Prepared for:

University of Twente

Salt intrusion in the Selangor Estuary in Malaysia

Model study with Delft3D

Report

R1504

June 2008

Title **Salt intrusion in the Selangor Estuary in Malaysia**

Abstract

The Selangor River in Malaysia is the main source for drinking water for the densely populated area around Kuala Lumpur. Nowadays more than half of the river discharge is extracted, which causes the salt intrusion to advance further upstream in the downstream part of the river. For this study a numerical model is build with Delft3D to assess the impact of the water extraction on the salt intrusion. The point of departure was an existing large scale tidal flow model, which was refined and optimised to generate accurate boundary conditions for the coastal zone near the Selangor River. Subsequently a 3-dimensional model of the Selangor Estuary was build, which is capable of accurate predictions of the dynamic process of salt intrusion. The results of the study can be used to determine the effects for the valuable eco-system in the estuary and to improve the river basin management. The study was accommodated by Alkyon Hydraulic Consultancy & Research in the Netherlands. Two months of the research were carried out in Malaysia, hosted by the National Hydraulic Research Institute of Malaysia (NAHRIM).

References

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Preface

This Master thesis is the final graduation project for my study Civil Engineering at the University of Twente. It is written in cooperation with Alkyon and NAHRIM (National Hydraulic Research Institute of Malaysia). The study concerns the Selangor Estuary, located on the west coast of the Malaysian Peninsular about 60 kilometres from Kuala Lumpur. Most of the study was carried out in the Netherlands in the rural area of the Noordoostpolder where the office of Alkyon is located. Two months of the study were carried out in Malaysia in the office of NAHRIM.

During this study I gained a lot of experience with the numerical model Delft3D. Numerical models are constantly improving and especially hydrodynamic behaviour of water masses can be simulated with great accuracy. Nowadays, the results of a model depend mostly on the accuracy of the available data and of the modeller. In the setup, processing and comparison of a model, accuracy is essential. A little mistake in the setup can make a simulation worthless, and a misconceived time zone, coordinate or geodetic datum can completely confuse the results of the model. Although I always considered myself a perfectionist, this study putted me to the test. During my research I collected and generated more than 310 gigabytes of data, simulations, literature etc., which I all needed to manage properly. This final report shows just the tip of the iceberg and describes the red line of the study without the many side streets that appeared dead ended.

One of the challenges of this research was to obtain data, especially for the Selangor Estuary. Malaysian organisations are more reluctant to share data, even between governmental institutions mutually. The attitude is that the collection of data costs a lot of money so this will not be given away for free. A Danish engineer explained it to me with the words: “Data is power in Malaysia”. Nevertheless sufficient data is obtained for the purpose of this study. With a lot of effort and persistence these data resulted in a reliable model of the Selangor Estuary.

Much gratitude is owed to Alkyon for the sharing of their expertise, the use of the PC’s and office and their support for my trip to Malaysia. During my stay I enjoyed the atmosphere in the office and the adjoining forest is unique for a work environment in The Netherlands. It offered me the possibility for a refreshing run to clear my mind. Furthermore much gratitude is owed to the non-profit foundation Netherlands Engineering Consultants (NEDECO) and NAHRIM; NEDECO for the financial support of my stay in Malaysia and NAHRIM for accommodating my stay.

Many people helped me during the period of my graduation. Besides my friends and family, who are hopefully already aware of my gratitude towards them, I would like to mention a few people for their support during my study:

Jan Ribberink and Kathelijne Wijnberg, my supervisors from the University of Twente, for their support and helpful comments.

Gijs van Banning, my supervisor from Alkyon, for his involvement and many helpful remarks and discussions. Furthermore I would like to thank Paul Olijslager, Luitze Perk, Jeroen Adema, Gerrit Hartsuiker, Bart Grasmeijer for their support and Jaap de Groot, Lykle Voort, Olger Koop, David Hurdle and Wojciech Misiag for the countless rides from Zwolle to the office.

Lee Hin Lee, Karthigeyan A/L Veerasamy and Dunstan Anthony Pereira from NAHRIM for the warm welcome they gave me in Malaysia.

All data and documents used in this study are provided free of charge. The completion of this study should not have been the same without the generous help of Abdul Kadir Ishaf, researcher at the Malaysian Nuclear Agency, Bruce Nelson, professor emeritus at the University of Virginia, Nada Badruddin, researcher at the Forest Research Institute of Malaysia and Haslina Amer, researcher at the Selangor Water Management Board (LUAS).

I hope you will enjoy reading the result!

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Executive's summary

The Selangor River is one of the many rivers along the west coast of the Malaysian Peninsula discharging into the Malacca Strait. The river basin adjoins the densely populated area around Kuala Lumpur in the southeast. The upstream land of the river is still a pristine, natural environment and the river is preserved from large scale pollution. When the demand for drinking water started to increase in the eighties and nineties, the Selangor River was assigned as a source of good quality water. Extensive infrastructure was build to extract the water from the river and transport it to the millions of people in Kuala Lumpur and surroundings. Nowadays more than half of the discharge of the Selangor River is used as drinking water. This change in discharge regime will cause the salt intrusion to advance further upstream in the estuary part of the river. The Selangor Estuary is a valuable mangrove-ecosystem and is home to the synchronous flashing fireflies. This phenomenon attracts thousands of visitors and is the driving force behind the local tourism industry. The concern is that the advancing salt intrusion will harm the ecosystem. For this study a numerical model is build with Delft3D to assess the impact of the water extraction on the salt intrusion.

The hydrodynamic behaviour in estuaries is determined by the fluvial regime and the tide-dominated marine regime. For the generation of boundary conditions for the Selangor Estuary Model a 2-dimensional flow model of the coastal zone is created. The point of departure was an existing large scale tidal flow model covering all coastal waters surrounding Malaysia. This large scale model appeared to be too coarse and inaccurate for direct derivation of boundary conditions. Two steps of refinement and optimisation are applied, which resulted in the Malacca Strait Model and the Northern Approach Model. These models are both forced by astronomical constituents and calibrated with known constituents. A calibration technique was developed which optimises the boundary conditions for each partial wave. Secondly the propagation and shoaling of the partial waves is analysed and the model setup was optimised based on these results.

The results of the most refined Northern Approach Model were used as boundary conditions for a detailed, 3-dimensional model of the Selangor Estuary. Water levels and flow velocities were combined in a Riemann boundary to obtain the highest accuracy. Density induced flow is controlled by salinity only. To capture the dynamic process of salt intrusion a stable situation is assumed for most conditions. To simulate this process one tidal cycle is selected and restarted with the results at the end of the former simulation, until model results are stabilized. The Selangor Estuary Model is calibrated and validated with water levels, flow velocity and salinity and showed good results. Salinity was predicted within a range of a few ppt and stratification was also included.

The validated model is used to assess the impact of the water extraction in the river. The required base flow in the Selangor River is 3.5 m^3/s, while before water extraction the average dry season discharge was 30 m^3/s. This results in the maximum salt limit of 6.5 ppt at the surface to advance 3.4 kilometres further upstream for an average tidal range. A constant salinity of 6.5 is known to be harmful for the ecosystem. Further research should clarify the effects of variable salt levels and what the role of the salt intrusion is in the downgrade of the firefly population.

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1 Introduction

1.1 Project framework

The west coast of the Malaysian Peninsula is an area which has developed rapidly over the past decades. The centre of this development is the Malaysian capital Kuala Lumpur, which is nowadays a metropolis with over a million inhabitants. The surrounding fluvial plane is part of the State Selangor and is the State with the highest population growth rate in Malaysia, an average of 6.1 percent annually in the last decade of the twentieth century [Dep. of Statistics Malaysia]. In the same period the average wealth of the population increased and for many Malaysians the standard of living was raised. The combined effect of population and wealth growth raised the pressure on natural resources. Environmental issues arose amongst which many are water related. Water quality deteriorated by pollution from industrial and domestic waste, urban areas suffered floods because changes in land use accelerated the runoff of rivers, coastal erosion because of clearing of coastal vegetation. Moreover the demand for good quality water for irrigation, drinking water and recreational water increased. To cope with these issues a profound understanding of the processes and good water management is needed.

In the surroundings of the Kuala Lumpur the demand for drinking water more than tripled in the period from 1990 till today [SPLASH]. Traditionally drinking water is extracted from surface water in Malaysia. However most of the surface water in the vicinity of Kuala Lumpur suffered from pollution and could not be used for drinking water without extensive and expensive treatment. The exception is the Selangor River, which drains into the Malacca Strait northwest of Kuala Lumpur. This river is preserved from large scale pollution and was the logical source for good quality drinking water for the millions of Malaysians living in and around the capital. Nowadays the Selangor River is the main source of drinking water for the whole state of Selangor, including Kuala Lumpur. Infrastructure is build for the treatment and transport of the fresh water from the river to the densely populated areas. The result of this major water extraction for the river is that the average discharge at the mouth almost halved in the last decade. Major concerns have risen to what the effects of this change will be on the ecosystem in the downstream part of the river. The last stretch of river is home to the synchronous flashing fireflies. These creatures attract many visitors each year and are the driving force behind the local tourism industry. The part of the river where they live is influenced by the tide and the river discharge. The concern is that the decreasing river discharge will cause the saline sea water to penetrate further upstream. The ecosystem with the fireflies is sensitive for salinity and the decline in the population of fireflies in the last decade is blamed to the water extraction upstream.

This study will use the numerical modelling software Delft3D to simulate the hydrodynamic behaviour, including salinity, of the downstream part of the Selangor River and asses how the decrease in discharge affects this part of the river. The logical next step is to assess the consequences for the ecosystem but this is beyond the scope of this study. A model also creates the possibility to optimise the river management. The discharge of the Selangor is largely controlled by humans and can be adjusted in such a manner that harmful salinity levels are avoided. Last, a model offers the possibility to predict the effects of future developments and human interventions.

1.2 Research Objective

The Selangor River is one of the best monitored rivers in Malaysia and has been the subject of several studies. However, all of these studies are based on visual observations, measurements and 1-D modelling. These studies involved the behaviour of suspended sediment [Nelson, 2002], water, salt and sediment dynamics [Abdul Kadir 2000, 2002] and 1-dimensional river modelling [Kheong, 2002c]. The studies based on observations and measurements only indicate the state of the river under the specific conditions during the research. The scale of these studies is insufficient to derive reliable relations for the behaviour of salinity. The 1-dimensional model is not capable of predicting the highly dynamic process of tidal intrusion accurately. Saline intrusion is most often associated with stratification and hysteresis effects. The Delft3D software offers the possibility to develop a 3-dimensional model capable of simulating such complex processes. A detailed model of the Selangor Estuary can provide answers to the question of what the impact of the water extraction is on the salinity levels in the river is.

The research objective is formulated:

The objective of the research is to simulate the hydrodynamic behaviour of the Selangor Estuary at the Malaysian west coast by utilizing a 3D numerical model and to assess the impact of water extraction for the salinity levels in the estuary.

The behaviour of the Selangor Estuary is controlled by the fresh water discharge and the tidal wave in the Malacca Strait. To simulate the Selangor Estuary the behaviour of the tidal wave in the coastal zone near the estuary has to be known. A large-scale tidal model of the Malaysian waters, developed by Alkyon, will be the point of departure for the development of a more refined tidal model near the Selangor Estuary.

Based on this aim the following research questions are derived:

1. What refinement and optimisation of the tidal model of Alkyon is needed to obtain accurate seaside boundary conditions for the estuary?
2. How well do the simulated hydrodynamic behaviour of the Selangor Estuary agree with measurements?
3. What is the effect of the water extraction on the salinity levels in the estuary?

1.3 Study Area

The location of the Selangor Estuary is shown in figure 1.1 and 1.2. The hydrodynamic behaviour of the Selangor Estuary is controlled by the tidal wave in the Malacca Strait and the discharge regime of the Selangor River.

1.3.1 Malacca Strait

The Malacca Strait is the shallow passage between the Malay Peninsula and Sumatra (figure 1.3). The Strait connects the Andaman Sea and the Indian Ocean in the north with the South China Sea in the south. The length of the Strait is about 1000 kilometre and its width varies between 60 and 400 kilometres. Islands are abounded, especially in the southeast near Singapore. Along the northern coastline of Malaysia the well-known holiday islands Penang and Langkawi are situated. The Malacca Strait is one of the major seaways in the world. Many ships pass through the Strait as it is the main sea connection between the eastern and western part of the Eurasian continent. Additionally, the major harbor of Malaysia, Port Kelang, and the harbor of Singapore are visited by thousands of ships each year. In 1998 more than 219,000 ships utilized the waterway and this number is steadily increasing

[Kamaruzaman, 1999]. The Malacca Strait provides a rich marine environment with soft-bottom habitats, fringing coral reefs, seagrass beds and mangroves [Tan and Yusoff, 2002]. The area is amongst the most important fishing ground for both Malaysia and Indonesia [MASDEC]. The heavy traffic in the Strait brings along the burden of pollution. In the year 2000, an estimated 880,000 tonnes of solid waste, sewage water and oil spills was generated by vessels [MASDEC].

Strong tidal flows can occur especially in the narrow part of the channel. Flow velocities average between 0.5 and 1.0 m/s in the centre of the strait, but closer to shore and in restricted channels they may reach 1.8 m/s during spring tides [Keller, 1967]. Besides the oscillating tidal flows a net current is usually present throughout the year. The predominating direction of this current is north-westerly. This current is generated by monsoonal effects on the neighbouring seas. Two seasons are predominant, the Northeast monsoon from December till February and the Southwest monsoon from June till August [Hii, 2006]. The Malacca Strait itself is sheltered by the mainland of Malaysia and Sumatra. Wind conditions are in general very calm in the Strait and wind speeds seldom exceed 5 m/s [MMS, 1984]. Occasional thunderstorms do occur with squalls giving rise to wind gusting up to 26 m/s in the south-western region of the Peninsular Malaysia [Kamaruzaman, 1999]. The Northeast monsoon causes the strongest current in the Strait. The mean sea level at the south-eastern entrance can be up to 50 centimetres higher than the north-western entrance and the base current can reach a value of 0.18 m/s. The current is lowest during the Southwest monsoon when sea level difference is only about 10 centimetres and current drops to a value of 0.05 m/s [Wyrtki, 1961]. During the Southwest monsoon the current is even recorded to change direction when the water in the Andaman Sea is piled up by the monsoon winds [Keller, 1967].

Bottom sediments in the Malacca Strait primarily consist of muddy sands, with large areas of mud in the vicinity of river mouths and in the Andaman Sea [Keller, 1967]. In the narrow part of the Strait ridges in the longitudinal direction are found and perpendicular to the flow sand waves occur.
These waves have wave lengths of approximately 241 to 900 meter and heights of 4.6 to 15.3 meter. [Keller, 1967; Wyrtki, 1961] The level of salinity and temperature are rather constant. On average the salinity amounts 31.22 ± 1.01 ppt and the temperature is 29.60 ± 0.68 ºC [Hii, 2006]. Because of the location near the equator very little seasonal effects will be shown by the water temperature. There is no stratification in temperature or salinity in the southern part of the Strait. The deeper, northern part of the Strait does shows minor signs of stratification [Hii, 2006].

1.3.2 Selangor River

The Selangor River is one of the many rivers along the west coast of the Malaysian Peninsular. Although relatively close to the densely populated area around Kuala Lumpur, the river and its tributaries flow through a relatively pristine, natural environment. When the demand for fresh water started to increase in the late eighties, the Selangor River was the obvious source to supply good quality fresh water. This trend continued and nowadays the Selangor River provides water for approximately 4 million people in the State of Selangor. The expanding development of Kuala Lumpur did not occur without affecting the region at all. Especially in the downstream area the natural river habitat is disappearing and water quality is deteriorating.

Catchment Area
The Selangor river flows in the state Selangor through three districts, Kuala Selangor (means: Selangor Estuary), Hulu Selangor (means: Upstream Selangor) and Gombak. The southern border of the river basin touches the outskirts of the city of Kuala Lumpur. The catchment area

of the Selangor River covers up an area of about 1960 km^2 [Lee, 2002, Volume II]. In the northeast it reaches up to the Titiwangsa Mountain Range which forms the backbone of the Malaysian Peninsular. Summits of over 1500 m +MSL contribute to the Selangor River Basin. The upstream tributaries are fast flowing streams through granite mountain and sedimentary bedrock, interrupted by rapids and waterfalls. In the lower part of the basin the river enters the fluvial plain and changes into a low gradient, meandering river. The slope of the river bed in the last 30 to 40 kilometres is about zero, at some point even negative. The slopes of the mountains are for the most part covered with forest. The central and western part of the catchment area is mainly used for agriculture, mostly palm oil and rubber plantations. The agricultural land is irrigated by an extensive system of channels, dams and sluices. Mining activity concerns the extraction of tin but most mines have already ceased production. Figures 1.4 and 1.5 show respectively the relief map and the land use of the Selangor River Basin. In both figures the boundaries of sub-basins are shown and labelled with red letters. Sub-basin 'SB13' is a fresh water swamp and this drainage area does not or hardly contribute to the discharge of the Selangor River. In the northern part of the basin two reservoirs are located, indicated with blue patches. The water of the most westerly reservoir is controlled by the Tinggi Dam. In 2005 the Selangor Dam in the east was finished with an even bigger storage capacity. Together both reservoirs can store up to 338 million m^3 of water. The function of these reservoirs is to guarantee a sufficient supply of fresh water throughout the year, so even in the dry season enough drinking water can be extracted from the river. Nowadays, the infrastructure to treat and transport drinking water has a capacity of about 3000 million litres per day, which equals a flow of 35 m^3/s. More than 90 percent of the water is extracted from the river at the Batang Berjuntai Barrage. At this intake the water is pumped into pipelines towards treatment plants and the river discharge is controlled by a dam (figure 1.6).

