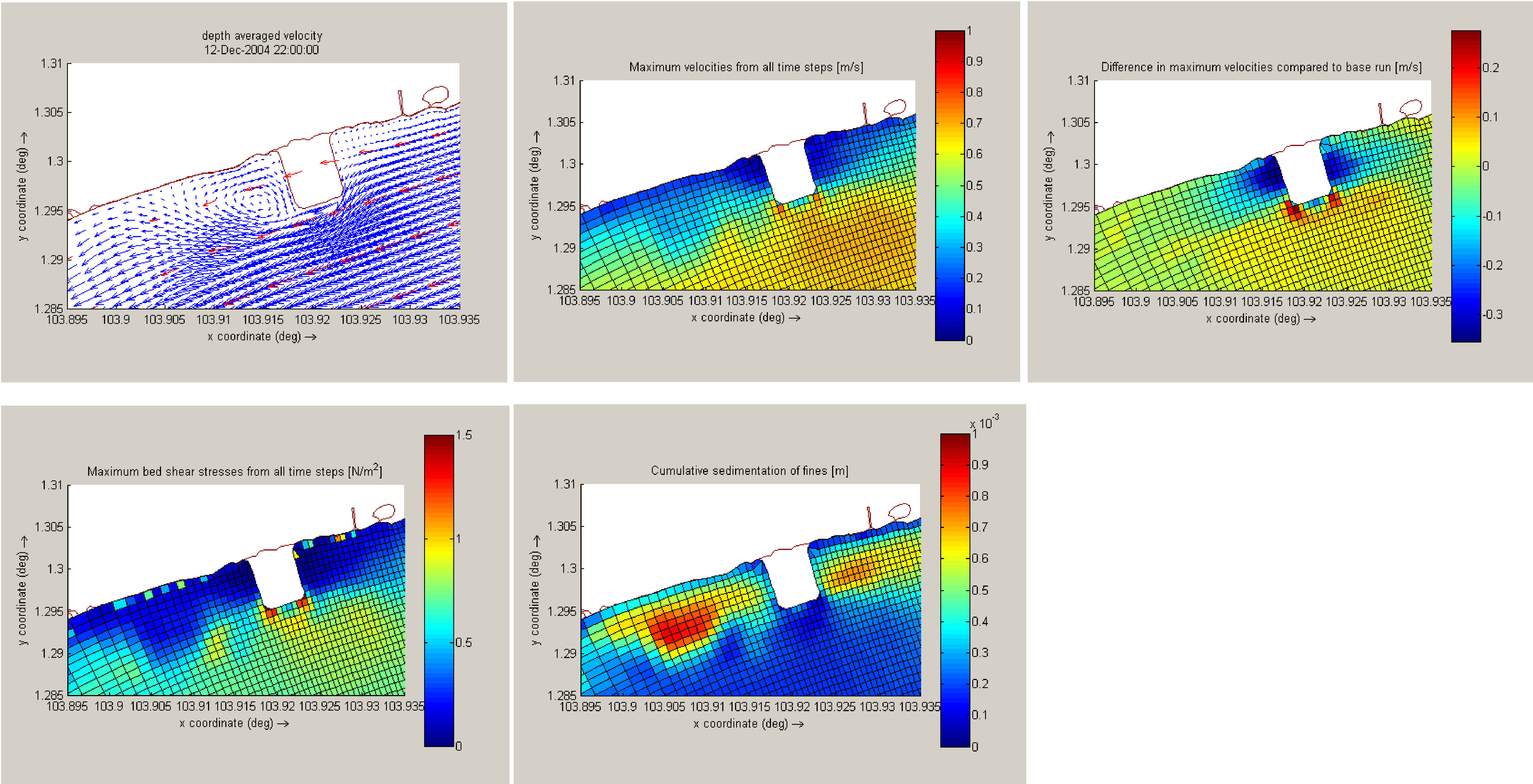


Figure 0.70 | Delft3D Results Cube Unprotected Seagrass (Design 4)

K.1.5 BANANA PROTECTED MANGROVES (DESIGN 5)

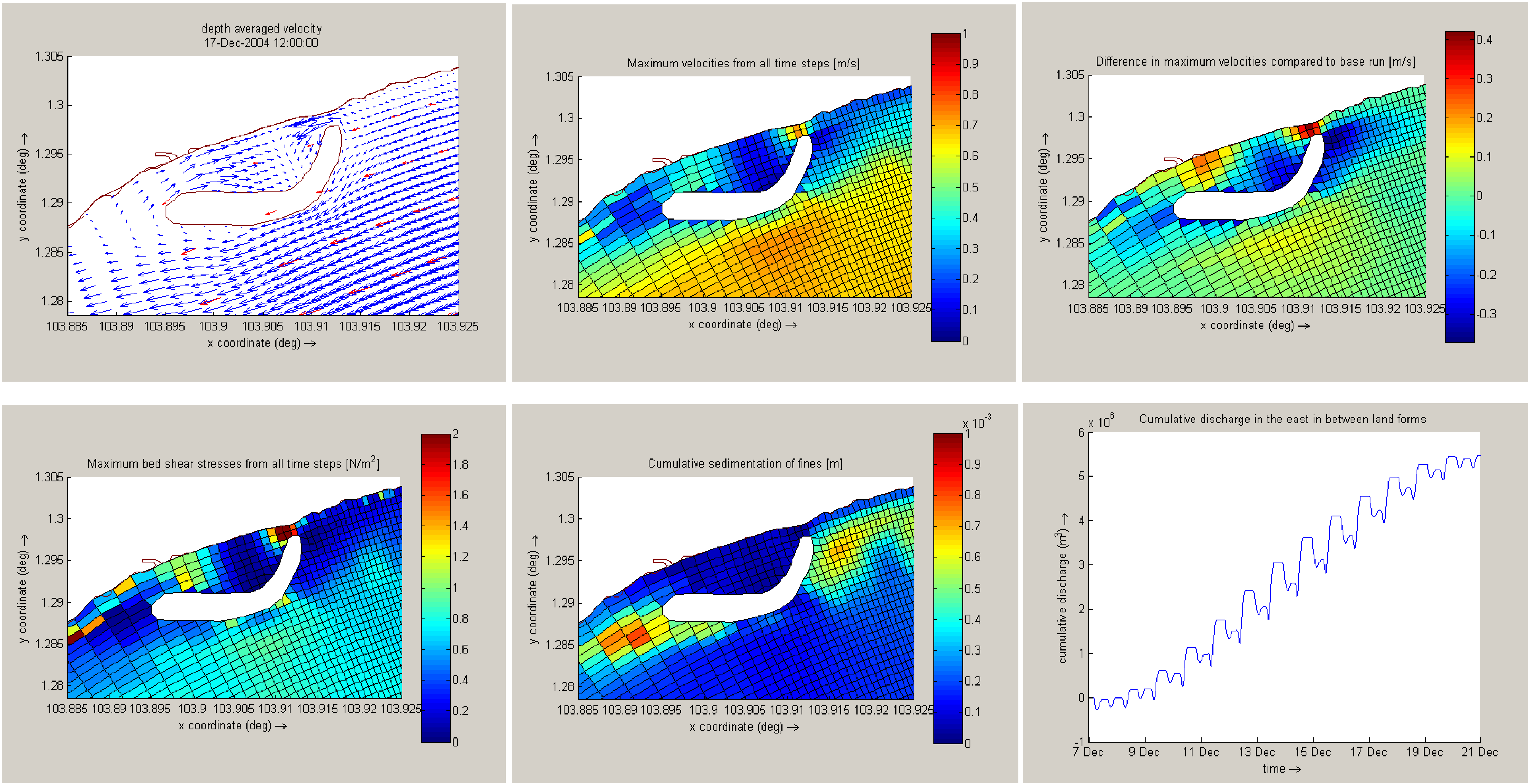


Figure 0.71 | Delft3D Results Banana Protected Mangroves (Design 5)

K.1.6 BANANA PROTECTED SEAGRASS (DESIGN 6)

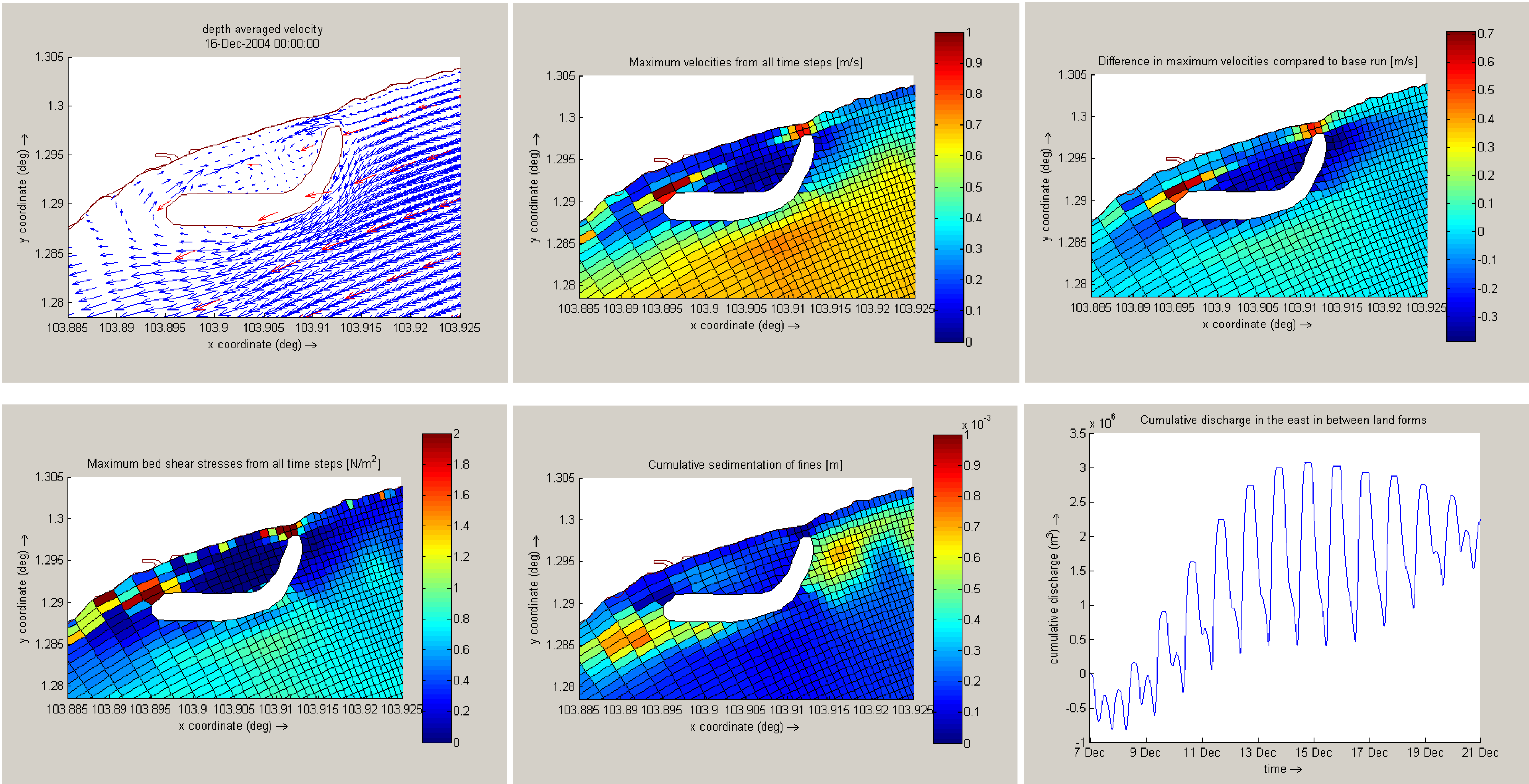


Figure 0.72 | Delft3D Results Banana Protected Seagrass (Design 6)

K.1.7 ATTACHED BANANA PROTECTED SEAGRASS (DESIGN 7)

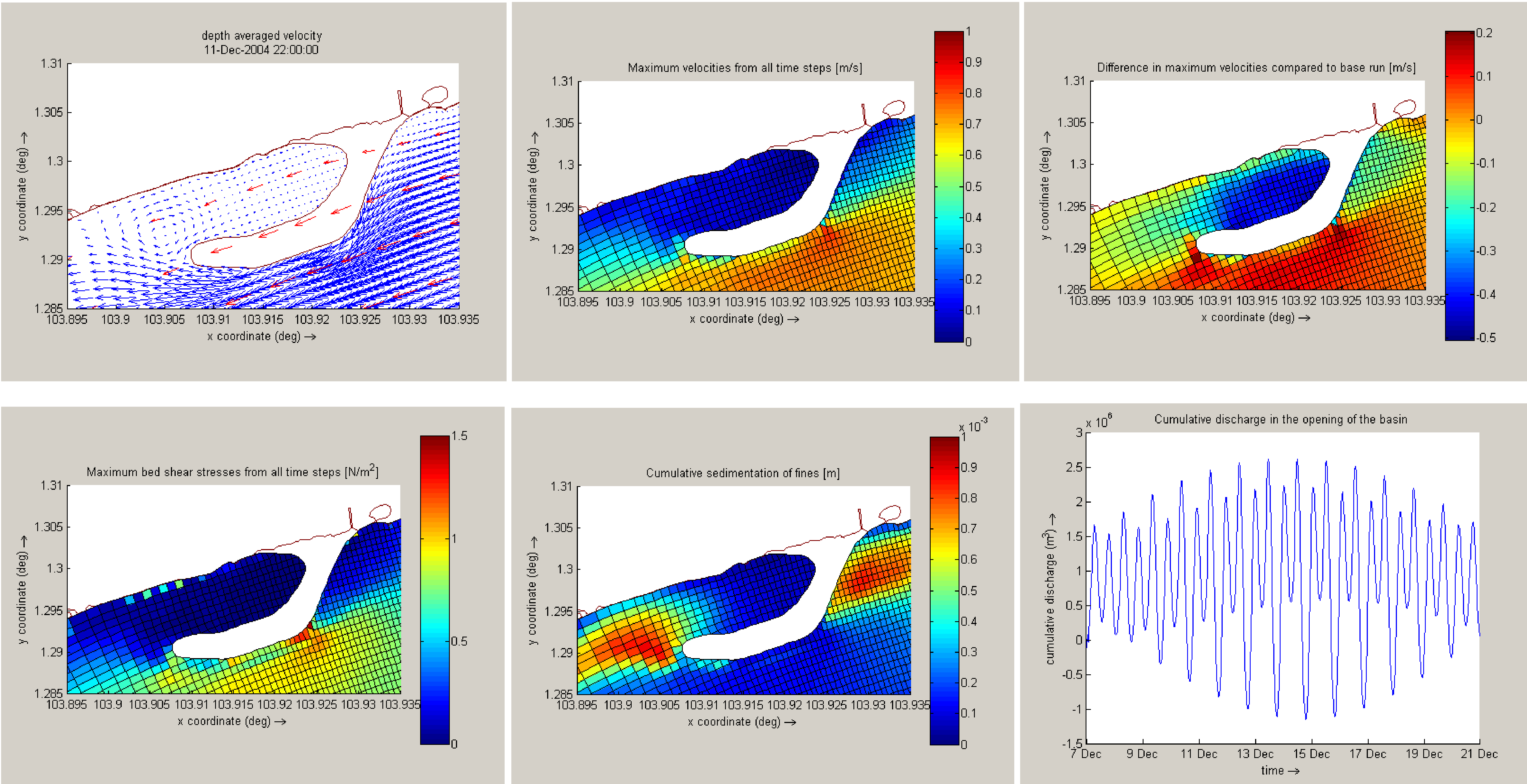


Figure 0.73 | Delft3D Results Attached Banana Protected Seagrass (Design 7)