Figure 1.6 Batang Berjuntai Barrage (location in figure 1.4)

Selangor has a tropical, humid climate with very little variation in temperatures around the year. On average the temperature rises during daytime up to 32 ˚C and falls down to 23 ˚C at night. The highlands are slightly cooler. Average rainfall varies between 2000 and 3000 mm annually throughout the basin [DID HydroNet]. The uplands generally receive more precipitation. There are two monsoon periods per year in November-December and April-May. In these four months almost fifty percent of the annual rainfall pours down the sky. Evaporation is less monitored in the area but is estimated at 1600 mm per year [DID HydroNet]. A permanent discharge station is located near Rantau Panjang (figure 1.4). Discharge data from 1960 to 2000 [DID HydroNet] are analysed and plotted in figure 1.7. The rainfall station of Kubu Bahru (figure 1.4) is assumed representative for the upstream catchment area. The rainfall data of this station are shown in figure 1.7. Finally the water extraction capacity is added to the figure. During the main dry season (July-August) the average discharge is less than the water extraction capacity. The upstream dams are built to release water during the dry periods to guarantee a sufficient discharge.

Located in the vicinity of the Malaysian capital and metropolis Kuala Lumpur, the area has to deal with a rapidly increasing urbanization. The growing population puts the natural environment under pressure. Water quality deteriorates due to land clearing and logging, livestock and pig farming, sewage and waste from manufacturing and agro-based industries [DID, 2003]. These developments are not without consequences for the Selangor River. In past decades the renowned high water quality of the river has been on the downgrade. One of the areas mostly affected is the valuable ecosystem in the most downstream stretch of river, which is home to the flashing fireflies. The change in land use upstream also caused the discharge regime to change. Water is no longer stored in the higher regions of the basin and water levels can rise rapidly. This is partly undone by the dams upstream but nevertheless the area suffers from frequent flooding.

Selangor Estuary

The average discharge of the Selangor River is 60 m^3/s [DID Hydronet]. Seasonal variations in rainfall cause the flow to exceed 122 m^3/s or to fall below 23 m^3/s about 10 percent of the time [Nelson, 2002]. The average depth in the Selangor Estuary is 5-6 meters. In some meanders the depth increases to as much as 9 meter and at the entrance of the estuary there is a shoal with depths less than 5 meter. The estuary is mesotidal (2-4 m) and a dominantly ‘partially mixed’ estuary, although during neap tide and with high discharge a salt wedge can be formed [Nelson, 2002]. The tidal range varies between 3.9 m during spring tide and 1.4 m during neap tide. Currents in the estuary can reach values up to 1.3 m/s. Salt intrusion extends about 20 kilometre upstream from the mouth. The supply of very fine sediments from upstream is abundant, sediment concentration in the top of water column vary under normal conditions between 200 and 500 mg/l. Total annual sediment yield amounts nearly 900,000 tons, which equals a volume of approximately 600,000 m^3 mud with a density of 1400 kg/m^3 [FAO]. This figure corresponds with the average discharge and sediment concentration.

The Selangor River discharges into the Malacca Strait about 50 kilometres north of the major harbor “Port Kelang”. A few kilometres offshore is the northern approach to this harbor and thousands of cargo ships pass by here annually. The depth of this natural trench is sufficient for all ship sizes. In the close vicinity of Port Kelang however intensive dredging takes place. In the Selangor River shipping is limited to small scale fishery near the mouth and firefly watching boat trips. The depth of the estuary is sufficient for the vessels that are used for these purposes.

Approximately 40,000 people live in the downstream area of the Selangor River Basin, from Batang berjuntai until the rivermouth [DID, 2002]. A few kilometers upstream from the mouth two little villages are situated. Kuala Selangor[i] on the southern bank and Pasir Penambang on the northern bank. Both are small towns which rely economically on small scale fishery and tourism. The most important touristical attractions are the fireflies further upstream and the mangroves of the Selangor Nature Reserve. For these villages the Selangor River is the main economic source and preserving the river is essential for their living. Kuala Selangor is however relatively small compared to Kuala Lumpur, and the demand for clean drinking water, agricultural products and space to expand is hard to withstand.

[i] Kuala Selangor is the name of the town as well as the district.

2 Modelling Strategy

A commonly used technique in numerical flow modelling is nesting. With this technique a more detailed model is created by deriving the boundary conditions from a larger scale flow model. Especially for tidal flow models this technique has proven to be successful. For this study a calibrated and validated tidal flow model was supplied by Alkyon. This model is called the Malaysia Overall Model and covers the Malacca Strait, the Gulf of Thailand and large parts of the South China Sea. The model was developed specifically to generate boundary conditions for more detailed models [Chiru, 2007]. Figure 2.1 shows the area which is modelled. In the purple frame is enclosed the project location of this study in more detail. The curvilinear grid consists of 108,341 cells. Grid cell sizes vary from 200 m in the shallow region particularly near Singapore to 11 km in the deeper waters along the seaward boundary in the South China Sea. The grid cells near the Selangor Estuary are roughly two by four kilometres. As the figure shows the grid cells are too course to follow the land boundary exactly. The influence of such inaccuracies on the scale of the model is negligible. However for the Selangor Estuary a more refined tidal flow model will be needed to determine accurate flow velocities and water levels near the river mouth. This chapter describes the approach which will finally lead to the Selangor Estuary Model. One of the main criterions of the model setup was to restrict the calculation time of one model simulation to the maximum of one night. This enables the possibility to quickly review different model setups. Accuracy of the model was another important criterion. These two criteria are contradictory and were balanced for each of the models.

2.1 Process

The process of modelling will be divided in several steps, starting large scale and ending small scale. As figure 2.1 shows the Malaysia Overall Model is too coarse to generate boundary conditions for a small scale model of the Selangor Estuary. The seaside of the estuary is represented by only a few grid cells. For accurate boundary conditions near the Selangor Estuary the grid has to be refined by an estimated factor ten. This is a very high factor of refinement and will lead to an exponential increase in calculation time. To keep the calculation time within the limit of one day the model is refined in two steps. First a part of the Malacca Strait is selected and secondly the coastal zone near the Selangor Estuary is selected. The final model will be the Selangor Estuary Model. The first three models are tidal flow models with boundaries which are controlled by astronomical constituents. This means the water level at a boundary is calculated based on the amplitudes and phases of the partial tides. All of the tidal models will be 2-dimensional to reduce calculation time. This leads to the following overview of models used in the study:

- Malaysia Overall Model, large scale 2-D tidal flow model provided by Alkyon.
- Malacca Strait Model, refined 2-D tidal flow model covering a part of the Malacca Strait.
- Northern Approach Model, more refined 2-D tidal flow model covering the coastal zone near the Selangor Estuary. This area is the northern approach to Port Kelang which explains the name.
- Selangor Estuary Model, the detailed 3-D flow model of the Selangor Estuary.

This denomination will be used in the reminder of this report. Figure 2.2 gives an overview of the areas that are covered by each of the models. The complete set-up of each of the models is described in chapters three and four.

The process of modelling is visualised in a flow chart which is shown in figure 2.3. The purpose of the figure is to clarify the steps that are taken in the process. The point of departure is the Malaysia Overall Model. This two-dimensional flow model covers almost all of the waters surrounding Malaysia. The set-up and the results of the model are analysed to estimate the accuracy of this model. Simultaneously the available data of the tidal wave in the Malacca Strait is analysed. Most important is the behaviour of the tidal wave trough the Strait and the contribution of the various tidal constituents. Based on these results the boundary conditions for the Malacca Strait Model are derived. For this model a new bathymetry is created, based on six digitised Admiralty Charts. The areas which are covered by these maps are shown in figure 2.2. The more refined grid and accurate bathymetry should lead to a better prediction of the tidal flow. The model is further improved by calibration. The same process is repeated for the Northern Approach Model. However, this model covers a relatively small area and little calibration data is available. This emphasizes the importance of the calibration of the Malacca Strait Model. When this model provides accurate boundary conditions, the calibration of the Northern Approach Model will be limited to fine-tuning. The Northern Approach Model will be validated for both flow velocities and water levels. Both of these parameters will be included in the boundary conditions for the Selangor Estuary Model. This model will include salinity and a fresh water discharge. The bathymetry in the river will be based on measured cross-section profiles. The model is calibrated for flow velocity, water levels and salinity. Due to the limited availability of data the model is only validated for salinity. Salinity levels are controlled by flow velocities and water levels so a validation of only salinity is assumed to be sufficient.

2.2 Software

All modelling in this study is done by using the Delft3D software. This package encompasses several modules which are developed for specific purposes. In this study the following modules are used:

- TIDE
  A program which is able to analyse a time series of water levels and convert these into harmonic constituents. For this analysis the program has 234 constituents internally available. The program is also capable of predicting water levels when tidal constituents are known.
- RGFGRID
  A program to create, modify and visualise a grid for the Delft3D flow module. The program offers tools which can optimise the properties of the grid. For a curvilinear grid the most important properties are the orthogonality and smoothness.
- QUICKIN
  A program to create, modify and visualise a bathymetry for the Delft3D flow module. When a grid is finalised with RGFGRID, the next step is to implement bottom depths in the model. QUICKIN can also be used to create maps when parameters, like bottom roughness, are spatially altered. These
- FLOW
  The Delft3D Flow module is the main component of the Delft3D software package. This module can simulate flows in 2 or 3 dimensions with the momentum and continuity equations.
- QUICKPLOT
  A program to visualise and animate the results produced by Delft3D modules. QUICKPLOT provides a user-friendly and flexible tool to quickly visualise the results of a flow simulation. The program has been developed using MATLAB.
- TRIANA
  A program which uses the same technique as the TIDE program but specifically designed for the processing of Delft3D output. This program is capable of analysing a time series of water levels which is generated by the Delft3D flow-module and

compare the results with known values for constituents. The program is used in two ways. First to generate boundary conditions for a nested model and secondly to compare the model results with measurements and calibrate the model.

- NESTHD1 & NESTHD2
  These programs are developed to facilitate the nesting of models. They create the observation points in the coarse model and also the boundary condition files for the nested model.

The Delft3D output has been processed with MATLAB. The advantage of MATLAB is the use of scripts which can be applied to different model simulation. With only the adjustment of a directory the script can be run and the requested plots will be created instantly. Another advantage is that more than one run can be loaded and edited. This enables the possibility to create figures that show the difference between two simulations. Matlab also has the functionality to create movies, which is very useful for visualising dynamic processes. Geographic conversions were carried out with The Geographic Calculator from Blue Marble Geographics. Supportive software was used for editing and file management, mainly Textpad and Total Commander. These programs are essential for fast processing of input data and files.

2.3 Theoretical background

The main theory applicable for this research can be divided into three components. The following paragraphs will briefly clarify the underlying theory of the Delft3D model for the hydrodynamics, the tidal analyses and the salinity transport. These three subjects are the relevant parts of the Delft3D software for this research.

2.3.1 Hydrodynamics

The core of the Delft3D software is the FLOW module. This module can be applied for any type of open water conditions, like rivers, oceans, coastal shelves and lakes. Delft3D FLOW solves the continuity equations and the Navier Stokes equations for an incompressible fluid. The set of partial differential equations in combination with an appropriate set of initial and boundary conditions is solved on a finite difference grid. The equations are discretized on a staggered grid (Arawaka C-grid). In a staggered grid not all quantities, such as the water level, the depth, the velocity components or concentration of substances are defined at the same location in the numerical grid.

In Delft3D the formulas are formulated in orthogonal curvilinear horizontal co-ordinates. Orthogonal means that for each grid cell, the two lines drawn from the adjoining, opposite grid cell centres must intersect (nearly) perpendicular. Orthogonality is required to ensure accurate calculation. Curvilinear means that a row of grid cells can curve. The advantages are that a grid can follow the boundary of the water mass (instead of the “stair case boundary”) and a high grid resolution can be created in the area of interest. The coordinates of a grid can be implemented with a Cartesian coordinate system or a spherical coordinate system. The first uses a horizontal reference plane, the latter the Earth’s curvature according to the World Geodetic System 1984 (WGS84). For 3-dimensional calculations Delft3D FLOW divides each grid cell in a fixed number of layers. Because the surface is moving freely the depth of the dividing planes changes over time. For each layer a set of coupled conservation equations is solved. Vertical velocities are calculated relative to the dividing horizontal plane. Real flow velocities include the calculated velocity and the movement of the horizontal plane.

The most important hydrodynamic equations are listed in a simplified version below. The main simplifications are related to the curvilinear grid. External sink and source terms are left out of the equations. Delft3D FLOW calculates the momentum and continuity equations in the horizontal direction. For 3-dimensional calculations the vertical velocities are computed from the continuity equation. In the vertical momentum equation the vertical accelerations are neglected, which leads to the hydrostatic pressure equation.

Momentum equations in horizontal direction:

$$\frac{\delta u}{\delta t} + u\frac{\delta u}{\delta x} + v\frac{\delta u}{\delta y} + \frac{\omega}{(d+\zeta)}\frac{\delta u}{\delta \sigma} - fv = -\frac{1}{\rho_0}P_x + F_x + \frac{1}{(d+\zeta)^2}\frac{\delta}{\delta \sigma}\left(\upsilon_V \frac{\delta u}{\delta \sigma}\right)$$

$$\frac{\delta v}{\delta t} + u\frac{\delta v}{\delta x} + v\frac{\delta v}{\delta y} + \frac{\omega}{(d+\zeta)}\frac{\delta v}{\delta \sigma} - fu = -\frac{1}{\rho_0}P_y + F_y + \frac{1}{(d+\zeta)^2}\frac{\delta}{\delta \sigma}\left(\upsilon_V \frac{\delta v}{\delta \sigma}\right)$$

In which:

u and v	=	flow velocities	[m/s]
ω	=	flow velocity relative to the horizontal plane	[m/s]
d	=	water depth	[m]
ζ	=	free surface elevation	[m]
σ	=	vertical coordinate defined by $(z-\zeta)/(d+\zeta)$	[-]
		(in which: z = vertical coordinate in physical space)	
f	=	Coriolis parameter	[1/s]
ρ_0	=	reference density of water	[kg/m^3]
P_x	=	hydrostatic pressure gradient	[kg/m^{2}s^2]
F_x	=	turbulent momentum flux (Reynold's stresses)	[m/s^2]
υ_V	=	vertical eddy viscosity	[m^2/s]

Continuity equations

$$\frac{\delta \zeta}{\delta t} + \frac{\delta[(d+\zeta)U]}{\delta x} + \frac{\delta[(d+\zeta)V]}{\delta y} = 0$$

$$\frac{\delta \omega}{\delta t} = -\frac{\delta \zeta}{\delta t} - \frac{\delta[(d+\zeta)u]}{\delta x} - \frac{\delta[(d+\zeta)v]}{\delta y}$$

In which:

U and V	=	depth averaged flow velocities	[m/s]

Pressure term

$$\frac{1}{\rho_0}P_x = g\frac{\delta \zeta}{\delta x} + g\frac{\delta+\zeta}{\rho_0}\int_{\sigma}^{0}\left(\frac{\delta \rho}{\delta x} + \frac{\delta \sigma'}{\delta x}\frac{\delta \rho}{\delta \sigma'}\right)\delta \sigma'$$

$$\frac{1}{\rho_0}P_y = g\frac{\delta \zeta}{\delta y} + g\frac{\delta+\zeta}{\rho_0}\int_{\sigma}^{0}\left(\frac{\delta \rho}{\delta y} + \frac{\delta \sigma'}{\delta y}\frac{\delta \rho}{\delta \sigma'}\right)\delta \sigma'$$

In which:

g	=	gravitational constant	[m/s^2]
ρ	=	density of water (including the effect of salt)	[kg/m^3]

In numerical models the grid size is usually too coarse and the time step too large to resolve the turbulent scales of motion. The turbulent processes are added "sub-grid" in Delft3D FLOW. The turbulence closure model used in this study is the k-ε turbulence closure model.

k-ε turbulence model

$$\upsilon_V = c'_\mu L\sqrt{k}$$

$$L = c_D \frac{k\sqrt{k}}{\varepsilon}$$

In which:

c'_μ	=	constant of Kolmogorov-Prandtl	[-]
L	=	mixing length	[m]
k	=	turbulent kinetic energy	[m^2/s^2]
c_D	=	constant of the k-ε model	[-]
ε	=	dissipation of turbulent kinetic energy	[m^2/s^3]

The most important assumptions applied in Delft3D FLOW are [Delft Hydraulics, 2006c].:

- Shallow water assumption: depth is assumed to be much smaller than the horizontal length scale. Under this assumption the vertical momentum can be reduced to the hydrostatic pressure relation.
- Boussinesq assumption: The effect of variable density is only taken into account in the pressure term.