K.1.8 CIGAR PROTECTED MANGROVES (DESIGN 8)

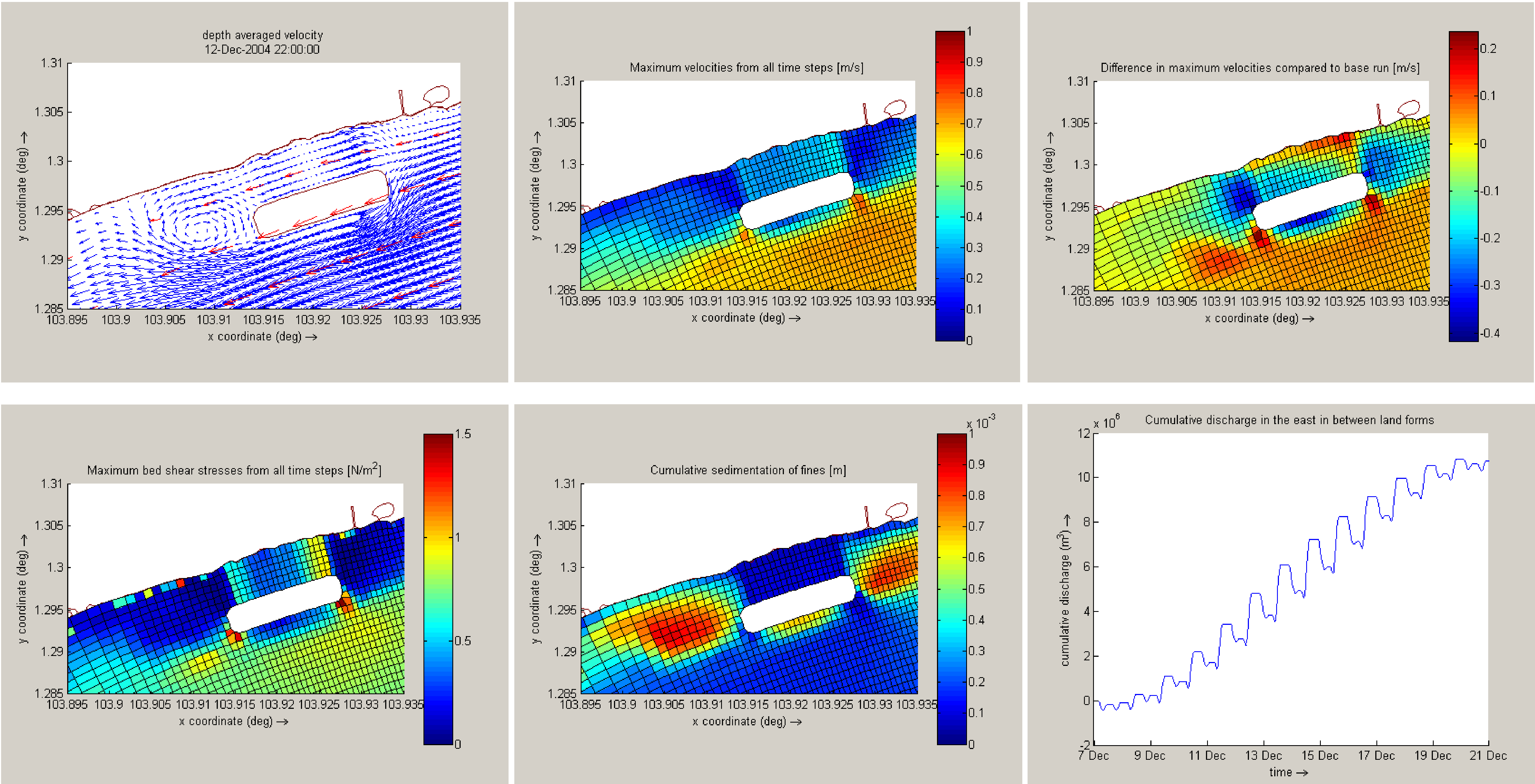


Figure 0.74 | Delft3D Results Cigar Protected Mangroves (Design 8)

K.1.9 CIGAR PROTECTED SEAGRASS (DESIGN 9)

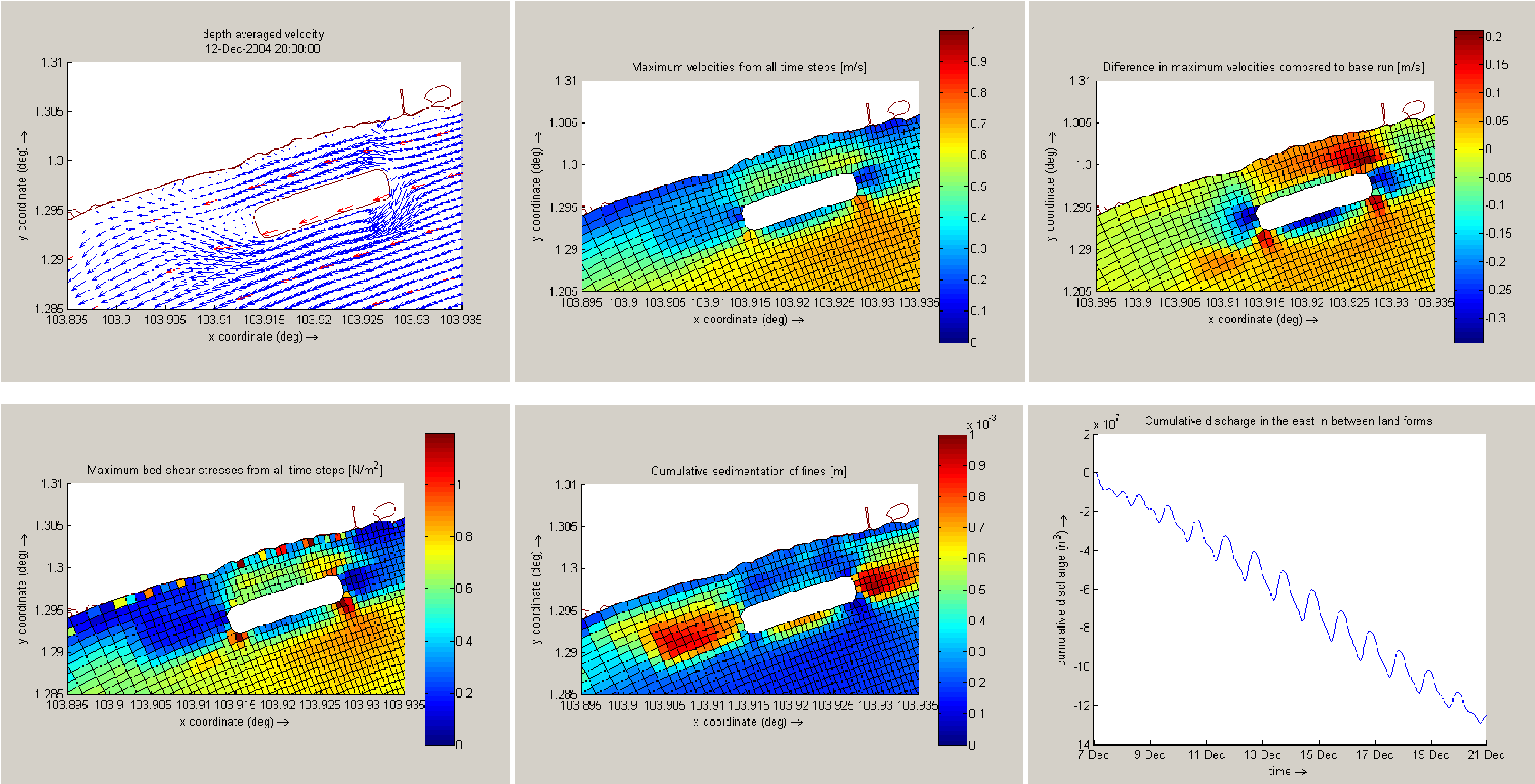


Figure 0.75 | Delft3D Results Cigar Protected Seagrasss (Design 9)