2.3.2 Tides

The tide is the result of the tractive forces of the sun and the moon in combination with the rotation of the earth. This generates long waves which propagate trough all oceans and shallow coastal waters. These waves cause the rhythmic rise and fall of sea-level over a period of half a day or a day [Wright, 1999]. A time-series of oscillating water levels can be analysed and converted into harmonic constituents (partial tides) that all have a specific frequency (and accompanying period). These frequencies correspond to components of the movement of the sun, moon and earth. Seasonal influences on the water levels, like for example the effect of monsoon winds, are related to long term changes of the orbit of the earth around the moon. These influences also behave harmonic and can be converted into constituents with corresponding periods of half a year and a year. Every harmonic constituent consists of an amplitude and a phase. These values differ for every location and describe the size of the wave and the propagation. The general formula for the astronomical tide is:

$$H(t) = A_0 + \sum_{i=1}^{k} A_i \cdot F_i \cdot \cos(\varpi_i \cdot t + (V_0 + u)_i - G_i)$$

In which:

H(t)	=	water level at time t	[m]
A_0	=	mean water level over a certain period	[m]
k	=	number of relevant constituents	[-]
i	=	index of a constituent	[-]
A_i	=	local tidal amplitude of a constituent	[m]
F_i	=	nodal amplitude factor	[-]
ω_i	=	angular velocity	[°/s]
t	=	time relative to 1-jan-1900 00:00 GMT	[sec]
(V_0+u)	=	astronomical argument	[°]
G_i	=	local phase lag	[°]

F and (V_0+u) are time dependent factors which can be calculated for any particular date and time. V_0 is the phase correction for a local time frame. F and u are slowly varying amplitude and phase corrections related to the shift of the lunar orbit around the earth. The position of lunar orbit rotates in a 18.6 year cycle. A_0, A_i and G_i are position dependent factors which represent the tide for a specific location. The water level at a specific location at a specific time can be predicted when all parameters are known for every constituent. As many as 390 harmonic constituents have been identified although in most cases only a few constituents dominate the water level movement. The four main constituents are M2, S2, K1 and O1. In shallow water amplitudes (A_i) increase and overtides and compound tides will arise. Overtides are simple multiples of the frequencies of main components, compound tides are simple multiples of different main components. For example the overtide M4 has an angular frequency of 57.97, twice the frequency of the M2 tide. The compound tide 2MS6 has an angular frequency of 87.96, exactly twice the frequency of the M2 tide plus the frequency of one S2 tide. Overtides and compound tides result from the frictional interaction between the sea-bed and the ebb and flood of the tide. Especially in shallow coastal waters the top of the tidal wave travels faster than the trough of a tidal wave. Tidal waves usually behave as shallow water waves and the accompanying equations apply:

$$c = \sqrt{gd}$$

In which:

c	=	wave speed	[m/s]
g	=	gravitational constant	[m/s^2]
d	=	water depth	[m]

2.3.3 Salinity

In Delft3D-FLOW the transport of salinity is modelled by an advection-diffusion equation in three co-ordinate directions. For each grid cell the mass balance equation is solved. A simplified version of the formula is:

$$\frac{\partial c}{\partial t} + \frac{\partial uc}{\partial x} + \frac{\partial vc}{\partial y} + \frac{\partial wc}{\partial z} - \frac{\partial}{\partial x}\left(\varepsilon_{s,x}\frac{\partial c}{\partial x}\right) - \frac{\partial}{\partial y}\left(\varepsilon_{s,y}\frac{\partial c}{\partial y}\right) - \frac{\partial}{\partial z}\left(\varepsilon_{s,z}\frac{\partial c}{\partial z}\right) = 0$$

In which:

c	= salinity concentration	[ppt]
u,v and w	= flow velocity (for each dimension x,y and z)	[m/s]
ε	= eddy diffusivity (for each dimension x,y and z)	[m^2/s]

2.4 Data sources

In numerical flow modelling the reliability of data is extremely important. Flow equations are well known and the Delft3D software has proven to be able to calculate hydrodynamic processes very accurately. The reliability of model results depends mainly on the efforts of the modeller and the accuracy of the data.

For the Malacca Strait Model and the Northern Approach Model the following sources of data are used:

Admiralty Charts

Standard Nautical Charts produced by the United Kingdom Hydrographic Office. These charts are intended for navigational purposes but they contain a lot of valuable data for a flow model. These Charts provide depth measurements, a land boundary and in some cases flow velocities. For this study six relevant Charts were available which are shown in figure 2.2. The most detailed Admiralty Charts are found near the project location. The hardcopy maps are scanned and digitised by the Alkyon affiliate in India. The digital data included coordinates and depth and was ready for use with the Delft3D software. The digital xyz-data was checked with the original Chart and only the data of the most southern Chart appeared to contain many errors. These data were corrected for the area of interest. When Admiralty Charts are used for hydrodynamic modelling two major issues have to be kept in mind. The Admiralty Charts focus more on shallow areas as these are the main interest of navigators. Secondly the maps have the tendency to underestimate the depth as this will guarantee a sufficient depth for vessels. When depth-measurements are not completely clear, map makers rather raise the bottom in the Chart to prevent ships to run aground on a shallow which was not on the map. Some of the Charts are partly based on old soundings, up to fifty years back. In those days the equipment to measure the location, the reference level and the actual depth was very inaccurate. The Global Position System has only been available from 1995, and from the year 2000 with full accuracy. Acoustic echo sounders already existed halfway the 20th century but have gone through significant developments.

Admiralty Tide Tables

The Admiralty Tide Table (ATT) is also produced by the United Kingdom Hydrographic Office. The main purpose of this table is also to predict tidal conditions in ports for navigational purposes.

Besides the tidal range of many stations in the Malacca Strait, the table also provide amplitudes and phases of the four main partial tides M2, S2, K1 and O1. In the area of the Malacca Strait Model 17 stations along the Malaysian coast and 11 stations along the Indonesian coastline are found. For all of these stations the high and low water levels are provided for neap- and springtide conditions. Information about the partial tides is missing for three stations along the Malaysian coast. The harmonic constituents for the Malaysian stations are checked and updated with more recent values [National Hydrographic Centre, 2008].

Satellite data

In 1992 the TOPEX/Poseidon mission started to measure the ocean surface topography. A satellite, equipped with altimeters, was launched to measure the sea level with an accuracy of 4.2 cm [NASA]. Because the satellite is continuously moving no time series of water levels for a single location can be measured. To perform tidal analyses on these irregular data models are developed. The satellite data used for this study is from a global ocean tide model of 16 major constituents with a spatial resolution of 0.5° which is based on an assimilation of about 5 years of TOPEX/POSEIDON altimeter data [Matsumoto et al., 2000]. Models based on TOPEX/Poseidon satellite data are known to be more accurate in deep oceans than in shallow seas. The depth in the Malacca Strait Model varies between 100 and 20 meter, which is relatively shallow. The uncertainty of these data should be considered when they are used for calibration.

Long term water level measurements

Water level data from stations all over the world is recorded and provided online by the University of Hawaii Sea Level Centre (UHSLC) for several decades. The website of the UHSLC is “http://uhslc.soest.hawaii.edu/uhslc/data.html”. In the area of the Malacca Strait Model data is available for three stations, all on the Malaysian side of the Strait. These stations are found close to the northwest boundary, halfway in Port Kelang and near the southeast boundary. The same stations are also included in the Admiralty Tide Table. A tidal analysis of several years can provide more information than the Table provides. Water level data can be analysed with Delft3D TIDE to obtain amplitudes and phases of all relevant partial tides.

An overview of the available data of the tidal wave is given in figure 2.4. The figure shows the ATT stations, locations of the satellite based model and the three UHSLC-stations.

For the Selangor Estuary Model the following sources of data are used:

National Hydraulic Research Institute of Malaysia (NAHRIM)

The National Hydraulic Research Institute of Malaysia provided cross-section profiles of the Selangor River for the complete stretch of river included in the model. NAHRIM also provided an accurate land boundary and enabled a site visit at the Selangor Estuary.

Malaysian Nuclear Agency (MINT)

The Malaysian Nuclear Agency experimented with nuclear charged sediment tracers in the Selangor Estuary. In continuation of this research dr. Abdul Kadir Ishaf studied the salt intrusion in the estuary. For this purpose he did measurements of flow velocity, sediment concentrations and salinity for several periods in the year 2000. These data are used in this research to calibrate the model.

Malaysian Drainage and Irrigation Department (DID)

The Malaysian Drainage and Irrigation Department is the governmental organisation responsible for all executive water related projects. The DID provided long term discharge data for the Selangor River at Rantau Panjang. Most hydrological data can also be downloaded from “http://h2o.water.gov.my/v2/fail/Invstations/selangor.html”. Moreover the library of the DID Kuala Lumpur provided literature on the Selangor River.

Professor Bruce Nelson

From 1984 till 1989 the Selangor Estuary has been studied by Bruce Nelson from the Department of Environmental Sciences of the University of Virginia. Nowadays Bruce Nelson is professor emeritus but he was willing to share the raw data of his research. One of the purposes of his work was to supply some qualitative field observations that show the interaction between stratification, the behaviour of cohesive sediments and the formation of a turbidity maximum. Two types of measurements were carried out under various conditions, slack runs (with turning tide) and anchor runs (fixed place over a certain period). Measured data include depths, salinity, temperature and suspended sediment concentration in the first 20 kilometres upstream from the mouth.

Forest Research Institute of Malaysia (FRIM)

The forest research institute provided data about the ecosystem in the Selangor River. This information is used as background information for the Fireflies Case described in chapter five. The Forest Research Institute of Malaysia is still involved in research for the fireflies and hopefully this report will attribute to their research.

Selangor Water Management Board (LUAS)

The Selangor Water Management Board is responsible for the water resource management in the state of Selangor, including the Selangor River Basin. LUAS controls and measures the flow at the Batang Berjuntai Barrage and provided the Management Plan for the Selangor River Basin. Real time information on the flow is provided online on “http://219.94.110.101/”.

GoogleEarth

GoogleEarth is used to visualise the study areas of this research and to compare the coordinates of digital data and land boundaries with aerial photographs.

Site Visit

A visit to the Selangor Estuary was facilitated by NAHRIM. The visit included a boat trip up and downstream the river, from the mouth to the Batang Berjuntai Barrage. During the visit photographs were taken, visual observations were noted and GPS-data were collected.

3 Tidal Flow Modelling

3.1 Introduction

The set up of a tidal model requires a good understanding of the behaviour of the tidal wave. A thorough analysis of the available data gives insight in the tidal wave but also in the reliability of the data. This knowledge in combination with the general theory of tidal waves is essential for the later stage of calibrating the model. Effects of a phase shift or an increase in bottom roughness have to be well understood in order to obtain an optimal result.

3.2 Tidal Analysis

The Admiralty Tide Table (ATT) [Admiralty, 2006] provides two types of parameters for the tidal wave. Mean values for high and low water levels are given for spring and neap conditions. And secondly, amplitudes and phases for the main four tidal constituents are provided. These data for the Malacca Strait Model are shown in respectively table 3.1 and 3.2. Both tables first list the Malaysian stations from northwest to southeast and below the Sumatran stations are listed in the same direction. The exact locations of the tidal stations are plotted in figure 2.4.

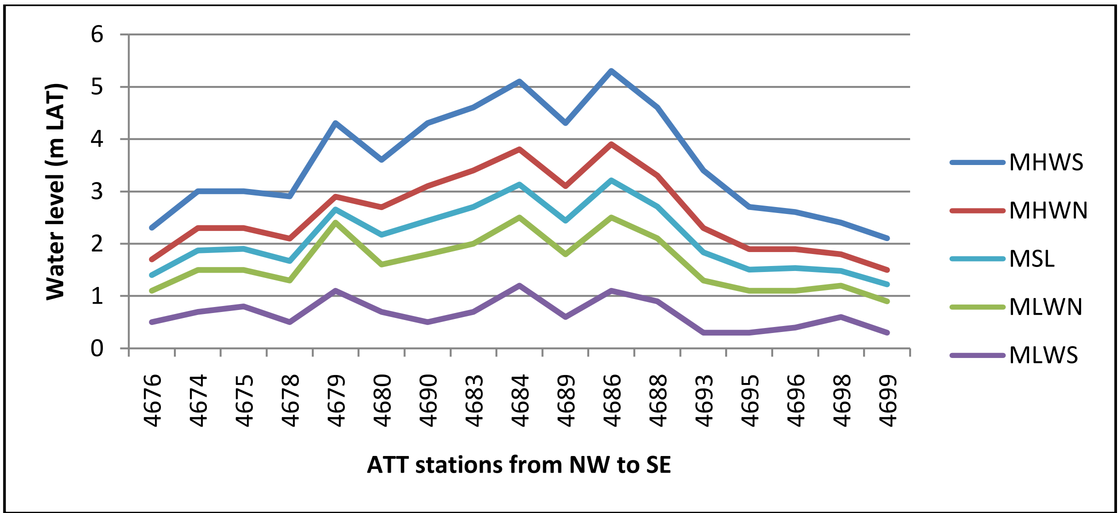

Figure 3.1 Water levels ATT Stations along the Malaysian coast.

The data of table 3.1 for the Malaysian stations is plotted in figure 3.1 and shows that the highest tidal range is found near Port Kelang (station 4686). Figure 2.4 shows that this part of the Malacca Strait not only narrows but also becomes shallower. Especially the area west of Port Kelang which is called “One fathom bank”, referring to a depth of one fathom which is about 1.8 meter. The figure also shows the exact locations of the stations. Figure 3.1 only shows the sequence of the stations from NW to SE, there is no distance at the x-axis.
The tidal wave is slowed down in the shallow water and wave energy is converted into an increased wave height. Figure 3.1 clearly shows the tidal wave height increasing until Port Kelang and further to the southeast decreasing again. Discrepancies in the line can be explained by the local conditions of a station. Intan Bay (station 4679) for example is located far upstream in a river inlet which explains the higher water levels at this location. For the analysis of the tidal wave trough the Malacca Strait such a location is not very suitable, because such local effects cannot be included in a large scale tidal model. The water levels of the stations along the coast of Sumatra are not plotted but show a similar shoaling pattern as

figure 3.1. The Selangor Estuary (station 4683) is found just before the point where the tidal range reaches its maximum.

In table 3.2 the amplitudes and phases of the four main constituents are given for the ATT stations. The constituents M2, S2, K1 and O1 are the partial tides with the highest amplitude in an equilibrium tide. This does not necessarily mean that these are also the four main constituents in the Malacca Strait, but their combined effect on the tidal wave will be dominant. Figure 3.2 shows the behaviour of the four main constituents along the Malaysian coast from the northwest to the southeast. The amplitudes of the M2 and S2 tides show a clear shoaling effect near Port Kelang which was also visible in figure 3.1. The periods of the M2 and S2 tides are in close range, respectively 12.42 and 12 hours, which make their behaviour quite similar. The phase difference between the first and the last station is for The M2 tide 125 degrees and for the S2 tide 130 degrees. This means both waves travel in 4.3 hours from the first to the last station. The distance between Lumut Pier (station 4674) and Melakka (station 4699) is about 300 kilometres, which leads to an average wave speed of 19 m/s. Wave speed of tidal waves is limited by the depth, which is expressed in the shallow-water waves equation $c = \sqrt{gd}$. Based on figure 2.4 the average depth is estimated at 50 meter, which makes the maximum wave speed 22 m/s. The propagation of the M2 and S2 tides agrees well with the simplified calculation of a shallow-water wave.

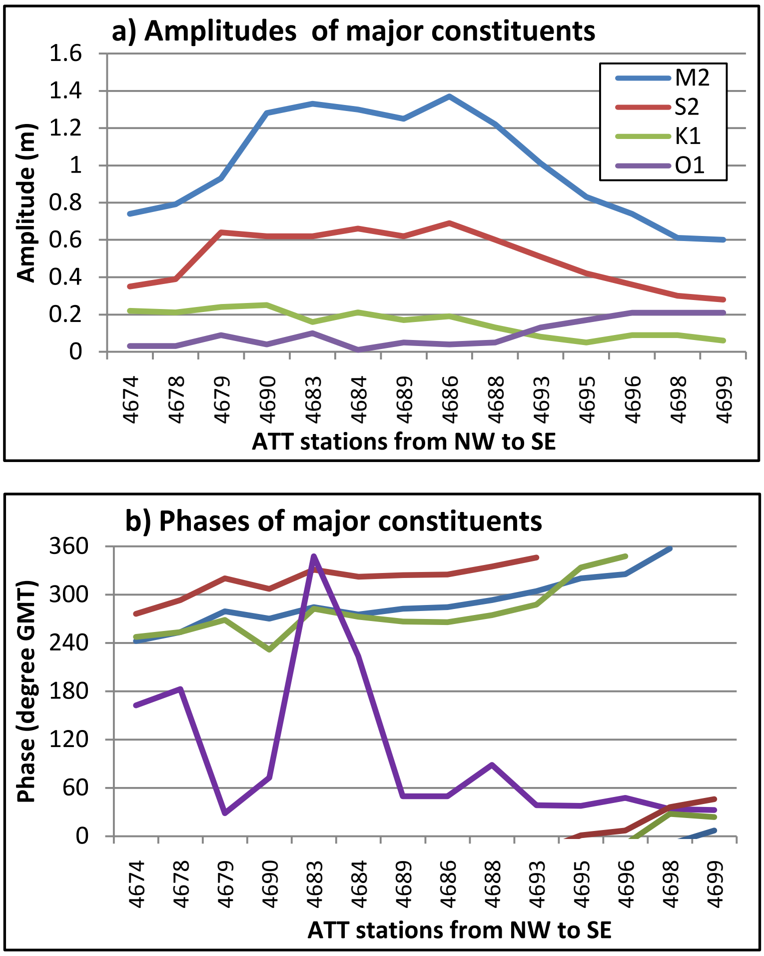

Figure 3.2 Amplitudes and phases of the main constituents

The phase difference between the first and the last station for the K1 tide is almost similar as for the M2 and S2 tide. However the period of the K1 tide is 23.93 hours. The K1 wave travels in about nine hours from the first to the last station. The wave speed of the K1 tide is only 9 m/s. This slow propagation is attributed to the bathymetry of the Malacca Strait and the wavelength of the K1 tide. The fact that the K1-wave does not propagate as a shallow water wave explains why no shoaling effect is visible in the amplitude in the shallow region near Port Kelang (figure 3.2a).

The graphs of the O1 tide indicate an amphidromic point within the selected area. The amplitudes are close to zero for the stations from Lumut Pier (station 4674) to Port Kelang (station 4686). Table 3.2 shows that for four stations along the coast of Sumatra there is no amplitude at all, which confirms the conclusion that an amphidromic point of the O1 tide is located close to these stations. The phases of the O1 tide in figure 3.2b do not show a smooth line which is probably due to the fact that the amplitudes are too small. Some of the ATT stations are non-permanent stations and the constituents are based on a short period of measurements. An analysis of a short series of data cannot produce an accurate phase when the amplitude is too close to zero. When only the phases of the standard ports are considered and stations outside the modelled area are included the direction of the tidal wave becomes clear. Along the Malaysian coastline the O1-tidal wave travels from Southeast to Northwest and along the Sumatran coastline the O1-wave travels in the opposite direction. This confirms the existence of an anticlockwise amphidromic system for the O1-tide in the Malacca Strait. This direction is in line with the expected direction for amphidromic systems in the Northern Hemispere. The Coriolis force causes tidal waves of amphidromic systems in general to rotate anticlockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere [Wright, 1999].

The M2, S2 and K1 constituents travel all from the north-west to the south-east as can be seen by the phases in figure 3.2. This means the top of the tidal wave (i.e. High Water) enters the Strait at the Northwestern boundary and propagates in Southeastern direction. High water conditions in Port Kelang (station 4686) will be a few hours later than in Lumut Pier (station 4674).

Examination of the data also provides an indication of the reliability of the data. As mentioned before tidal analyses are more reliable when a long period of preferably several years are analysed. Moreover, local conditions, such as waves and ship manoeuvring and quality of the equipment influence the outcome of an analysis. In the preceding text the conclusion was made that because of the low amplitude, not all phases of the O1-tidal wave can be considered reliable. A sifting between reliable and unreliable data is difficult but in general the standard ports are more reliable. Table 3.2 shows that the phases of the M2-wave in Selangor River (station 4683) and Port Kelang (station 4686) are exactly the same. This means that the top of the M2-wave reaches these stations at the same time. The locations of both stations can be seen in figure 2.4, the distance between the stations as the crow flies is 35 kilometres. The average speed of the M2-wave is around 70 km/h, in the shallow area near Port Kelang even lower. In spite of the fact that Selangor River is located upstream in a river, the top of the M2-wave can never reach both stations at the same time. This leads to the conclusion that these phases cannot be correct. In this case the phase of Port Kelang, a permanent water level station in a world harbor, will be closest to the real value. More examples can be found in the table, this example is singled out to show that the data should be interpreted with caution.

For three stations water level data for several years are provided online by the University of Hawaii. These stations are all located on the Malaysian side of the Malacca Strait and are shown in figure 2.4. The same locations are mentioned in the ATT-table as numbers 4674, 4686 and 4698. For each of the stations a three year period with uninterrupted measurements was selected for a tidal analysis. The water levels are analysed with DELFT3D-TIDE and additionally checked with the Matlab-based Tidemat. The results of both packages differed at most one tenth percent of the amplitude. The data are analysed for a set of 66 components. This set included all harmonic constituents which could possibly make a significant contribution to the tidal wave. The observed water levels, the hindcast of the analysis and the residue are plotted for an arbitrary period (the first five days of the second year) in figure 3.3. Note that the scale of the y-axis differs for each subplot. The average absolute value of the residues divided by the sum of the amplitudes of all constituents is less than three percent for each analysis. Examination of the residue did not show any pattern which could indicate that an important constituent was missed. The residue is attributed to local disturbance of the water level by for example meteorological conditions.

Table 3.3 and figure 3.4 show the results of the analyses. The constituents are sorted by the amplitudes at station Lumut Pier and constituents with amplitudes less than four millimetres

are not shown. For the selection of relevant constituents for the Malacca Strait Model, Lumut Pier is the most suitable station. It is located close to the boundary where the tidal wave enters the model and close to deep water which is representative for the boundary. As mentioned before the shallowing of the Malacca Strait generates an increase in amplitude of the tidal constituents. Other effects in shallow water are the development of overtides and compound tides. This is very well visible in figure 3.4. The station Port Kelang shows high amplitudes for the overtides M4 and M6 and for the compound tides 2MS6 and MS4. These constituents are assumed to be negligible at the boundaries, where the average waterdepth is around 60 meters. The overtides and compound tides will not be included in the boundary conditions of the Malacca Strait Model but will be generated by the Delft3D flow model in shallow areas.
Figure 3.4 also shows the dominance of the M2 and S2 tides. Tides can be classified according to the ratio (F) of the sum of the amplitudes of the two main diurnal constituents (K1 and O1) to the sum of the amplitudes of the two main semi-diurnal constituents (M2 and S2) [Wright, 1999]. For Lumut, Kelang and Keling this ratio is respectively 0.23, 0.11 and 0.33. These low values imply a semi-diurnal tide in this area of the Malacca Strait. This means high water and low water will both occur twice each day.

In figure 3.4 is also indicated which constituents are included in the boundary of the Malacca Strait Model. Besides the overtides and compound tides only the S1 and the LABDA2 are not included. These tides have amplitudes of respectively between 2.4 and 3.8 centimetres and between 1.1 and 3.1 centimetres. For these constituents is no additional data available for calibration except the analyses of these three stations. Because of the relatively small amplitudes, these two constituents are excluded from the boundary conditions.

The accuracy of a tidal analysis depends on the time span over which water level data has been collected. When the period of data is too short, constituents with comparable frequencies cannot be resolved properly. The lower limit is determined by the Rayleigh criterion. For the analysis of a three year period this is not an issue. However model simulations cover usually a shorter period in order to reduce calculation times. For tidal flow models a simulated period of 33 days is standard. The Rayleigh criterion for this period is:

$$\Delta\varpi = \frac{360^\circ}{T} = \frac{360^\circ}{33\,days * 24\,hours} = 0.455$$

When the difference of the frequencies of two tidal constituents is less than the criterion, tidal analysis software, like TIDE and TRIANA, is not capable of resolving the constituents properly. Table 3.4 shows which constituents do not fulfil the Rayleigh criterion. This problem can be overcome by coupling these constituents. For a relative small area as the Malacca Strait model the relation between constituents is almost uniform. When the difference in amplitude and phase is known these constituents can be resolved by TRIANA. Condition is that one of these constituents has a significantly larger amplitude than the other. In table 3.4 the main constituents, the coupled constituents and their relations are given. Coupling relations are obtained by averaging the relations for the three UHSLC-stations, for five locations of the satellite based model and for the equilibrium tide [WL | Delft Hydraulics, 2006g]. These three different methods show for most constituents similar results. However for the long-period components (SA, SSA and MSM) the analysis of UHSLC-data showed significantly different results. Moreover the amplitude of the SA component is the largest while the satellite data indicate the SSA component as the largest, main component. The coupling relations of the satellite data are assumed to be the most representative for the whole Malacca Strait Model and will be used for the tidal analysis of model simulations with TRIANA. The coupling relations of the UHSLC stations showed quite some variety which points out the disadvantage of the method. The coupling relations for the amplitudes between P1 and K1 for example is 0.36, 0.39 and 0.31 for respectively Lumut, Kelang and Keling. This indicates that the assumption of one coupling relation for the whole area is not fully correct. The absence of an alternative impels to the acceptance of this inaccuracy. Increasing the simulation time to avoid coupling would cause a too big delay for this research.

Another condition for a reliable tidal analysis is a correct measurement interval. The requirement is that the measurement interval (Δt) is at most half the smallest wave period (T_{min}) present in the signal. This is called the Nyquist criterion [WL | Delft Hydraulics, 2006g]. The smallest wave period of the 66 constituents applied to the UHSLC data is the 2(MS)N10 constituent with a wave period of 2.46 hours. The interval of the UHSLC data is one hour so the Nyquist condition is fulfilled. For the analyses of the model simulations the critical constituent is K2 with a wave period of nearly 12 hours. The minimum interval should be 6 hours which is by far more than the usual range for storage of water level data in Delft3D.

3.3 Malaysia Overall Model

The large-scale flow model of the Malaysian waters was provided by Alkyon as the basis for this study. For this study the model and accompanying report was analysed before the model was applied to generate boundary conditions. The Malaysia Overall Model simulates the 2D water flow for all coastal regions of Malaysia. The model covers the Malacca Strait, the Gulf of Thailand and large parts of the South China Sea. A curvilinear grid was generated which has proven to give the best results as grid cells are directed in the same direction as the predominating flow. Grid sizes vary from 200 m in shallow regions to 11 km in the deeper waters [Chiru, 2007]. Near the Selangor Estuary grid cells are 2 by 4 kilometres. The coordinates of the grid are spherical with geodetic datum WGS84. This means the coordinates are saved as latitudes and longitudes.

The tidal movement of the water mass is forced in two ways. First along the open boundaries of the model the water level is forced by astronomical constituents. These constituents were derived from the global ocean tide model of Matsumoto. 16 short-period tidal constituents (Q1, O1, M1, P1, K1, J1, OO1, 2N2, MU2, N2, NU2, M2, L2, T2, S2 and K2) and seven long-period tidal constituents (MTM, MF, MSF, MM, MSM, SSA and SA) were used. The second way to force the water flow is by implementing tidal forces. For large scale tidal models only the boundaries are not sufficient to force the water movement. The tractive forces of moon and sun have to be included to obtain a reliable simulation. In the overall model four semi-diurnal (M2, S2, N2, K2), four diurnal (K1, O1, P1, Q1) and three long period (MF, MM, SSA) modes are included.

The model was calibrated only for the four main constituents (M2, S2, K1, O1) based on the values of ATT-stations. The other constituents have smaller amplitudes and were not included in the calibration process. More than 60 simulations were carried out by changing the boundary conditions, bed roughness and by improving the bathymetry locally. The calibration was based on plots of measured and calculated amplitudes and phases. Unfortunately the adjustments are not explicitly mentioned in the report [Chiru, 2007]. The adjustments to the bathymetry and to the boundary conditions cannot be reproduced. The final roughness of the Malaysia Overall Model is represented by a Manning value of 0.015 m. This value corresponds with a Nikuradse roughness height of 0.003 m. This value indicates a very smooth bottom, comparable with unfinished concrete. [Ribberink, 2003]. Considering the water depths in the Malacca Strait the Chézy value will vary between 90 and 100 $m^{1/2}/s$. For a real sea bottom these values are not really representative. For a seabed with sediment transport Nikuradse roughness heights are usually in the order of 0.05 and 0.1 m. However, in a tidal flow model the roughness is often adjusted to improve the output of the model. The final value will not always represent the reality but can be out of range to compensate for other errors.

A major flaw in the Malaysia Overall Model was the setting of the time step. In order to simulate the water flow with the highest accuracy, a suitable time step can be calculated based on grid size and water depth. The accuracy of a model can be checked by running the model with a smaller time step and compare this run with the original model. When model results are the same for both runs the time step was well chosen. However this appeared to be not the case for the overall model. The original time step of 10 minutes appeared to be too large. The result of this mistake was that the model calibration was based on an inaccurate model. Adjustment of the time step in the calibrated model will not necessarily improve the output of the model. The solution would be to restart the calibration process from scratch. This was not an option within the time limit of this study. Because the validation figures of the Malaysia Overall Model showed acceptable results the model is still applied to generate boundary conditions for the Malacca Strait Model. In figure 3.11 the validation of the Malaysia Overall Model for Port Kelang is included which grounds this decision.

The model was calibrated and validated with a simulation of 35 days from 1 October 2006 till 5 November 2006. With two days to eliminate start-up effects an effective period of 33 days was generated to perform the tidal analyses. Along the open boundaries of the Malacca Strait Model observation points were created. For these points the water levels were stored in a file during the simulation. After the simulation these data can be converted into astronomical constituents again with the program TRIANA. The 21 tidal constituents which are included in these analyses are shown in table 3.3. Table 3.4 shows the coupling relations which are needed to analyse a limited period of 33 days. The result of the tidal analyses can serve as boundary conditions for the Malacca Strait Model.

3.4 First Nested Model: Malacca Strait Model

Earlier attempts have been made to create a numerical flow model of the tidal wave in the Malacca Strait. However these researches were restricted to only the M2 partial tide [Rizal et al., 1994; Rizal, 2000]. For this study all relevant partial tides are included in the tidal flow model.

3.4.1 Model Set-up

Grid generation

The grid for the Malacca Strait Model was created by selecting an appropriate part of the Malaysia Overall Model. This part of the grid is refined to generate the new grid. The advantage of using the Malaysia Overall grid is that the boundaries and observation points of the new Malacca Strait grid fit exactly in the original grid. This simplifies the process of deriving boundary conditions and comparing model results. An appropriate area for the Malacca Strait Model was selected by three criteria.

- A width-length ratio of 0.5 or less, in order to create sufficient length for the tidal wave to propagate and make calibration possible for several stations along the coast. When the distance between boundaries becomes too small, the boundary conditions dominate the flow. The influence of bathymetry, roughness and other flow parameters will only become significant when the boundaries are located far enough from each other.
- The project location should be located in the centre of the model as to avoid boundary conditions to become dominant for the area of interest.

- The new boundaries should not cross islands or be situated close to islands. The large number of islands in the southern part of the Malacca Strait complicates the selection of a suitable area.

The chosen region is shown in figure 2.2, the area covers 5579 cells of the total number of 108341 cells of the overall model, about 1/20th. Of this new grid 620 cells are located on the main land of Malaysia and Sumatra and these grid cells are made inactive to save calculation time. The following step is to refine the grid within the limitation of an acceptable calculation time. A refinement of the grid in both directions will multiply the total number of grid cells with the square of this refinement factor. Refinement of the grid also requires an adaptation of the used time step. The accuracy of the model is, amongst several other parameters, dependent on the Courant number (Cr), defined by:

$$Cr = \frac{\Delta t * \sqrt{gH}}{\{\Delta x, \Delta y\}}$$

In which:

Δt	=	time step [s]
$\sqrt{gH}$	=	square root of the water depth times the gravitational constant [m/s]
	=	wave speed in shallow water [m/s]
$\{\Delta x, \Delta y\}$	=	a characteristic value (in many cases the minimal value) of the grid spacing in either direction [m]

Courant numbers should not exceed a value of ten, seven is recommended [WL | Hydraulics, 2006c]. An equal refinement factor for both gird directions will divide the {Δx,Δy} value by this refinement factor. To maintain a correct Courant number the time step should be divided by the refinement factor as well. If the simulated period remains the same, the total time steps will be multiplied by the refinement factor as well. The total effect of a grid refinement will be the refinement factor to the power three. A refinement with a factor 2 will increase the calculation time by a factor 8, a refinement with a factor 3 will increase the calculation time by a factor 27. Moreover, in this case the time step of the overall model was chosen too large so the time step should be divided by an even bigger factor than the refinement factor. When the grid is refined by a factor three the time step has to be refined with a factor 10 to keep the Courant Number below a value of ten. The time step will be reduced from 10 minutes in the Malaysia Overall Model to one minute in the Malacca Strait Model. The resulting calculation time for a refinement factor three is calculated by the following calculations:

The calculation time of a 2-dimensional Delft3D model is defined as:

$$\frac{Number\ \ of\ \ grid\ \ cells\,(-) * time\ \ steps\,(-) * processor\ \ speed\,(\text{calculations}\ \ /\text{sec})}{3600\ sec/hour} = calculation\ time\ (hours)$$

For the overall model this becomes:

$$\frac{108341 * 5040 * 2.9E{-}5}{3600} = 4.48\ hours$$

For a nested model refined by a factor three and with a timestep of one minute this becomes:

$$\frac{(5579-620) * 3^2 * 5040 * ({}^{10}/{}_{1}) * 2.9E{-}5}{3600} = 18.12\ hours$$

This is a bit longer than the desired one night calculation time but in reality it turned out that most computers were capable of finishing a simulation within 14 hours. The above calculation of simulation time is only a rough indication. In reality more factors are involved like computer memory and model setup.