K.1.10 ATTACHED CIGAR PROTECTED SEAGRASS (DESIGN 10)

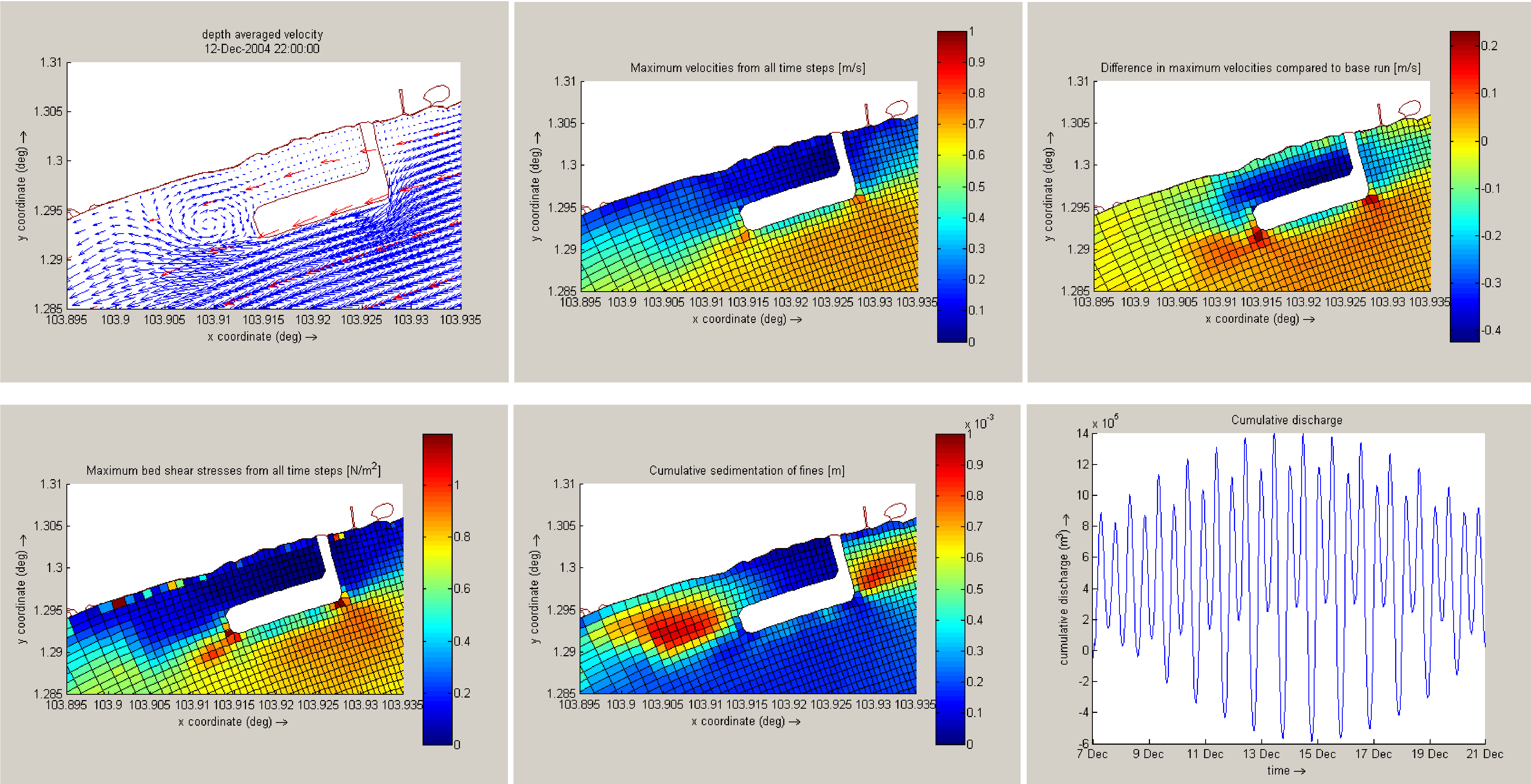


Figure 0.76 | Delft3D Results Attached Cigar Protected Seagrass (Design 10)

K.1.11 LAGOON UNPROTECTED CORAL (DESIGN 11)

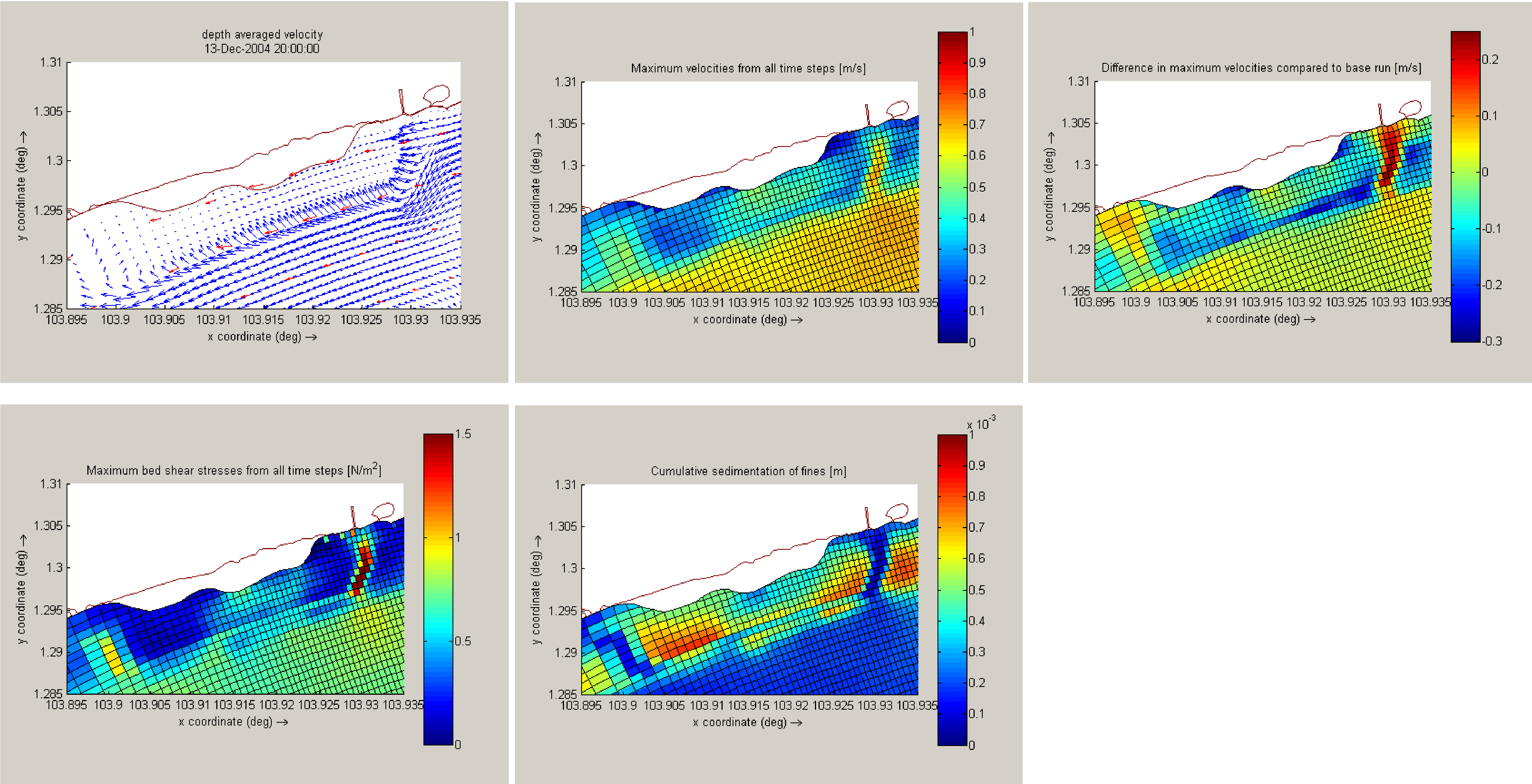


Figure 0.77 | Delft3D Results Lagoon Unprotected Coral (Design 11)