Bathymetry

The bathymetry of the Malacca Strait was based on six Admiralty Charts of the region. Figure 2.2 shows the areas for which digital Admiralty Charts were available. Two main Charts cover the whole area, and four, more detailed charts cover smaller areas in the vicinity of the Kuala Selangor river mouth. To implement the bathymetry as accurate as possible, all six charts are used to implement the depth in the model. In the areas where the depth data was denser than the grid cells, the technique of grid cell averaging was applied. In areas with several depth data per grid cell, the technique of triangular interpolation was applied. For most of the model the density of grid cells was higher than the density of depth data and triangular interpolation had to be applied. The created bathymetry was checked by comparing the model with the Chart as shown in figure 3.9 for the Northern Approach Model. For some areas the Admiralty Charts did not supply depths and a most likely bathymetry was created manually. This was done for the channel behind the island in the south and the area halfway the Sumatra coast where a very wide river flows into the Malacca Strait. A final processing had to be made to correct the different reference levels of the model and the charts. The depths in the Admiralty Charts are in reference to the Lowest Astronomical Tide (LAT) while the most convenient reference level in Delft3D is Mean Sea Level (MSL). The difference between LAT and MSL varies in the area between 1.5 and 3 meter according to the data of the Admiralty [Admiralty, 2006]. The highest differences are found at stations with large tidal ranges, which was shown in figure 3.2a. To correct the bathymetry as accurate as possible these differences were also mapped via triangular interpolation and this map was added to the existing bathymetry.

Boundaries

The Malacca Strait Model has two open boundaries, in the northwest and in the southeast. Both boundaries are drawn perpendicular to the predominant flow direction. The northwest boundary is approximately 170 kilometres long and the southeast boundary 80 kilometres. To enable the implementation of amplitude and phase difference along the boundary, the boundaries are divided into sections. The northwest boundary is divided in five sections. The southeast boundary is assumed to be influenced by the close proximity of the island and is divided in six sections to be able to implement local differences. The initial boundary conditions are derived from the Malaysia Overall Model.

Initial Parameter settings

The Malacca Strait Model is a 2-dimensional flow model. This implies the assumption that stratification is negligible. Some stratification is observed in the northern part of the strait but the effect on the depth averaged flow velocities and water levels is assumed to be close to zero. With the average temperature and salinity level in the Malacca Strait the average water density can be calculated. With an average temperature of 29.6° Celsius and a salinity level of 31.2 ppt the density will be 1019.6 kg/m^3 according to the most recent density-equation [Sun, 2007].

The bottom roughness of the Strait is a more complicated parameter. The big share of mud in the bottom indicates a smooth bottom. On the other hand the existence of sandwaves in the narrow part of the strait indicates a higher roughness. The characteristics of these sandwaves differ slightly in various sources: wavelengths of 241 to 900 meter and wave heights from 4.6 to 15.3 meter [Keller, 1967], wavelengths 250 to 450 meter and wave heights from 4 to 7 meter [Wyrtki, 1961] and wave heights 13 meters [Admiralty, 2003b]. De length of the grid cells in the area of the sandwaves is between 1 and 1.4 kilometres. The sandwaves are too small to be included in the bathymetry. Unfortunately too little information exists to form a field of roughness coefficients for the area. Initially a uniform value is applied which also has the advantage that this value can easily be adjusted in the calibration process. Rizal and Sündermann (1994) derived a depth dependent function for the Chézy-coefficient which showed good results for their M2-model of the Malacca Strait:

$C = 62.64$	$[m^{1/2}/s]$	for	$H_b \leq 40m$
$C = 62.64 + (H_b - 40)$	$[m^{1/2}/s]$	for	$40m < H_b \leq 65m$
$C = 87.64$	$[m^{1/2}/s]$	for	$65m < H_b$

The bottom roughness of a model for one partial tide will not give similar results for a model including all relevant constituents. Depending on the share of a constituent the bottom friction has to be increased for a single partial tide model to obtain the same results as for a model with all relevant constituents (Amin and Flather, 1996). This is caused by the fact that shear stress at the bed is not a linear function of the flow velocity. For the Malacca Strait Model the bottom roughness is implemented with the White-Colebrook formulation. This formula uses the Nikuradse roughness height to calculate the Chézy value. This latter is part of the shear stress formula within Delft3D:

$$C = 18 \cdot {}^{10}\log\left(\frac{12 \cdot H}{k_s}\right)$$

In which:
C = Chézy value
H = Water depth
K_s = Nikuradse Rouhness Height

The shear stress at the bed is calculated by:

$$\vec{\tau_b} = \frac{\rho_0\, g \vec{U} \left|\vec{U}\right|}{C^2}$$

In which:
τ_b = Shear stress
ρ_0 = Water density
U = Flow velocity

The value of the Nikuradse height increases for a rougher bottom, Chézy values on the other hand are an indicator for the smoothness of the bottom. The advantage of the White-Colebrook formula is the inclusion of the water depth in the formula, which is assumed to be more accurate than a uniform Chézy value. The initial setting for the Nikuradse roughness height is 0.018 meter. This roughness is considered to be able to include the effects of the sand waves in the area. Figure 3.5 shows the bottom roughness of the Malaysia Overall Model, the model of Rizal & Sündermann and the Malacca Strait Model.

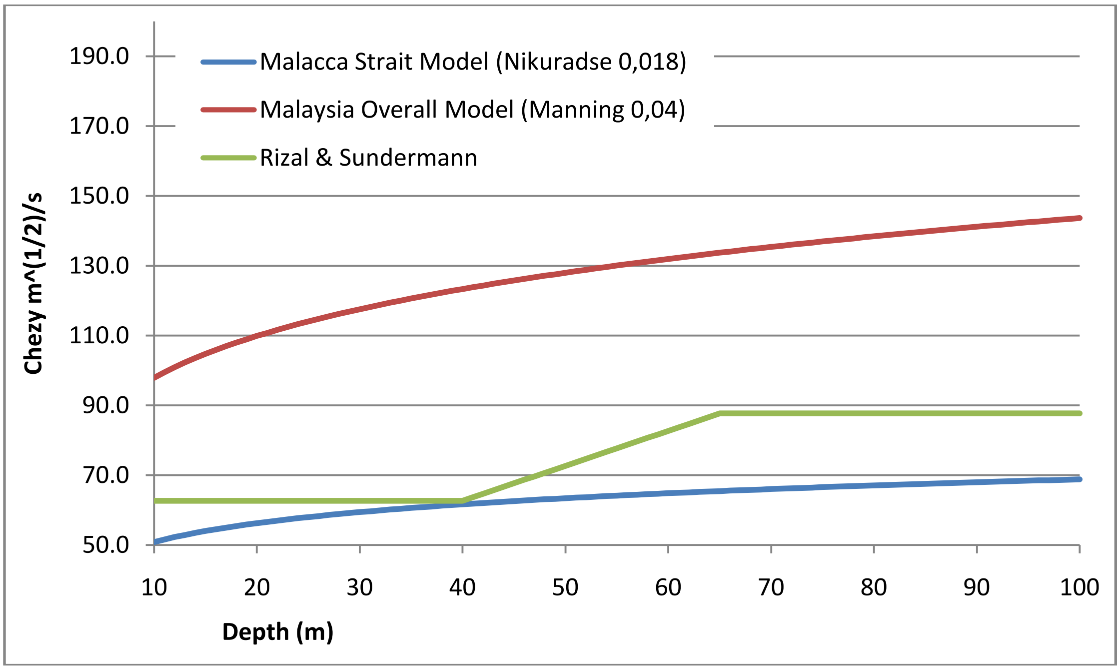

Figure 3.5: Bottom roughness values for various models

The time frame is set equal to the Malaysia Overall Model. This means a simulation time of 35 days with a start-up time of two days and 33 days of reliable output. The first five hours of the simulation the water levels are slowly raised from zero to their actual values according to the boundary conditions. This avoids unwanted effects in the initial stage and favours the fast development of stable conditions.

As mentioned in chapter 1.3.1 a predominant north-westerly current flows through the Malacca Strait, besides the semi-diurnal tidal flow. This current is implemented in the model by the long term constituents SA and SSA and the average water level at both boundaries. The SA and SSA constituent have periods of respectively 365.24 and 182.62 days. These periods coincides exactly with one year and half a year, when intercalary years are taken into account. The difference in water level at the southern and northern boundaries, combined with the SA and SSA constituents, will simulate the seasonal changes in the current.

3.4.2 Calibration

A model which is forced by tidal constituents can only be calibrated by comparing these same constituents. A comparison of time series of water level or flow velocity data with the model output can provide information on the accuracy of the model but it is almost impossible to determine which boundary or parameter has to be adjusted and in what way. The water movement in the Malacca Strait behaves in general as a shallow water wave and to calibrate the model the properties of the calculated wave have to be compared with the known properties of the tidal wave from water level stations and the satellite model. The subsequent adjustments to the boundaries and flow parameters request a lot of insight in the behaviour of the tidal wave in the Malacca Strait. In the Delft3D model the boundaries are forced on two sides of the channel. This implies that the amplitude and phase for every partial tide is fixed on both sides and that this partial tide has to propagate trough the strait within these limits. The performance of the model depends on two factors:

1. The determination of the boundary conditions on each side of the model.
2. The parameters which control the propagation of the wave within the model.

To obtain the best model results both factors have to be optimised. The tidal model includes 21 tidal constituents which all affect the water levels and flow velocities. Accurate calibration can only be carried out if the behaviour of each of the individual tidal waves is analysed. For the locations of the ATT-stations and the satellite data (figure 2.4) observation points are added in the Malacca Strait Model. For these points the water levels are saved and can be converted into tidal constituents with the TRIANA software. The output of the TRIANA-analysis can be compared with the known constituents of the ATT-stations and the satellite model. This will lead to a result which gives insight in the propagation and shoaling of each component of the tidal wave. The theory of the behaviour of tidal waves is well-known and based on the results the boundary conditions and parameters can be adjusted to fit the calculated tidal wave with the measured tidal constituents. However it remains a difficult and time-consuming process to get a perfect fit of the model. The strategy used in this research was to start by adjusting the boundary conditions to fit the measured constituents. Secondly the flow-parameters within the model were adjusted to improve the results.

The model is calibrated with the data from the ATT-table and from the satellite-model. However a sorting has been made in these data. Some of the tidal stations are located upstream in river inlets and behind islands where the tidal wave is influenced considerably by local and shallow water effects. The Malacca Strait Model is not capable of simulating these local effects so these stations are not included. The satellite model is known to be less accurate in shallow areas so only locations in relatively deep water are included. Figure 3.6 shows the elected stations.

Fitting the Boundary Conditions

The Malacca Strait Model has two open boundaries where the water level is enforced by astronomical constituents. Each of these constituents consists of an amplitude and a phase. The tidal wave has to propagate within the limits of these boundaries. This means that for every partial tide the phase difference between the two boundaries is fixed and the top of each wave has to travel from one boundary to the other within the enforced time. The same is applicable for the amplitudes of the partial wave. Because of the length-width ratio of the model area, the propagation of the tidal wave in the middle part will be controlled by the bathymetry and the flow parameters. The first step of the calibration was to optimise the boundary conditions. This process is described in Appendix A.

The results of the simulation with optimised boundary conditions was visualised to interpret the results. Visualised values are the calculated phase minus the observed phase (Gc-Go) and the calculated amplitude divided by the observed amplitude (Hc/Ho). Figures 3.7a and 3.7b show the results of a simulation with optimised boundary conditions in the plots on top. Too clarify the effects the results are shown in patches according to the closest observation point. Two values are added in the figures: the mean of all stations and the root mean square error (r.m.s. error). The r.m.s. error (also known as standard deviation) is a statistical term to express the difference between the observed and calculated values.

The figures with the deviation for the amplitude (Hc/Ho) indicate if the shoaling of the tidal waves is simulated correctly. A too high amplitude is represented by red patches, a too low amplitude with blue patches. Figure 3.7a (top) shows that the initial parameter settings resulted in an overestimation of the shoaling effect in the middle of the Malacca Strait Model.

The figures with the deviation for the phase (Gc-Go) indicate if the propagation of the wave is correct. The red patches indicate that the calculated phase is higher, which means that in the model the top of the wave arrives too late. Blue patches indicate the top of the wave arriving too early. Figure 3.7a (top) shows that the color patches changes from blue to red in the southeastern direction, this means the propagation of the tidal wave is slower than the observed tidal wave. Near the southeastern boundary the tidal wave increases in speed. This is ascribed to the boundary condition which is enforced and causes this acceleration. Because the direction of the M2 wave is from northwest to southeast the model set-up underestimates the propagation of the flow. Near the southeast boundary the tidal wave is controlled by the boundary conditions rather than by the flow parameters.

Adjusting the flow parameters

The first calibration step resulted in the conclusion that the model overestimated the shoaling effect and underestimated the propagation of the tidal wave. In this second step the flow parameters will be adjusted to optimise the model. This is done by an inventory of the relevant parameters and their influence on the tidal wave. These influences are analysed by plotting the Hc/Ho and Gc-Go for the initial and changed parameters for the main partial tides. In this report only figures of the M2 wave are shown. This partial tide is the most important and propagates as a shallow water wave as shown in paragraph 3.2. Some parameters, like the water density, are not included in the calibration process as the initial parameter setting is supposed to be the most accurate approximation. The included parameters are:

- **Roughness** As mentioned before the roughness in the area of the Malacca Strait Model is one of the uncertain factors. The method to implement the roughness will continue to be White-Colebrook as this is generally accepted as the most accurate possibility within Delft3D. To estimate the effect of the roughness on the tidal wave two simulations were run with different Nikuradse roughness coefficients (k_s), ceteris paribus. The result of these runs for the M2 wave is plotted in figures 3.7a and 3.7b. This figure shows that the effect of an increased roughness is that the shoaling effect declines and that the propagation of the tidal wave is slowed down. These results are in accordance with the theory. An increased roughness will cause more energy dissipation at the bottom so less energy can be converted into height energy. The flow velocities will be lower with an increased roughness which explains the decrease in wave speed.

- **Bathymetry** The implementation of the data of the Admiralty Charts has been done with great accuracy. Nevertheless the bathymetry of the model can differ from the reality because the data from the Admiralty Charts is not correct. As mentioned in chapter two the Admiralty is inclined to underestimate depths because of the navigational purposes of the charts. The conclusion that the tidal wave propagates too slow, indicates that the bottom of the Malacca Strait Model indeed is too high. The propagation of the tidal wave is determined by $c = \sqrt{gd}$ so a bed level lowering will increase the depth and consequently the wave speed. To estimate the effect a simulation with a uniform bed level lowering of two meters was run, ceteris paribus. The result of this lowering is compared with the initial simulation in figures 3.8a and 3.8b. Figure 3.8b shows a clear acceleration of the M2 wave as expected. Figure 3.8a shows that the shoaling pattern is almost similar as for the initial bathymetry.
- **Horizontal eddy viscosity** The value for the horizontal eddy viscosity (HEV) depends on the flow and the grid size used in the simulation. For detailed models (grid sizes of several tens of meters or less) the value for HEV ranges from 1 to 10 and for large (tidal) models (grid sizes of hundreds of metres or more) this value ranges from 10 to 100 m^2/s. The optimal value of this parameter for a specific model has to be determined in the calibration process [FLOW, 2006]. The nested model was run with a value of 1 and 10, ceteris paribus. The parameter appeared to have an insignificant effect on the water levels in the model. The horizontal eddy viscosity is assumed to be of more importance for small scale models where effects of eddies are more significant. In the calibration process of the nested models this value is kept constant at a value of 10.

The results of the initial parameter settings indicated an overestimation of the shoaling effect. To eliminate this effect in the model the roughness could be increased. A uniform depth increase would not affect the shoaling significantly. However when the bottom is lowered only in the middle part of the model the shoaling effect will diminish. The results of the initial parameter setting also indicated an underestimation of the propagation of the tidal wave. This effect can be eliminated by a decrease in the roughness or by a bed level lowering.

As shown here the results of the model with the initial conditions could indicate both an increase and a decrease of the roughness. The bed level lowering on the other hand only has a positive effect on the propagation of the tidal wave trough the model. The calibration process is continued by fitting the boundary conditions for the model with the uniform lowered bed. This resulted in an almost perfect fit of the propagation of the tidal wave.

3.5 Second Nested Model: Northern Approach Model

The approach for the Northern Approach Model resembles in many ways the Malacca Strait Model. The model is also a 2-dimensional tidal flow model forced by astronomical constituents. This second nested model was needed in order to obtain a sufficient level of refinement along the boundaries of the Selangor Estuary. The model covers the Northern Approach to Port Kelang and also covers the harbor area completely. The explanation in this chapter will focus on the differences in the set-up and calibration of the model.

Grid generation

The grid for the Northern Approach Model is based on the Malacca Strait Model. An area was selected which included the islands and the shallows north-westerly of Port Kelang. The objective was to avoid boundaries crossing the islands or the shallows. The selected area is shown in figure 3.6 by the yellow line. A refinement factor of four is applied in the direction parallel to the coast and a refinement factor three is applied in the direction perpendicular to the coastline. Different factors were applied to create a grid with width-length ratio closer to one. The created grid cells measure about 350 by 250 meters in the coastal zone near Selangor.

Bathymetry

For the bathymetry of the Northern Approach Model more detailed Admiralty Charts are available as shown in figure 2.2. Additionally these maps are based on more recent, and probably more accurate, depth measurements. The better monitoring of the area is probably related to the location of Port Kelang. The implementation of the depth data could be done with the averaging technique for most of the area. The created bathymetry is compared with the original Admiralty Chart in figure 3.9. The shown bathymetry is before the LAT-MSL correction.

Boundaries

The north-western boundary is split in three sections, the south-western boundary in six sections and the south-eastern boundary is one section. The boundary conditions for the Northern Approach Model are derived from the Malacca Strait Model. The approach is almost similar as used for the Malacca Strait Model. However the boundaries of the Northern Approach Model are located in more shallow water than the Malacca Strait Model. For these boundaries the shallow water effects can no longer be neglected. Fourteen overtides and compound tides with an amplitude higher than one centimetre in Port Kelang are included in the boundary conditions. They are derived from the tidal analysis of the results of the Malacca Strait Model. Because they were not included in the boundaries of the Malacca Strait Model, they are fully generated by this model as a result of shallow water effects on the main partial tides. A total of 35 constituent are imposed at the boundary of the Northern Approach Model. It should be noted that the boundary conditions for the Northern Approach Model are not derived from the best performing Malacca Strait Model. As mentioned before the developed calibration technique is time-consuming and progress of the project was given priority, rather than the slight advantage of a fully optimised Malacca Strait Model.

Calibration

The Northern Approach Model only includes four ATT stations and no satellite model locations. The propagation and shoaling of the tidal wave is more difficult to compare with this limited number of stations. Because the Malacca Strait Model was already calibrated the Northern Approach Model showed initially good results. Only slight manual adjustments of the amplitudes and phases of the three main constituents (M2, S2, K1) were applied. The principal diurnal lunar component (O1) was not included as this amplitude is insignificant and the ATT values for the phase of the O1 show a strange pattern, which could not be recreated in the model. This is probably due to inaccurate tidal analyses because the low amplitude of the O1 wave. For the three main constituents the deviations between calculated and observed amplitudes and phases are plotted in figures 3.10a till 3.10f. The color patches in the figure are based on the nearest station. Only four stations are located in the area, which are indicated by the squares. Note that scales differ for each constituent. A value of 1.02 for the deviation of the amplitude means the calculated amplitude is 2 percent higher than the observed amplitude. A value of 6 degrees for the deviation of the phase means the top of the calculated wave will reach the observation too early. The time related to the phase lag differs for each constituent, depending on the angular frequency. For the M2 wave a phase lag of 6 degrees corresponds to:

$$\frac{6°}{28.9841 \, °/_{hour}} * 60 \, {}^{min}/_{hour} = 12.4 \, minutes$$

For the K1 wave the same phase lag corresponds to:

$$\frac{6°}{15.0411 \, °/_{hour}} * 60 \, {}^{min}/_{hour} = 23.9 \, minutes$$

The overtides and compound tides were calibrated by a comparison with the results of the tidal analysis of the Port Kelang water levels. Based on this comparison the amplitude and phases at the boundaries were adjusted.

3.6 Validation

Both models are validated with the hindcast of the water levels at Port Kelang. This hindcast is generated by the tidal analysis of the UHSLC water level data, as explained in paragraph 3.2. The advantage of the hindcast over the real water level data is that the influence of the weather, ship manoeuvring and other disturbances are filtered out. The comparison is purely the tidal wave as generated by the model and observed in the station. The hindcast includes all 66 constituent. All three tidal models, the Malaysia Overall Model, the Malacca Strait Model and the Northern Approach Model, are compared with the hindcast. Figure 3.11 shows the predicted water levels of the various models and the hindcast for one spring-neap cycle, for neap tide and for spring tide. As expected the level of accuracy is the lowest for the Malaysia Overall Model and the highest for the Northern Approach Model. For all three models should be noted that the location of the Port Kelang station behind islands is not an ideal reference. Water level data of location further offshore would probably give better results.

A second validation was carried out for the Selangor Estuary. For the period of just over a month, water levels were monitored about eight kilometres upstream in the Selangor River. These water levels are compared with a prediction of the Northern Approach Model. The observation point in the Northern Approach Model could not be located upstream in the river but was situated close to the mouth of the Selangor. The results are plotted in figure 3.12. The measured water levels include non-tidal effects. For example in the second plot the water level seems to have a lower limit, which is probably due to some failure of the measurement device. River discharge and weather conditions are also considered import factors to affect the waterlevel. However in general the figure shows good results for the Northern Approach Model. This means the model is suitable to generate accurate boundary conditions for the Selangor Estuary Model.

A final validation of the Northern Approach Model was done for the flow velocities. Admiralty Chart 2139 contains flow velocities for both spring and neap conditions for a location near the Selangor Estuary and shown in figure 3.6 as a yellow diamond with the letter A inside. The data stems from the British Navy in the World War Two. The flow velocities are given for each hour from six hours before high water in Port Kelang till six hours after high water. Both direction and magnitude are included, flow directions are assumed to be similar for spring and neap conditions. The results for both neap and spring are compared with the model results in figure 3.13a and 3.13b. The figures are both based on the same data and differ in the presentation. In figure 3.13a the data is represented by vectors and in 3.13b the magnitude and direction are compared separately. The calculated flow velocity is depth average can be assumed to be lower than the surface flow velocity measured by the British. Considered the fact that the data are sixty years old, they agree pretty well with the model results.

3.7 Results and discussion

The final results of first nested model are shown in figures 3.14a till 3.14h. For each of the tidal constituents the amplitude is shown compared to the ATT-values and the satellite data. The same is done for the phases of each of the main constituents. The field of amplitudes and phases in the figures is generated by an online fourier analysis of each of the grid cells. The condition of this analysis is that only one constituent at a time can be analysed accurately. The boundaries have to be forced with only one constituent as well. The result will be that flow velocities will be lower than in the model with all constituents. The energy loss of the tidal wave due to bottom friction is not a linear relation with the flow velocity. The result will be that the figures of the fourier analysis will not be exactly the same as the original model. However they do provide a good visualisation of the shoaling and propagation of each of the main partial tides.

The flow velocities for an average tidal cycle in the Northern Approach Model are shown in figure 3.15 similar to figure 3.13a. The figure shows the magnitude of the flow velocities at different locations and also the directions. Thirteen vectors are shown with each one hour interval. This means a period of twelve hours is covered which is almost one tidal cycle in a semi-diurnal tide. The vectors at “time = -6 hours” and “time = +6 hours” are both close to low water. In the trench in front of the Selangor Estuary the flow velocity appears to be very one-dimensional. In the trench the highest flow velocities occur almost exactly in between high and low water.

The Northern Approach Model is simulated for the period of two years to analyse the tide for the Selangor Estuary. Figure 3.16 shows the distribution of the tidal range in the coastal zone near the Selangor River. The calculated average tidal range is 2.7 meters, which categorises the area as mesotidal. It should be noted that most constituents slowly vary a little over a period of 18.6 years, which is neglected in this analysis. The graph agrees well with the values from earlier researches: average tidal 2.7 meter, mean neaps 1.3 meter and mean springs 4.1 meter [Nelson, 2002].

4 Selangor Estuary Model

Estuaries define the transition between the fluvial and marine regime. The hydrodynamic processes in an estuary depend on the tidal wave in the coastal zone and the fresh water discharge coming from the hinterland. The result is a very dynamic process in which the difference in density between salt and fresh water plays an important role. Salt water has a higher density than the fresh river water and this can have the effect that fresh water will flow on top of the heavier salt water layer. This is called the stratification of an estuary and causes a flow pattern called gravitational circulation. In estuaries flow velocities change direction with the upcoming and retreating tide. The flow velocities averaged over a tidal cycle show a flow upstream near the bottom and seawards at the surface. The pattern of average flow velocities resembles a circulation. The net flow near the bottom subsides until a point is reached where the net flow is downstream over the whole depth of the river. The gravitational circulation causes sediment to get trapped near the point where the average velocity near the bottom is zero. This point is the turbidity maximum with high sediment concentrations. The location of the turbidity maximum in the Selangor Estuary extends from 8 to 14 kilometres upstream from the mouth [Nelson, 2002].

Estuaries are categorised by the extent of stratification. The Selangor estuary is hard to classify in these categories as the behaviour changes with the conditions. When discharge is low and tidal range is high the Selangor Estuary behaves as a mixed estuary. When discharge is high and tidal range low, stratification will occur and the Selangor Estuary can be classified as a partial mixed or even a stratified estuary [Nelson, 2002]. An overview of the Selangor Estuary is shown in figure 4.1.

4.1 Model set-up

The commonly used geographic coordinate system in Peninsular Malaysia is the Rectified Skew Orthomorphic (RSO) system and the accompanying geodetic datum is Kertau 1948. The most common system worldwide is latitude-longitude with geodetic datum WGS84. This system is also used for the Malaysia Overall Model, the Malacca Strait Model and the Northern Approach Model. For the convenience of processing local data from Malaysian organisations the Selangor Estuary Model is created with the Malaysian RSO grid and Kertau 1948 as geodetic datum. Another advantage of this grid is the use of meters instead of degrees, which simplifies the calculation of distances. Last the accuracy of a location in degrees depends on many digits beyond the dot. Some software processes locations with a limited number of digits beyond the dot. For a small scale model like the Selangor Estuary Model this can lead to inaccuracies.

Grid generation

The boundaries of the Selangor Estuary can be divided in three parts, the land boundary, the upstream boundary and the seaside boundary.

For this study two land boundaries were available. One land boundary was created with AutoCAD by combining a digitised Admiralty Chart, a scanned map of the Selangor Estuary and GoogleEarth. A second land boundary was provided by NAHRIM as an ArcGIS (mapping software from ESRI) shape file. Both land boundaries were compared with the GPS-data collected during the site visit. The GPS-data were measured during the boat trip and should be located within the land boundary. The land boundary from NAHRIM showed the best fit (figure 4.4). The ArcGIS shape file was converted in a valid Delft3D format and was used for the outline of the grid for the Selangor Estuary Model.

The open boundary in the river should be located far enough upstream to ensure that the influence of the tide on the water level is completely disappeared. At this point a constant discharge can be imposed at the boundary. If the water level changes with the tidal cycle a volume of water is temporarily stored upstream of that point and the discharge will vary over the tidal cycle. The point where the tidal influence is completely absent was difficult to determine because no reliable data of waterlevels along the river were available. This problem was solved by continuing the grid till the Batang Berjuntai Barrage about 50 kilometres upstream. At this barrage the discharge is controlled and tidal influence will certainly not continue upstream. For the year 2006 discharge and waterlevels measurements from the barrage are provided by LUAS. Analysis of these data showed no sign of tidal influence.

The location of seaside boundary was chosen in the coastal zone where the influence of the fluvial regime was assumed to be absent. Secondly the boundary had to be far enough from the mouth to prevent boundary conditions to become predominant in the area of interest. And last the boundaries had to be in relative deep water, because the Northern Approach Model is assumed to be more reliable further offshore. Figure 4.2 shows the boundaries of the Selangor Estuary Model. In the figure the distance between two tick marks is 0.02 degrees, which equals 2.22 kilometres for both axes. The northwest boundary measures 7.3 km, the southwest boundary 10.3 km and the southeast boundary 7.7 km. The depth at the boundary varies between zero and 25 metres. The peak discharge of the Selangor River is about 300 m^3/s. This discharge disperses over a boundary of 25.3 km. When the average depth along the boundary is estimated conservatively at ten metres the flow velocity caused by the fresh water discharge will be 0.001 m/s along the boundary. This velocity is negligible compared to the tidal flow velocities as shown in figure 4.2. This justifies the location of the boundaries as well as the fact that no discharge is implemented in the Northern Approach Model.

The intention for the Selangor Estuary Model was to keep the calculation time of one tidal cycle (12.42 hours) within the limit of one night as mentioned in chapter 2. The size and density of the grid affects the calculation time in two ways. The number of grid cells has a direct effect and the density of the grid cells determines the required time step. The Selangor Estuary will be modelled 3-dimensional with ten layers, which is considered the minimum for accurate 3-dimensional calculations. The total calculation time of the model will be multiplied by the number of layers. These considerations led to a grid with 12,412 grid cells. The grid inside the river exists of ten lanes in the final stretch and six lanes in the upstream stretch. The resolution (square root of grid cell area) of the grid in the last 20 kilometres is between 20 and 50 meters. The required time step for this grid was determined at 0.1 minute with the method explained in paragraph 3.4.1. The period of one tidal cycle contains 7452 time steps.

The calculation time of a 3-dimensional Delft3D model is defined as:

$$\frac{Number\ \ of\ \ grid\ \ cells\,(-)*layers\ *time\ \ steps\,(-)*processor\ \ speed\,(\mathrm{calc\,/sec})}{3600\ sec/hour} = calculation\ time\ (hours)$$

For the Selangor Estuary Model this becomes:

$$\frac{12412*10*7452*2.9E{-5}}{3600} = 7.45\ hours$$

In reality the calculation time appeared to be almost double this time. This can be explained by the 3-dimensional calculation, advanced turbulence modelling and the addition of salinity. However it also reveals the limitation of the formula for the calculation time. This formula simplifies the Delft3D calculation which is not always justified. The aforementioned grid parameters resulted in an acceptable balance between calculation time and accuracy (resolution of the grid). The final grid is shown in figures 4.3 and 4.4. In the last mentioned figure the GPS-data collected during the site visit is added as a red line. These data fit perfectly in the grid which confirms the correctness of the used land boundary.

Bathymetry

The Bathymetry of the Selangor Estuary Model was based on the most accurate Admiralty Chart (Chart 2155) and cross-sections profiles of the river provided by NAHRIM. These cross-sections were available for about every river kilometre, in the last kilometres near the mouth every 500 meters. This is little accuracy for a detailed flow model but no accurate sounding has been carried in the Selangor Estuary as far as known.

The coastal area of the Selangor Estuary was implemented by grid cell averaging of the Admiralty data. In areas where too little data was available the bathymetry was created by linear interpolation between depth points. The bathymetry was finished by filling the empty grid cells smoothly with the so-called internal diffusion function of Delft3D QUICKIN.
The bathymetry in the river section needed a different approach. Linear interpolation between two cross-sections in a bend is not possible. The optimal result was considered an interpolation between cross sections along the direction of the flow. Delft3D QUICKIN does not offer this possibility. To overcome this problem a second grid was created with a straight river. In this grid linear interpolation was applied to the cross-sections. The bathymetry which was created with this grid could be implemented in the original grid which showed good results. Because relatively little cross-sections were available the slope of the river showed some abrupt transitions. To reduce these effects the river bathymetry was smoothened until a more gradual transition was established. The bathymetry of the model is visualised in figure 4.1. The slope of the river can be seen in figures 4.9 for the whole river and in figure 4.5 for the first 30 kilometres of the river. The latter figure is more representative because it shows the deepest points along the river while the slope in figure 4.9 follows one line of grid cells.

Boundary conditions

The Selangor Estuary Model is driven by two open boundaries, the upstream limit with a fresh water discharge and the sea side which is controlled by the tidal wave.

The discharge of the river is implemented as a constant flow during the tidal cycle. A constant value is enforced because available discharge data are provided as daily means. Moreover a constant value makes the model results better interpretable and hourly variations are assumed to be negligible for the controlled discharge at the Batang Berjuntai Barrage.

The seaside boundary is divided in 17 sections, with lengths varying between 1.2 and 2 kilometres. For these segments the enforced boundary conditions are uniform and variations in water levels and currents are assumed to be little. The boundary conditions at the seaside are derived from the Northern Approach Model. For each possible period in the past or the future the Northern Approach Model can provide accurate predictions of water levels and flow velocities. For each of the calibration and validation runs in this chapter the boundary conditions are derived from the Northern Approach Model. The boundaries of the Selangor Estuary Model do not coincide exactly with the grid cells of the Northern Approach Model. For each boundary point of the Selangor Estuary Model the three closest grid cells of the Northern Approach Model are selected and the water level and flow velocity is obtained by interpolation of these three grid cells. This resulted in two boundary condition files, one with water levels and one with flow velocities. Both can be enforced on the model, however the most accurate results are obtained with a combination of both in a Riemann boundary. The Riemann signal can be calculated from the water level, the flow velocity and the local water depth. In cooperation with Alkyon a program in the programming language Fortran was written to enable this transformation quickly. The boundaries closest to the shore are defined as water level boundaries because these areas are subject to drying and flooding and a Riemann boundary is not suitable for these conditions.

Initial conditions

Tidal intrusion and salt water intrusion is a highly dynamic process and initial conditions are difficult to determine. Without correct initial conditions Delft3D FLOW will need considerable time to stabilise. For water levels and flow velocity this is usually in the order of hours, but for salinity this can mount up to several days. As it takes nearly one hour of real time to simulate one hour, the importance of initial conditions is clear. Another difficulty is to assess whether the model results can be considered stabilised. To resolve these issues the strategy is used to simulate exactly one tidal cycle. The model results at the end of this simulation are used as initial conditions for a new simulation. This iterative procedure continues until salinity levels have stabilised. When the salinity of the two subsequent simulations differs no more than 1 ppt for the same point of time, the simulation is considered stabilised. Figure 4.5 shows this procedure for a stabilised simulation. The initial conditions of a stabilised simulation offer the opportunity to quickly determine the effects of different parameters and optimise the model results. The qualitative effects of a change in parameters can be assessed within one night, as intended. The method has the disadvantage that under certain conditions the situation in the estuary will not be stable. After a high peak discharge salt water can be flushed completely and during a drought salt water can intrude far upstream. After these conditions a hysteresis effect can occur and the modelling strategy will not be justified. In most cases however the discharge (and tidal range) will change gradually and the method can be applied.