K.2 TABLES DELFT3D RESULTS

The results of the Delft3D runs are summarized in 4 tables (Table 31, Table 32, Table 33 and Table 34).

Table 31 | Part 1 of the Delft3D results of the designs

	Closed arms protected mangroves (design 1)	Open arms protected seagrass (design 2)	Cube unprotected mangroves (design 3)	Cube unprotected seagrass (design 4)	Banana protected mangroves (design 5)	Banana protected seagrass (design 6)
Vector field depth average velocity	Eddies with the length scale of the extension develop on the east and west side of the extension	Eddies with the length scale of the extension develop on the east and west side of the extension and eddies develop in the middle between the extensions	Eddies of the length scale of the extension develop on the east and west side of the mudflat	Eddies in the order of a length scale larger than the length of the land extension develop on the east and west side of the extension	An eddy develops east of the island. However there are no eddies on the west side	Two eddies form behind the island
		High flow velocities develop at the tips of the land extensions	There are increased flow velocities at the two corners of the land extension at high tide	High flow velocities at the corners of the land extension develop, because of the deeper waters	High flow velocities develop between the coast and island at the right and left corners of the island	High flow velocities develop between the coast and island at the right and left corner of the island
					At high tide the mudflat fills up from two sides, which creates a watershed	An eddy develops at the east of the island
Maximum velocities within entire time domain	In front of the structure (offshore) the maximum flow velocities increase with 0.1 m/s compared to the baserun to 0.7 m/s.	The maximum flow velocities of about 0.7 m/s develop around the tips of the extension. This is 0.18 m/s higher than in the base run.	Because of the mudflats on the west and east side of the extension the design is streamlined. The flow goes gentle around the extension	The maximum flow velocities at the corners of the land extension are 0.75 m/s. This is 0.23 m/s higher than in the base run	The maximum flow velocities of about 0.75 m/s develop around the east corner of the island. This is an increase of 0.4 m/s compared to the base run. The maximum flow velocity is about 0.4 m/s at the west corner. This is an increase of 0.2 m/s compared to the base run.	The maximum flow velocities of about 1 m/s develop around the east corner of the island. This is an increase of 0.55 m/s compared to the base run. The maximum flow velocity is about 0.7 m/s at the west corner. This is an increase of 0.35 m/s compared to the base run.
	Along the structure the maximum flow velocities decrease significantly	Along the structure a decrease in maximum flow velocities is visible. To the west and east of the structure the maximum flow velocities decrease slightly	On the mud flats the maximum flow velocities have decreased in comparison to the base run	On the west and east side of the extension the maximum flow velocities are decreased to the requirements for seagrass (<0.25 m/s)	Around the other parts of the island the maximum flow velocities decrease	Around the other parts of the island a decrease in maximum flow velocities is visible
	To the west and east of the structure the maximum flow velocities decrease slightly and a sheltered basin is created	A sheltered basin is created and also on the west and east side of the extension the maximum flow velocities are decreased to the requirements for seagrass (<0.25 m/s)	The area for mangroves is sheltered by the extension and the height of the mud flat		A sheltered area is created for mangroves	A sheltered area is created for seagrass
	The maximum flow velocities are highest in the opening between the arms (0.62 m/s) This is an increase of 0.2 m/s compared to the base run.	In between the extensions the maximum flow velocities decrease with 0.35 m/s compared to the base run to 0.2 m/s.				

Table 32 | Part 2 of the Delft3D results of the designs

	Closed arms protected mangroves (design 1)	Open arms protected seagrass (design 2)	Cube unprotected mangroves (design 3)	Cube unprotected seagrass (design 4)	Banana protected mangroves (design 5)	Banana protected seagrass (design 6)
Maximum bed shear stresses from entire time domain	The maximum bed shear stresses in the opening are 2.5 N/m^2. This is very high	Because of the high flow velocities near the extensions tips, relatively high bed shear stresses up to 2 N/m^2 are found	Shear stresses are higher on the edges of the mudflats 0.6-0.8 N/m^2	Because of the high flow velocities near the corner of the extension, relatively high bed shear stresses up to 1.6 N/m^2 are found	Large bed shear stresses arise in both openings	Because of the high flow velocities near corners of the island, high bed shear stresses develop of respectively 3 N/m^2 and 0.5 N/m^2
	The bed shear stresses follow the changes of the velocities				In the rest of the domain the bed shear stresses decrease or stay the same	In the rest of the domain the bed shear stresses decrease or stay the same
	The maximum bed shear stresses in the middle of the basin are 0.3 N/m^2. This corresponds to a minimal seedling rootlenght of 3 cm according to (Thorsten Balke, 2011)		The maximum bed shear stresses in the middle of the basin are 0.2 N/m^2. This corresponds to a minimal seedling rootlenght of 2 cm according to (Thorsten Balke, 2011)		The maximum bed shear stresses in the middle of the basin are 0.3 N/m^2. This corresponds to a minimal seedling rootlenght of 3 cm according to (Thorsten Balke, 2011)	
Cumulative sedimentation of fines	To the east and the west of the design, where the eddies develop, a cumulative sediment accretion of fines is found. Within this fortnightly run this accretion is 0.85 mm / 2 weeks	To the east and the west of the design, where the eddies develop a cumulative sediment accretion of about 0.7 mm / 2 weeks is found	In front of the land extension there is a cumulative sediment accretion of 0.55 mm / 2 weeks	To the east and the west of the design, where the eddies develop a cumulative sediment accretion of fines is found. Within this fortnightly run this accumulation is about 0.7 mm / 2 weeks	To the east and the west of the design the cumulative sediment accretion is about 0.65 mm / 2 weeks	To the east and the west of the design the cumulative sediment accretion is about 0.65 mm / 2 weeks
	Inside the basin the accretion of fines is. 0.13 mm / 2 weeks in the fortnightly run	Inside the basin the accretion of fines is. 0.6 mm / 2 weeks	To the east and the west of the design, where the eddies develop an accumulation of fines of about 0.8 mm / 2 weeks is found		At the mudflat the accretion is about 0.05-0.1 mm / 2 weeks	In the sheltered area the sedimentation is about 0.2 mm / 2 weeks
Discharges and stagnant water	There is a complete filling and emptying of the basin in each tidal cycle. This is explained by the fact that the whole mudflat is modeled at mean sea level	No stagnant water, because the discharge is large enough	No stagnant water (see column 1)	No stagnant water possible	There is enough flow from both sides to prevent stagnant water	There is enough flow from both sides to prevent stagnant water
Conclusions of the design	The opening is too small for the tidal prism of the basin, induces high bed shear stresses and will erode	The tips of the extension are located perpendicular in the flow, which creates large current velocities and bed shear stresses around the tips	The mudflats streamline the design Small eddies and current velocities develop	Smoothing the depth around tips and corners reduces the amount of eddy formation and high current velocities	The right side of the island is located to close to the shore, creating high flow velocities and bed shear stresses	The right side of the island is located to close to the shore