The conditions of the very first simulation were a salinity of nearly zero (0.02 ppt) and a high uniform water level. This resulted in an initial overfill of the model, which will lead to the quickest development of stable waterlevels and flow velocities. The initial fresh water will quickly be replaced with salt water in the coastal zone because of the high flows through the seaside boundaries. For some simulations the initial condition file of another point in time was used but only if the salt intrusion under those conditions were known to be less. All iterative stabilisations were done with an advancing salt intrusion (opposed to a retreating salt intrusion) to ensure correct comparisons.

Assumptions

In the model the discharge of the river is assumed to be constant from the upstream point to the river mouth. The upstream boundary of the model is the Batang Berjuntai Barrage where a total discharge is imposed. Smaller tributary streams downstream of the barrage are not included in the model. The catchment area upstream of Batang Berjuntai is 1554 km^2. The catchment area of the part of the river included in the model is only 250 km^2 [DID, 2002]. The contribution of tributary streams along the modelled stretch of river is negligible compared to the total discharge. Additionally most of the precipitation downstream of the Batang Berjuntai Barrage is retained by dams and sluices to ensure a sufficient supply of irrigation water for agriculture.

Wind and waves are assumed to be negligible in the area. Caught between the landmasses of Sumatra and Malaysia, wind and waves are rarely of any significance in the Malacca Strait. Wave heights are most of the time less than 0.75 meters and seldomly exceed 1.75 meters [Stanley Consultants, 1985]. Waves generally travel in northwestern direction, parallel to the coast. The Selangor Estuary is sheltered by the islands and shoals in front of Port Kelang and is hardly affected by these waves. Dominant wind conditions are between 0 and 4 m/s. Wind velocity hardly exceeds 6 m/s [Jaffar, 2006].

Most of the west coast of the Malaysian Peninsula exists of muddy mangrove swamps. The Selangor Estuary forms no exception and consists of consolidated mud with at some point patches of fluid mud [Nelson, 2002]. Analysis of bed samples of the first 18 kilometres from the mouth showed a mean diameter ranging from 13.3 to 55.2 µm, which corresponds to silt in the Wentworth scale. The stretch of river from the mouth to the first bend appeared to contain slightly more sand, up to 30 percent [Kadir Ishak, 2000]. Further upstream near the bottom contains more sand [Lee, 2002]. Muddy bottoms are known to cause very little bottom friction, while a sandy bottom is rougher. In the Selangor Estuary Model the roughness is implemented with the Nikuradse height. For the downstream part and the coastal zone a very low value of 0.001 meter is applied and for the upstream part of the river a value of 0.05 meter is applied. Deposition of mud in the downstream part of the river is strongly related to the turbidity maximum. The transition from mud to sand is chosen just upstream of the turbidity maximum zone from 20 to 30 kilometres upstream.

The density of the water is assumed to be dependent on the salinity level only. In reality the temperature and sediment concentration will also have influence on the density but this is relatively little. In figure 4.6 the effect of temperature, salinity and sediment concentration on the water density is shown. For each of the variables the range of occurrence is plotted in the figure. For the temperature and salinity the formulas implemented in Delft3D [Eckart, 1958] are compared to a more accurate density equation [Sun, 2007]. The figure shows that salinity is the predominant factor controlling the water density in the Selangor Estuary. Temperatures are relatively uniform and are not subject to seasonal influences at this latitude. In general the runoff water from is a little colder than the temperature in the Malacca Strait. The range of temperature in the Estuary is 27 to 30 degrees Celsius [Kadir Ishak, 2002; Nelson, 2002]. The average temperature in the Malacca Strait is 29.60 ± 0.68 degrees Celsius [Hii, 2006]. Figure 4.6 shows that the influence of temperature on the water density is negligible compared to the influence of salinity. High sediment concentration can have a significant effect on the water density but this is very local. Sediment concentrations of 15 g/l can occur near the bottom in the turbidity maximum [Nelson, 2002]. These peaks are very local and predominant sediment concentrations are within the range 0.2-0.5 g/l [Nelson, 2002]. The sediment concentration will only have a significant effect in the turbidity maximum zone but for the whole estuary the influence is assumed negligible.

4.2 Calibration

A common technique in flow modelling is to start the calibration process with a 2-dimensional model. This model will have a significantly shorter simulation time and can be used to quickly assess the water movements. For the Selangor Estuary this strategy is used to calibrate the surface gradient of the river. For the year 2006 data of the discharge and water levels downstream of the Batang Berjuntai Barrage are provided by LUAS. From these data a relation between discharge and water level can be derived and compared with the model results. From the data and from the visual observations during the site visit can be concluded that no tidal effects are visible near the barrage.

The initial model set-up showed a significant underestimation of the water level near the barrage. Furthermore a strange, abrupt change in the waterlevel appeared near the mouth with low water. Both effects are contributed to inaccuracies in the bathymetry. Most of the cross-sections were wider than the width of the river according to the land boundary. This led to relative deep depths near the river banks and an overestimation of the cross-section area. To raise the surface gradient of the river the bottom near the river banks was raised to create a more smooth transition between the land and the river. The bathymetry near the mouth was created with relatively little depth data and showed some high bottom gradients. This area was smoothened to eliminate the abrupt changes in the water level. Simulations with the new bathymetry and various discharges showed good agreement with the Q-h relation near the barrage. Figure 4.7 shows the measured and calculated Q-h relation. The calculated water levels are one kilometre downstream of the barrage to avoid boundary conditions to become predominant. The nod in the calculated Q-h relation between 40 and 50 m^3/s is caused by the drying of some grid cells along the banks of the upper reach, when the discharge is 40 m^3/s or less. The calculated Q-h relation becomes less reliable for high discharges which can be due to the fact that the model cannot simulate the flooding of the river banks.

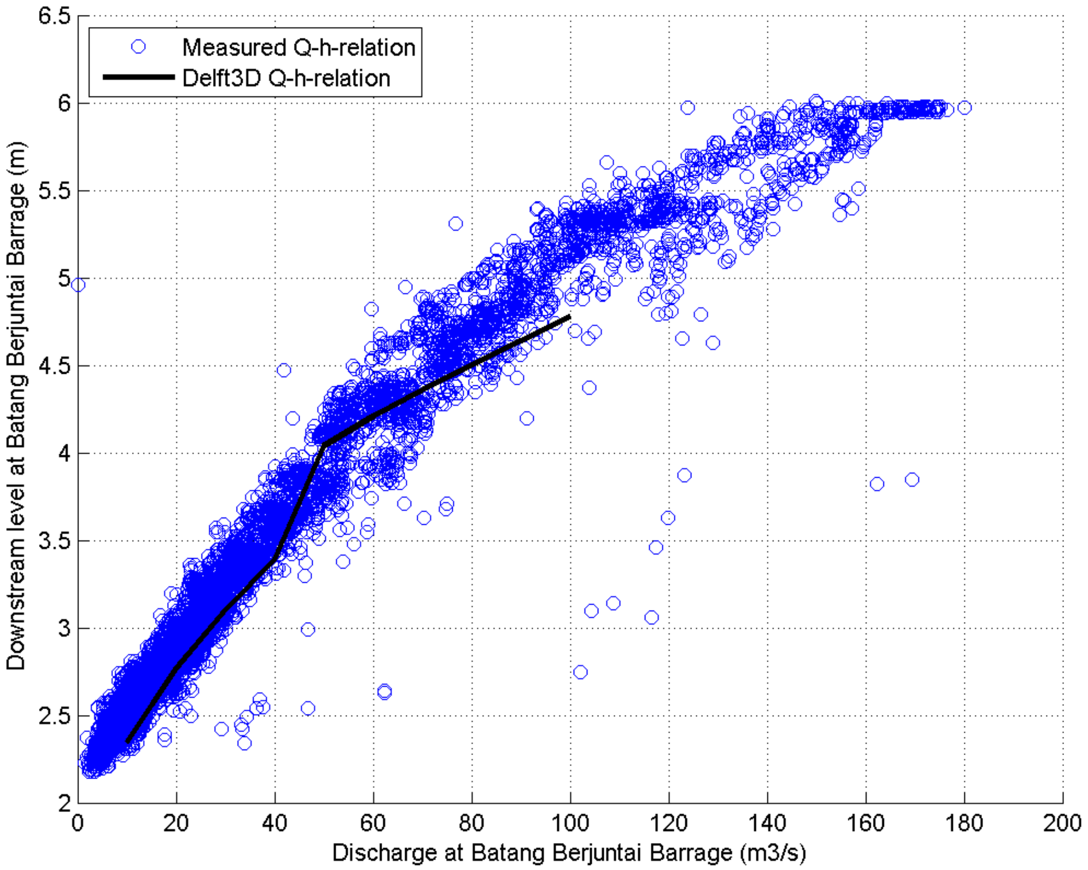

Figure 4.7: Comparison between measured Q-h relation and 2-d model results.

When the tidal wave travels upstream, energy is dissipated until a point where the tidal influence is fully subsided. The only known fact for the Selangor River is that no tidal influence is present in the water levels near the barrage. To analyse the tidal intrusion the Selangor Estuary Model is simulated for an average tidal cycle (2.7 metres) and a discharge of 60 m^3/s. The water levels along the longitudinal profile of the river are plotted in figure 4.8. The figure shows the water level for four conditions and the maximum and minimum water levels. Because of the flat (or even a negative slope) bed level, the amplitude of the tidal wave remains almost the same in the first 30 kilometres of the river. Approximately 10 kilometres before the barrage, the tidal wave is dissipated. Although the figure cannot be substantiated by data, the results are in agreement with the observations made during the site visit. With the maximum and minimum water levels and the surface area of the estuary, the tidal prism is determined at 14.3 million m^3 for an average tidal range (2.7 metres) and a discharge of 60 m^3/s. This volume of water flows in and out of the estuary during one tidal cycle.

For the calibration of the 3-dimensional Selangor Estuary Model, flow velocity and salinity data are provided by Dr. Abdul Kadir Ishaf. These data is measured during two periods, one in the dry season and one in the rain season. Figure 4.9a and 4.9b (next page) show the conditions under which the measurements are taken. The data of Dr. Kadir Ishaf included discharge data during both periods, which originated from the Department of Irrigation and Drainage (DID). For this study long term discharge data was requested from the DID, including the year 2000. Although the source of these discharge data is the same they do not completely match. In the figure the discharge is marked with the abbreviations AKI and DID, corresponding with respectively the original data from dr. Abdul Kadir Ishaf and the more recently acquired data from the DID. As the figure shows the data from both sources does show the same trend but the exact numbers differ.

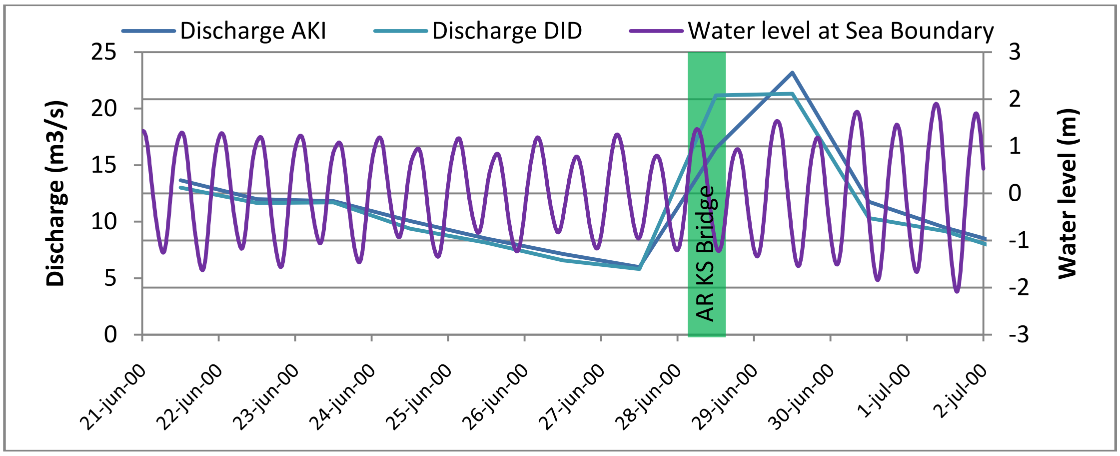

Figure 4.7a: Measurements and conditions dry season

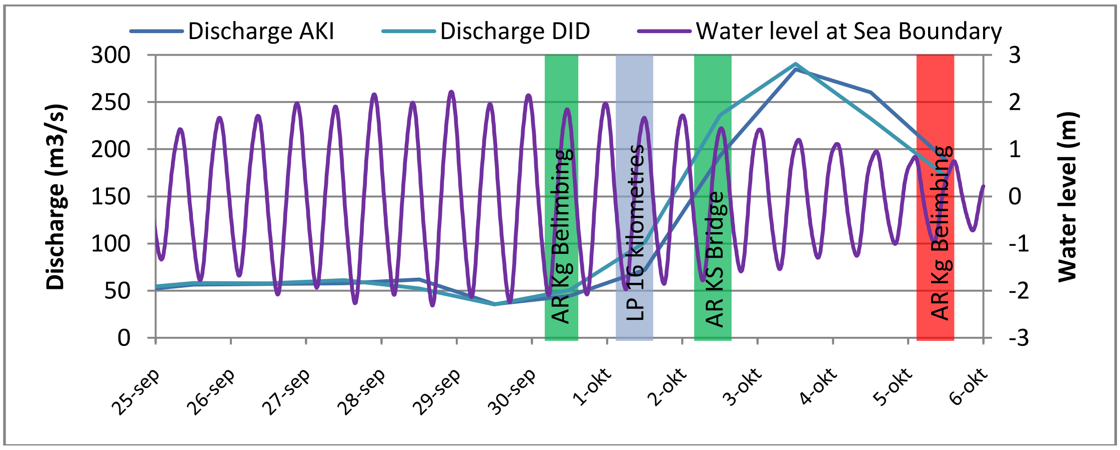

Figure 4.7b: Measurements and conditions wet season

The measurements of dr. Kadir consist of anchor runs (AR) at a fixed location and longitudinal salinity profiles (LP). The locations of the measurements are mentioned in these figures and are plotted in figure 4.1. As mentioned before the method of generating initial conditions is less reliable for strongly fluctuating discharges. During the measurements in the dry season the discharge was low, with only a slight peak during the anchor run at the 28th of June. This discharge during this peak will reach approximately 22 m^3/s, and will not have a significant hysteresis effect on the salinity levels. During the wet season very high discharges of more than 250 m^3/s were measured. The anchor run of the 5th of October is not used because a hysteresis effect is likely to occur. Additionally a discharge of 250 m^3/s is assumed to be more than bankfull and flooding conditions are not included in the model. The green shaded dates are considered suitable for the calibration of the model. The longitudinal profile (LP) of 16 river kilometres on the first of October will be used for the validation of the model.

The anchor runs consist of measured flow velocities and salinity levels at various depths. Although the water level is not measured, a rough indication can be obtained from the salinity profiles. These profiles are measured for every 0.2 meter from the water surface to the bottom. The deepest measurement can be used as an indication for the water depth at that specific time. For each of the three suitable anchor runs boundary conditions were generated and a model was setup. The results of the simulations compared to the measurements are shown in figures 4.10a till 4.10c. The plotted figures are the final calibration runs.

The model was calibrated by adjusting the following variables:

- One of the main uncertainties in the model set-up was the discharge. First of all the available data was not consistent (AKI vs DID). And second, no data were available of the water extraction in 2000. It is known that part of the current infrastructure was yet in function [DID, 2007]. Because the initial figures showed an underestimation of the salt intrusion the lowest discharges (AKI) less 10 m^3/s extracted water was enforced.
- The diffuse term of the salinity transport is dependent on the horizontal eddy diffusivity coefficient. An increase of this parameter will cause the salinity to intrude further upstream. An increase will also cause less stratification. Because the model tended to underestimate the stratification this value was kept at the default value of one.

The final figures 4.8a till 4.8c show the final simulations which were considered acceptable. Calculated salinity in figure 4.10b appears to differ from the measured values. However measured values are less than 1 ppt, which is the limit for a stabilised simulation. This small salinity values might develop when more iterative runs are made, but these simulations are not carried out. The conditions of figure 4.10c are a high tidal range and a very high discharge. The discharge of 193 m^3/s might even be more than bankfull. Although the model is not created for these conditions the calculated values show good agreement with the measured data.

4.3 Validation

The model is validated by comparing the model results with the longitudinal profile of the first of October. A second validation is carried out with measurements from Bruce Nelson. These measurements date from 1989, when no water was extracted from the Selangor River.

The difficulty with both longitudinal profiles is that the measurements are not instantaneous but over a period of up to several hours. This complicates the comparison with model results.
Longitudinal profiles are usually measured when the tide is turning. During these ‘slack runs’ the salinity levels are most constant over time. Unfortunately the measurements of Dr. Kadir were not carried out as planned and the data of the first of October are during falling tide. The data from Bruce Nelson is measured during slack. The measurements are compared with the calculated salinity field when the measurements started and with the calculated salinity field when the measurements ended. When the simulation is valid the first measurements agree with the first calculated field, the last measurements agree with the last calculated field and measurements in between should agree with an interpolated value of the first and last calculated field.