Table 33 | Part 3 of the Delft3D results of the designs

	Attached Banana protected seagrass (design 7)	Cigar protected mangroves (design 8)	Cigar protected seagrass (design 9)	Attached Cigar protected seagrass (design 10)	Lagoon unprotected coral (design 11)
Vector field depth average velocity	A large eddy in the order of length of the design is created on the east side of the island and an eddy develops in the opening of the basin	Two eddies in the order of the lengthscale of the island are created on the east and west side of the island	The flow velocities behind the island increase	Two eddies in the order of the lengthscale of the island are created on the east and west side of the island	There is no development of eddies
	There are very low maximum flow velocities behind the island in the basin	Filling and emptying of the mudflat	There is hardly any development of eddies to the east and the west	There is little flow behind the island	On top of the submerged barrier, the flow velocities increase, because of the decreased cross-section
	The design is streamlined, there is a little increase in flow velocities around the corners of the island		There is a slight increase of the flow velocities near the corners of the island	Acceleration of the flow at the western and eastern corner of the island and a decrease of flow velocities at the eastern side of the island	The barrier provides some sheltering from currents
Maximum velocities within entire time domain	There is an increase of the maximum flow velocities (0.1 m/s) on the southern side and corners of the island, but the increases are relatively small, because of the streamlined design.	Increase of the maximum flow velocities in front of the island at the corners of about 0.75 m/s	The maximum flow velocities behind the island are increased by 0.1 m/s compared to the base run to 0.5 m/s	Maximum flow velocities of about 0.75 m/s develop around the east and west corner of the island.	The maximum flow velocities develop on the eastern barrier and are about 0.75 m/s, which is an increase of 0.2 m/s compared to the base run
	The maximum flow velocities at the corners are about 0.7 m/s	Relativily high maximum flow velocities occur behind the island on the mudflat of about 0.35 m/s	There is sheltering at both sides of the island, but it is very little. The island does not create any sheltering behind it	There are very low maximum flow velocities behind the island of about 0.1 m/s, therefore a big decrease of flow velocities behind the island of about 0.35 m/s compared to the base run	Some sheltering is created at the south side of the land extension, but it is a very small increase of about 0.1 m/s compared to the base run. The flow velocities
	A sheltered area is created for seagrass	Sheltered areas behind the island next to the mudflat are created and there is a slight decrease of velocities on the mudflat. An increase of velocities on the eastern side of the mudflat	In front of the island around the corners the flow velocities increase to 0.7 m/s	A sheltered area is created for seagrass	The required 0.25 m/s for seagrass is not met in the sheltered zone

Table 34 | Part 4 of the Delft3D results of the designs

	Attached Banana protected seagrass (design 7)	Cigar protected mangroves (design 8)	Cigar protected seagrass (design 9)	Attached Cigar protected seagrass (design 10)	Lagoon unprotected coral (design 11)
Maximum bed shear stresses from entire time domain	Bed shear stresses are relatively small	High bed shear stresses in front of the island at the corners of about 1 N/m^2	Relatively high bed shear stresses behind the island of 0.75 N/m^2 and even higher bed shear stresses in front of the island at its corners of more than 1 N/m^2	There are almost no bed shear stresses (0.1 N/m^2) behind the island and directly to the east and the west of the island in the sheltered areas near the coast	Increased be shear stresses on the eastern and western barrier
	There is a possibility of erosion at the eastern corner of the island	High bed shear stress on the eastern side of the mudflat of 0.6 N/m^2. Therefore possible creation of erosion spots		Increase of bed shear stresses at the eastern and western corners. The bed shear stresses are more than 1 N/m^2	On the eastern barrier the shear stresses are about 1.6 N/m^2, which is very high
		The maximum bed shear stresses in the middle of the basin are 0.4 N/m^2. This corresponds to a minimal seedling rootlenght of 4 cm according to (Thorsten Balke, 2011)			
Cumulative sedimentation of fines	To the east and the west of the design the cumulative sediment accretion is about 0.9 mm / 2 weeks	To the east and the west of the design, adjacent to the muflat there is a cumulative sediment accretion of 0.9 mm / 2 weeks	There is accretion at both sides of the island of 0.9 mm / 2 weeks, because of the decrease in flow velocities	To the east and the west of the design the cumulative sediment accretion is about 0.9 mm / 2 weeks	There is an cumulative sediment accretion behind the barrier in the basin of about 0.85 mm / 2 weeks
	The sedimentation behind the island decreases from the west to the east from 0.5 mm / 2 weeks to 0.05 mm / 2 weeks	Directly in front of the island there is a cumulative accretion of about 0.6 mm. At the mudflat the accretion is about 0.05-0.1 mm / 2 weeks	There is accretion directly in front of the island of about 0.7 mm / 2 weeks	The sedimentation behind the island decreases from the west to the east from 0.35 mm / 2 weeks to 0.1 mm / 2 weeks	
Discharges and stagnant water	There is a possibility of stagnant water, because of the very low flow velocities inside the basin	There is enough flow from both sides to prevent stagnant water	There is enough flow from both sides to prevent stagnant water	There is a possibility of stagnant water, because of the very low flow velocities inside the basin	No stagnant water
Conclusions of the design	The increases of the flow velocities are relatively small, because of the streamlined design	The island creates little sheltering at the east and west side of the island The corners are not streamlined, which increases the flow velocities	This design creates no sheltering and increases the flow velocities behind the island	A sheltered basin is created	The barrier is not high enough to provide sheltering. The basin catches sediment

APPENDIX L MULTI-CRITERIA ANALYSIS

This section discusses how the MCA was performed. Section L.1.1 describes the structure of the MCA. Section L.1.2 explains the chosen weights. Section L.1.3 contains the resulting MCA tables and a brief table with the scores of each design grouped by principle.

L.1.1 STRUCTURE OF THE MCA

This section gives an overview of the principles, criteria groups, criteria, indicators and weights used in the MCA.

The principles used during the design were (see paragraph 3.3):

1. Enlarge the area suitable for recreation (main purpose)
2. Improve biodiversity and ecology (main purpose)
3. Prevent and reduce erosion
4. Use nature for engineering purposes
5. Make an constructible and economic design

These principles were translated in 5 groups of criteria:

1. Utility
2. Ecology
3. Coastal protection
4. “Building with nature”
5. Costs and constructability

The groups are given in Table 35. This table also gives the relative contribution of the criteria groups to the total weight. The weights add up to 100 in total.

Table 35 | The criteria groups and corresponding contribution to the final weight

Criteria group	Weight
Utility	25
Ecology	25
Coastal protection	20
Building with Nature	15
Costs	15
Sum	**100**

Utility and ecology receive the highest weights because they are highly related to the main goal of the project which is the creation of additional land for recreation with the inclusion and use of ecology.

Subsequently the criteria groups are divided into criteria. These criteria are specified and quantified using one or multiple indicators. The weights of the criteria groups were subdivided among the indicators (see Table 36). The sum of the weights of the indicators within 1 principle corresponds to the allocated weight in Table 35.

Table 36 describes the criteria groups, criteria, indicators and allocated weights. The relative contribution of the indicators to the weight of the principle is based on the importance of the criterion and indicator. This subdivision is further explained in the following paragraph (paragraph L.1.2).

Table 36 | Overview of the criteria groups, criteria's, indicators and weights used in the MCA

Criteria group	Criterion	Indicator	Weight factors	Absolute weight
Utility	Area suited for recreation	Total area created [m2]	6	25
		Extra length of the beaches [m]	3	
		Extra length of the coastline [m]	2	
		Area of mangroves [-]	-2	
		Area of seagrass [-]	2	
		Area of corals [-]	2	
	External safety	Minimum distance from the mooring line [m]	3	
	Swimmer safety	Current velocities next to beaches [m/s]	-3	
	Stagnant water	[m/s]	2	
Ecology	Area suitable for ecology	Area of mangroves [m2]	8	25
		Area of seagrass [m2]	8	
		Area of corals [m2]	8	
Coastal protection	Prevention of erosion	Length of the sheltered current coastline [m]	5	20
		Turbulence visible in Delft3D [-]	-5	
		Impression of the bed shearstresses [-]	-5	
		Length of the beaches [-]	-5	
Building with Nature	Effectiveness of ecology	Ecology serves (protects) the land [-]	7.5	15
	Effectiveness forces of nature	Use of forces of nature	7.5	
Costs	Materials and construction	Cost of establishing the ecology [-]	-1	15
		Required amount of landfill material [-]	-4	
		Length of hard revetment [m]	-3	
		Length of soft revetment [m]	-3	
		Length of ecology revetment [m]	-1	
	Constructability	Complexity of construction method [-]	-2	
	Flexibility in terms of future plans	Average distance from the mooring line [m]	1	

L.1.2 EXPLANATION CHOSEN INDICATORS AND WEIGHTS

This paragraph describes the reasons for the incorporation of the criteria and the reasons for the weights per criteria.

Area suited for recreation

Enlargement of the recreational area of ECP is the main purpose of the project. Beaches are quite important for the character of ECP. The total created area [m^2] is the main indicator for this criterion and receives the highest weight.

The creation of beaches at the additional land maintains the character. The extra length of the coastline also contributes to the character of ECP, but less than the beaches. This distinction is translated into a higher weight for extra beaches.

The weight of the area of mangroves concerning utility is negative because mangroves are associated with swamps and they block the view (refer Table 12). Seagrasses do serve recreational purposes as people tend to walk over the seagrass at low tide (if possible). Corals also attract a lot of people due to the fishes and animals associated with coral and the impressive, colorful appearance of the coral structures.

External safety

The minimum distance to the mooring line indicates how safe a design is with regards to the interaction with vessels. Vessels can collide with the shore or leak oil causing a threat to humans.

Swimmer safety

Although there are not many swimmers at ECP, the swimmer safety is considered to be of importance. A beach with dangerous eddies or high current velocities will certainly cause accidents.

Stagnant water

The weight for stagnant water is negative because it is not favorable. The stagnant water is not directly measured but estimated by looking at the ratio between the discharge that enters through an opening and the area of the top view behind that opening.

Area suitable for ecology

The area suitable for ecology is considered to be of great importance as it is one of the main purposes of the project to create wet sheltered areas which are suitable for ecology. That is why the area suitable for ecology contributes 25% to the final score. As the area of mangroves, seagrass and coral are related to each other, the scaled scores are computed by dividing the area of mangroves, seagrass or coral by the sum of the total area of mangroves, seagrasses and corals, where after they are multiplied by 3.

Prevention of erosion

The prevention of erosion is quite evident at ECP as the coastline retreat at some locations is in the order of 1 m/y. The prevention of this erosion is therefore of high importance in the design of additional land. The indicators for the prevention of erosion have an equal weight as they were considered to be of equal importance. The reduction of the hydrodynamic conditions has a positive weight. The sheltered area will induce a gradient in the longshore sediment transport and lead to sedimentation. Although the gradients in the longshore transport cause changes in the morphology, the availability of coarse-grained sediment is also important (as discussed in the analysis). The turbulence which is created by the new islands will transport these sediments. The higher the local bed shear stresses, the more transport will take place. The coarse-grained beaches are also subjected to this availability. That is why the turbulence, bed shear stresses and the length of the beaches have a negative score.

Effectiveness of ecology

The emphasis of the project is on the use of nature according to the "Building with Nature" philosophy. There are many ways in which nature can be used. A coral reef can for example be used to create sheltered sedimentary environments whereby it protects the additional land. The effectiveness of ecology gets the same weight as the next criterion.

Effectiveness of the forces of nature (waves, currents, outfall, etc.)

The effectiveness of the forces of nature is incorporated in the MCA as it is part of the "Building with Nature" philosophy. Waves, currents, outfalls and the tide can be used in the designs. The weight is equal to the weight of the effectiveness of ecology.

Materials and construction

The costs are incorporated as criterion in order to include the balance between values and costs. A design that gives higher costs might also give more value. Because the project is more focused on creating value than on reducing costs, the weight of these criteria is lower than the weight of the values. The values are incorporated in the criteria groups utility, ecology and coastal protection. The costs are indicated by the costs of establishing ecology, the required amount of landfill, the required length of revetment needed and the type of revetment.

The costs of establishing ecology are the costs that are needed for e.g. the seeds of the mangroves. The weights are divided based on the height of the costs made per indicator. The amount of landfill material is one of the most important indicators for the costs. The hard and soft revetments are the most expensive revetments followed by the ecological revetments.

Constructability

The constructability differs per design. Extensions of the current coastline can be done using land based equipment. This will influence the time and costs required.

Flexibility in terms of future plans

The average distance to the mooring line indicates how much space there is still left for the development of future plans. Considering the design period of 50 years, this is not considered to be of great importance as Singapore is reclaiming less and less land. It could however be of importance when considering the constant development of Singapore. The weight is positive because the design requires less space when it is further from the mooring line.

L.1.3 TABLES MCA RESULTS

This paragraph contains the MCA table (Table 37 and Table 38) and a brief version of the MCA (Table 39).

Table 37 | Part 1 of the MCA table

Criteria group	Criterion	Indicator	Weight factors	Absolute or scaled	Closed arms protected mangroves (design 1)	Open arms protected seagrass (design 2)	Cube unprotected mangroves (design 3)	Cube unprotected seagrass (design 4)	Banana protected mangroves (design 5)	Banana protected seagrass (design 6)	Attached Banana protected seagrass (design 7)	Cigar protected mangroves (design 8)	Cigar protected seagrass (design 9)	Attached Cigar protected seagrass (design 10)	Lagoon unprotected coral (design 11)
Utility	Area suited for recreation	Total area created [m2]	6	Absolute	*736000*	*686000*	*830000*	*830000*	*510000*	*510000*	*650000*	*850000*	*850000*	*890000*	*740000*
				Scaled	0.09	0.08	0.10	0.10	0.06	0.06	0.08	0.11	0.11	0.11	0.09
		Extra length of the beaches [m]	3	Absolute	*-1100*	*-900*	*-2400*	*-2400*	*-1600*	*0*	*120*	*-2550*	*-2550*	*-2500*	*170*
				Scaled	-0.07	-0.06	-0.15	-0.15	-0.10	0.00	0.01	-0.16	-0.16	-0.15	0.01
		Extra length of the coastline [m]	2	Absolute	*2800*	*2250*	*-350*	*-350*	*5300*	*5300*	*5100*	*5600*	*5600*	*3900*	*170*
				Scaled	0.08	0.06	-0.01	-0.01	0.14	0.14	0.14	0.15	0.15	0.11	0.00
		Area of mangroves [-]	-2	Scaled	0.21	0.00	0.17	0.00	0.40	0.00	0.00	0.32	0.00	0.00	0.00
		Area of seagrass [-]	2	Scaled	0.00	0.36	0.00	0.14	0.00	0.15	0.37	0.00	0.00	0.41	0.02
		Area of corals [-]	2	Scaled	0.02	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.29
	External safety	Minimum distance from the mooring line [m]	3	Absolute	*110*	*120*	*290*	*290*	*125*	*125*	*125*	*350*	*350*	*350*	*775*
				Scaled	0.04	0.04	0.10	0.10	0.04	0.04	0.04	0.12	0.12	0.12	0.26
	Swimmer safety	Current velocities next to beaches [m/s]	-3	Absolute	*0.25*	*0.15*	*0.35*	*0.45*	*0.75*	*1.00*	*0.15*	*0.30*	*0.45*	*0.10*	*0.50*
				Scaled	0.06	0.03	0.08	0.10	0.17	0.22	0.03	0.07	0.10	0.02	0.11
	Stagnant water	Discharge through opening / wet area in top view [m/s]	2	Absolute	*No stagnance*	*Possibility*	*No stagnance*	*No stagnance*	*No stagnance*	*No stagnance*	*Possibility*	*No stagnance*	*No stagnance*	*Possibility*	*No stagnance*
				Scaled	0.12	0.00	0.12	0.12	0.12	0.12	0.00	0.12	0.12	0.00	0.12
Ecology	Area suitable for ecology	Area of mangroves [m2]	8.3	Absolute	*625000*	*0*	*520000*	*0*	*1210000*	*0*	*0*	*972000*	*0*	*0*	*0*
				Scaled	*0.21*	*0.00*	*0.17*	*0.00*	*0.40*	*0.00*	*0.00*	*0.32*	*0.00*	*0.00*	*0.00*
		Area of seagrass [m2]	8.3	Absolute	*0*	*1095300*	*0*	*410760*	*0*	*456000*	*1130000*	*0*	*0*	*1250000*	*65200*
				Scaled	*0.00*	*0.36*	*0.00*	*0.14*	*0.00*	*0.15*	*0.37*	*0.00*	*0.00*	*0.41*	*0.02*
		Area of corals [m2]	8.3	Absolute	*51300*	*90450*	*48600*	*35100*	*40500*	*40500*	*33750*	*44550*	*44550*	*48600*	*881550*
				Scaled	*0.02*	*0.03*	*0.02*	*0.01*	*0.01*	*0.01*	*0.01*	*0.01*	*0.01*	*0.02*	*0.29*
Coastal protection	Prevention of erosion	Length of the sheltered current coastline [m]	5	Absolute	*650*	*650*	*1900*	*1900*	*2100*	*2100*	*1900*	*4100*	*4100*	*3100*	*1400*
				Scaled	0.03	0.03	0.08	0.08	0.09	0.09	0.08	0.17	0.17	0.13	0.06
		Turbulence visible in Delft3D [-]	-5	Absolute	*Large eddies left en right length scale larger than extension*	*Large eddies left en right length scale larger than extension*	*Eddies smaller than lenght of cube develop*	*Eddies larger than lenght of cube develop*	*One small eddie develops on the rigth, nothing on the left*	*One small eddie develops on the rigth, nothing on the left, in the basin two eddies*	*One small eddie develops on the left, large eddie on the right*	*Small eddies on the sides of the island order of size of the island*	*Almost no eddie formation, but also no sheltering of the current coastline*	*Two large eddies form on the left and right side of the island, there is a lot of sheltering behind the island*	*There are no eddies created and only larger flow velocities at the barrier itself*
				Scaled	0.18	0.18	0.09	0.18	0.05	0.04	0.06	0.05	0.05	0.09	0.03
		Impression of the bed shearstresses [-]	-5	Absolute	*Very high opening*	*High at tips*	*Med corners*	*High corners*	*High opening*	*Very high opening*	*High corners*	*Med corners*	*Med*	*High corners*	*Low*
				Scaled	0.26	0.09	0.04	0.09	0.09	0.13	0.09	0.04	0.04	0.09	0.03
		Length of the beaches [-]	-5	Absolute	2000	2250	850	850	0	0	0	0	0	0	0
				Scaled	0.34	0.38	0.14	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 38 | Part 2 of the MCA table

Principle	Criterion	Indicator	Weight factors per indicator	Absolute or scaled	Closed arms protected mangroves (design 1)	Open arms protected seagrass (design 2)	Cube unprotected mangroves (design 3)	Cube unprotected seagrass (design 4)	Banana protected mangroves (design 5)	Banana protected seagrass (design 6)	Attached Banana protected seagrass (design 7)	Cigar protected mangroves (design 8)	Cigar protected seagrass (design 9)	Attached Cigar protected seagrass (design 10)	Lagoon unprotected coral (design 11)
Building with Nature	Effectiveness of ecology	Ecology serves (protects) the land	7.5	Scaled	0.00	0.08	0.28	0.28	0.08	0.00	0.00	0.00	0.00	0.00	0.28
	Effectiveness forces of nature	Use of forces of nature	7.5	Scaled	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Costs	Materials and construction	Cost of establishing the ecology [-	-1	Scaled	0.11	0.07	0.08	0.03	0.19	0.03	0.07	0.23	0.00	0.08	0.11
		Required amount of landfill	-4	Scaled	0.11	0.04	0.09	0.02	0.16	0.07	0.10	0.13	0.07	0.14	0.07
		Length of hard revetment [m]	-3	Absolute	*3800*	*6700*	*3600*	*2600*	*3000*	*3000*	*2500*	*3300*	*3300*	*3600*	*5300*
				Scaled	0.09	0.16	0.09	0.06	0.07	0.07	0.06	0.08	0.08	0.09	0.13
		Length of soft revetment [m]	-3	Absolute	*1950*	*2150*	*850*	*850*	*0*	*0*	*0*	*0*	*0*	*0*	*3200*
				Scaled	0.22	0.24	0.09	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.36
		Length of ecology revetment [m]	-1	Absolute	*5600*	*6700*	*3600*	*2600*	*6800*	*5300*	*4800*	*8000*	*8000*	*8700*	*5300*
				Scaled	0.09	0.10	0.06	0.04	0.10	0.08	0.07	0.12	0.12	0.13	0.08
	Constructability	Complexity of construction	-2	Scaled	0.00	0.00	0.00	0.00	0.18	0.18	0.14	0.18	0.18	0.14	0.00
	Flexibility in terms of future plans	Average distance from the mooring line [m]	1	Absolute	*720*	*800*	*450*	*450*	*300*	*300*	*300*	*450*	*450*	*450*	*900*
				Scaled	0.13	0.14	0.08	0.08	0.05	0.05	0.05	0.08	0.08	0.08	0.16

Table 39 | Brief version of the MCA table, the scores are grouped by principle

		Principle	Absolute weight	Closed arms protected mangroves (design 1)	Open arms protected seagrass (design 2)	Cube unprotected mangroves (design 3)	Cube unprotected seagrass (design 4)	Banana protected mangroves (design 5)	Banana protected seagrass (design 6)	Attached Banana protected seagrass (design 7)	Cigar protected mangroves (design 8)	Cigar protected seagrass (design 9)	Attached Cigar protected seagrass (design 10)	Lagoon unprotected coral (design 11)
		Utility	25	0.3	1.3	0.1	0.7	-0.5	0.7	1.6	0.2	0.8	1.6	1.9
		Ecology	25	1.9	3.3	1.6	1.2	3.4	1.4	3.2	2.8	0.1	3.6	2.6
		Coastal protection	20	-3.8	-3.1	-1.0	-1.7	-0.2	-0.4	-0.4	0.4	0.4	-0.2	0.0
		Building with Nature	15	0.7	1.3	2.8	2.8	1.3	0.7	0.7	0.7	0.7	0.7	2.7
		Costs	15	-1.4	-1.4	-1.0	-0.5	-1.4	-0.9	-0.9	-1.4	-0.9	-1.2	-1.8
		Sum	**100**	**-2.4**	**1.3**	**2.5**	**2.5**	**2.5**	**1.4**	**4.1**	**2.7**	**1.1**	**4.4**	**5.4**