Figure 4.11 shows the comparison of the model results with the data from Dr. Kadir and figure 4.12 the comparison with the data from Bruce Nelson. The measurements of Dr. Kadir exist of depth profiles, which were converted into a salinity field. The measurements of Bruce Nelson were less dense and were added to the calculated fields. Bruce Nelson measured the conductivity in the field and collected water samples for laboratory research. Both measured data are included in the figure.

4.4 Results and discussion

In general the model shows very reasonable results, especially considered the many uncertain factors in the model. The dynamic process of salt intrusion, including stratification, is simulated with the model as expected from the theory and shows good agreement with the available measurements. Based on figures 4.11 and 4.12 the calculated salinity is usually within the range of three ppt of the measured salinity.

A further improvement of the model is considered not feasible with the available data. The most limiting factors are the lack of reliable bottom depths and reliable discharge data. For the purpose of the study the created model is accurate enough to draw conclusions.

5 Fireflies Case

The Selangor Estuary is listed in most tourist guides for a typical phenomenon which takes place every night. Along a small stretch of the Selangor River a population of fireflies is aggregated. When night falls these little creatures start massively flashing in the same rhythm. Such large-scale, long lasting and synchronous behaviour is seemingly unique in the animal Kingdom. [San, unknown] The result is an impressive spectacle which attracts many tourists. There are two sites along the river which offer facilities for firefly watching. Each month an average of 11,000 visitors come to the Selangor Estuary to watch the fireflies colony, about 35 percent of them is from outside Malaysia [MNS, 2002]. This number stems from 2000 and the increasing number of visitors in the ninetees is assumed to have proceeded in the present decade. The estimated total revenue of the firefly tourism was RM7.3 million (€ 1.6 million) in the year 2000 [MNS, 2002].

5.1 Fireflies of the Selangor River

The population of fireflies in the Selangor Estuary is dominated by one single specie which is the Pteroptyx Tener. The life cycle of P. Tener is about 130 days and consists of the egg, larval, pupa and adult stages. The female fireflies lay their eggs in moist but not inundated grounds up to 100 meter from the water edge [MNS, 2002]. After 13 to 15 days the eggs hatch and the P.Tener larvae start their search for food. The larvae are aggressive, carnivorous feeders. Their main source of food is the river snail, Cyclotropis Carinata. [DID, 2007]. The larvae start to emit a weak, not synchronised light when they are about two weeks old [DID, 2002, VIII]. After 80 to 90 days the larvae retreats in an underground chamber to pupate. The pupae take about 6 to 8 days to become adult fireflies and it takes another 3 to 4 days before the fireflies leave the underground chamber [MNS, 2002]. During the day adult fireflies are observed to be resting in the mangroves along the river or in the hinterland. After sunset the fireflies gather in the mangroves on the riverbanks to start their flashing activities. This behaviour is part of the mating ceremony. The synchronous flashing is most likely to enhance the chances for mating but is not yet fully understood by scientists [MNS, 2002]. The lifespan of the adult fireflies in laboratory conditions is about 12 days for males and 30 days for females [Nallakumar, 1998]. Fireflies are found aggregated near Kampung Kuantan, approximately 24 kilometres upstream of the mouth. Figure 5.1 shows the result of a monitoring study of 2003 [MNS, 2003].

5.2 Berembang Trees

The fireflies in the Selangor Estuary are associated with one type of mangroves. The S. Caseolaris or Berembang Tree plays a vital role in the biology, ecology and population dynamics of the fireflies in the Selangor Estuary [Nallakumar, 2000]. The leafs of the Berembang Trees produce a nectar which is the main food source for adult fireflies. This extrafloral nectar is believed to enable the chemical process in the flashing organs of the fireflies [San, unknown]. Extrafloral nectar is generally made to attract predatory insects to protect the plant or tree from insects that can harm them. In this case the Berembang Trees could produce the nectar to protect themselves or their seedlings from the river snails. However this theory could not be supported by any published research. Besides the extrafloral nectar the Berembang also produces floral nectar which is spread by bats for the pollination process [Lee, 2002n]. Berembang Trees are mangroves with pneumatophores, breathing roots, arising vertically from long roots buried just beneath the surface of the soil. In many cases the trees are along the shore and the roots become inundated each tidal cycle. The roots use a filtration technique to exclude salt but long exposure to high salinity levels will have a negative effect on the trees. Fireflies are found aggregated on young trees due to the higher content of nectar on their leafs [Nallakumar, 2000]. Berembang Trees used to extend from the river mouth up to 50 kilometre upstream but are now only concentrated in the lower part of the region. Figure 5.2 shows the distribution of adult trees and seedlings.

5.3 Threats to the ecosystem

The synchronous flashing fireflies are the visualisation of a complex eco-system as described before. It is clear that the pressure on this eco-system has increased over the years and this resulted in a downfall of the firefly population. Although regular monitoring of the fireflies has only been done since 2006, a visible reduction of the firefly population in the last decade has been observed by locals and scientists [Lee, 2002n]. Because of the relatively short lifecycle of this specie their numbers react quickly to changes in the environment. Berembang Trees react slowly to changes in the environment but many have been cut down to make place for developments. Because the fireflies are the driving force of the local tourism industry several studies have been carried out to find the cause of the deterioration. The major threats to the ecosystem in the Selangor Estuary are:

- Construction of new houses and other building along the river have been at the expense of the natural habitat of the fireflies.
- Oil palm plantation and orchards have expanded at the cost of the natural riverbank vegetation. In most cases the Berembang Trees are found closest to the river and are left undisturbed. However a few meters further the original habitat is cleared and plantations begin. The fireflies seem to prefer the original habitat with Sago Palms to lay their eggs [MNS, 2002]. This is closely related to the presence of river snails which prefer the cooler, more humid and more shaded Sago patches over the orchards and oil palm plantations [Kirton, 2006].
- The Selangor River is burdened with many forms of pollution. Petrol and diesel released into the river from motorboats, the use of pesticides and chemicals in agriculture, sewage water draining and solid waste dumping [Nallakumar, 1999]. Because in estuaries the direction of the flow changes with the tidal cycle, pollution and debris often is not flushed away easily, especially during low river discharges.
- Aqua-culture and shrimp farming disturbs the natural habitat of the river snail and the larvae.
- The discharge regime of the Selangor River is changing at an alarming rate. Water is extracted for drinking and irrigation water upstream and the flow in the downstream is reduced. Moreover two major reservoirs are built in the catchment area which will also affect the discharge regime. The construction of the second and largest dam raised concerns with the local population but they could not prevent the completion of this dam in 2005. The main threat for the eco-system is that saline sea water can intrude further upstream when the river discharge is smaller. A high salinity level has a negative impact on the health of the ecosystem.

This study will focus on the hydrodynamic characteristics of the Selangor River, including salinity. The conservation of the firefly population will need an integral approach. This is beyond the scope of this study and is a task of Malaysian politics. Fast action is needed because one more threat lies in wait. When the population of P. Tener weakens other firefly species can become more dominant. A more varied population of fireflies will cause a clashing of species-specific flashing rhythms and disturb the synchronous flashing [Buck and Buck, 1966]. When this happens the unique situation of an uniform population of fireflies congregated on a small stretch of river is probably lost forever. The unique phenomenon of synchronous flashing will disappear and Selangor will lose its valuable touristic attraction.

5.3.1 Influence of salinity

Because the aim of this research is to gain insight in the salinity in the estuary, the effects of the salinity level is analysed with more detail. Three aspects of the eco-system are supposed to be sensitive to the salinity level of the water.

- The Berembang Trees
- The larvae of the firefly
- The river snails

The focus of most research has been on the effect of salinity on the Berembang Tree. These trees are highly sensitive to salt and thrive in brackish water with low salinity. High salinity levels can reduce their growth [San, unknown].

In May 2000 a study of the vegetation of the Selangor Estuary has been conducted, with special attention for the Berembang Tree and the effect of salinity [Kheong, 2002b]. Figure 5.2 shows the results of the Berembang population study, visualised in the map of the Selangor Estuary. The density of seedlings is usually the best indicator of any trend. In this case the upstream part, where salinity is lowest, has no seedlings at all. There is no sign of an upstream shift of the Berembang Tree habitat. However in the months May and April, when most of the counted seedlings have probably germinated, the discharge was exceptional high. These high discharges have pushed the salt limit downstream in the months before the survey. The lack of seedlings upstream could have been caused by erosive effects of high flow velocities in this stretch of river. Due to the conditions during the measurement, the data cannot provide any information about the long term trend in the Berembang population.
The same research also comprehended a laboratory study for the sensitivity of Berembang Trees to salinity. Berembang seedlings were grown in five solutions of river water with constant salinity levels of 26, 13, 6.5, 3.25 and 0 ppt. At salinity levels of 6.5 and above the growth will be severely affected, producing shorter plant, smaller leaf area and shorter leaf length. The Berembang seedlings grew well in the solutions with salinity levels of 3.25 and 0 ppt. At salinity 26 ppt, most plants survived only for four weeks [Kheong, 2002b]. A study for the results of fluctuating levels has not yet been carried out.

Less is known about the influence of salinity levels on the larvae of the firefly and on the river snail. Only a few quotes are found in the available literature:

- “A higher salinity is detrimental for the survival of the P. Tener larvae that prefer low levels of salinity.” [Tan, 1999 in Nallakumar 2000 p17]
- “The larvae of P. Tener survive in water as well as on the land and have a tolerance to salinity similar to S. Caseolaris” [San, p9]
- “The most common snail Cyclotropis Carinata is common on wet ground near areas where there is fresh water or water that has a minimal salinity” [DID, 2007, p47].
- “The snail is a fresh water species but may tolerate low salinity since it was found on area with salinity about 2 ppt” [Othman, 2002, pD2-24]

All of the available sources confirm the fact that an increase in the salinity will have a negative effect on the fireflies in the Selangor Estuary. The exact effect on different components of the ecosystem is still not yet fully understood and needs additional research.

5.4 Water extraction from the Selangor River

Already in the 1960’s the Selangor River was indicated as a major source for water for the state of Selangor, including Kuala Lumpur. It lasted until the nineties before water was extracted on a large scale from the river. The first construction of water supply infrastructure was commissioned in 1993 [DID, 2007]. This initial step was the start of a rapid expansion of the infrastructure in the following period to satisfy the growing demand. The capacity was increased in three phases. The first phase consisted of the construction of the Tinggi Dam and water treatment works with a capacity of 950 million litre per day (mld). The second phase added another 950 mld to the treatment capacity. In the third phase the Selangor Dam was build and the total treatment capacity was enlarged to 3000 mld [DID, 2007]. The majority of the water extraction, 2700 mld, takes place at the Batang Berjuntai Barrage (figure 1.4). At this time all three phases are completed and the Selangor River supplies two third of the industrial and domestic water needs within Selangor and Kuala Lumpur [SPLASH]. The capacities of the Tinggi Dam and the Selangor Dam are respectively 103[i] and 235 million cubic meters (mcm) [SPLASH]. Figure 5.3 shows the annual water yield of the Selangor River for the period 1960-2000, compared to the current water extraction. The monthly discharge data contained a lot of missing values which were replaced with the average value for the specific month. The figure shows that in dry years, like 1990 and 1998, the water yield is nearly equal to the water extraction capacity. Even though the water yield in dry years can be filled up with the water from the reservoirs, the remaining flow in the downstream part of the river will diminish severely.

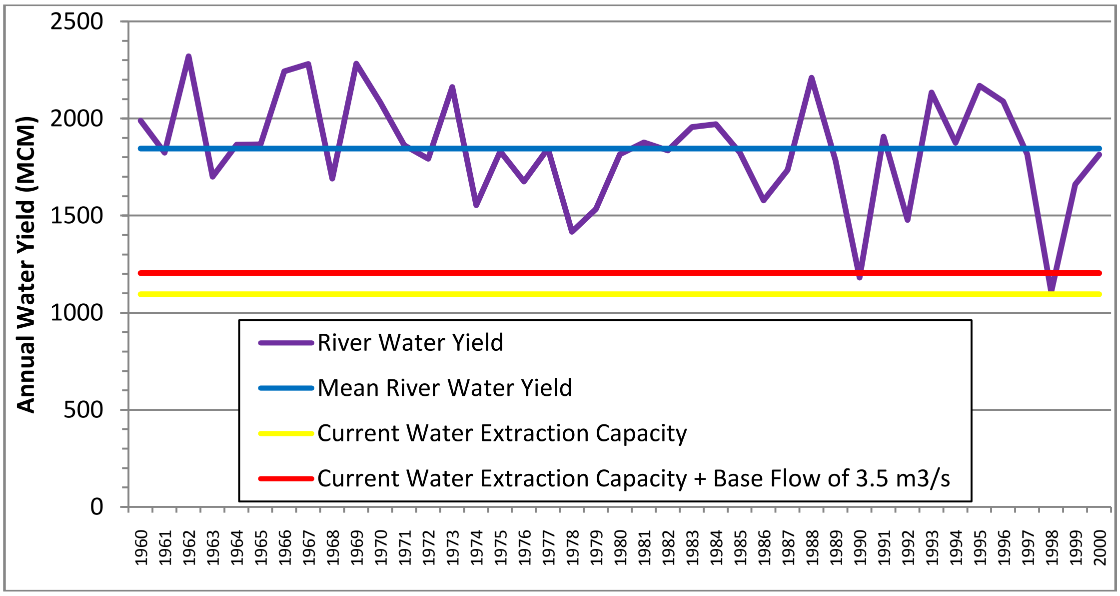

Figure 5.3: Analysis of annual water yields at Rantau Panjang (figure 1.4), compared to the current water extraction capacity and imposed base flow.

The demand for water is expected to continue to grow in the coming years. This extra demand will be supplied by water transported from the other side of the Titiwangsa mountain range trough a tunnel. The prospects are that this additional supply will only be sufficient until 2011. Future projects to satisfy the water demand are at this stage still uncertain.

5.5 River management

The two dams in the Selangor River Basin and the water supply infrastructure have a major impact on the river. At maximum capacity a flow of 35 m^3/s could be extracted from the river. The average discharge of the Selangor at Rantau Panjang is 60 m^3/s so the extraction of water can amounts to more than half of the average flow. During the dry season the maximum extraction is even bigger than the natural average flow. In these periods the water extraction has to be compensated by the release of water from the reservoirs. Most of the extracted

[i] According to DID 2007 the capacity of the Tinggi Dam is 114.5 million cubic meters

drinking water is transported to the Kelang River Basin and is not returned to the Selangor River.

In rivers where the flow regime is changed significantly in a short period, an important criterion is the environmental flow. This is a prescription of the necessary flow to maintain the natural ecosystem. These flow conditions can be divided into three components: low (base) flow, high flow pulses and floods [Richter, 2006]. The ecological role of the low flow is to maintain sufficient aquatic habitat of a good physical and chemical quality. The high pulse flows are related to morphodynamic processes in the river bed and the flushing capacity of waste. Floods are involved in the same ecological role as high pulse flows; however their function is extended with the ecological condition of the flood plains. In the lifecycles of both flora and fauna, floods often play a role in the distribution of seeds, provision of nutrients and the conservation of the transitional zone between aquatic and terrestrial environments.

Several researches have tried to determine the environmental flow for the Selangor River. The exact determination of which component is meant in these researches is vague but most studies appear to focus on the base flow of the river. Values for this low flow condition are summarised in the Selangor River Basin Management Plan [DID, 2007] and range between 3.47 and 19.6 m^3/s at the Batang Berjuntai Barrage, 50 kilometres upstream of the mouth. The low flow condition of 3.47 m^3/s was the outcome of the Environmental Impact Assessment (EIA) Report, which was written for the approval of the final phase of the Selangor River Water Supply. This discharge is set as the minimal residual flow at the Batang Berjuntai Barrage. However in August 2005, following a relatively dry rainy season, this requirement was reduced to as little as 1.16 m^3/s. After this period of water scarceness, the lower limit was set back to 3.47 m^3/s. The Batang Berjuntai Barrage is equipped with an acoustic Doppler Current Profiler to obtain accurate discharge data. Unfortunately this equipment has been out of service since half 2007 until the writing of this report because of a lack of maintenance. The imposed base flow added to the water extraction is compared to the annual water yield of the Selangor River in figure 5.3. The figure clarifies that in dry years the base flow will be difficult to fulfil, and the storage capacity of the dams is required to maintain the base flow. It does mean that in such a dry year the flow in the Selangor would hardly exceed the base flow in the whole year.

The base flow of 3.47 m^3/s is assumed to be sufficient to maintain the water quality in the downstream part of the river within acceptable levels, including the salt intrusion. In 2002 a research conducted by the Malaysian Nature Society revealed that the water extraction has no negative effect on the fireflies population. This study has been doubted by criticasters who suspected the outcome of the report to be influenced by the powerfull drinking water company. The reality is that the ecosystem of the Selangor Estuary is highly complex. To separate the effects of the changing flow regime from other negative influences is very difficult and requires a lot of insight and high quality monitoring. This research will contribute to the problem by clarifying the relation between tide, river discharge and salt intrusion.

It is clear that the conservation of the ecosystem in the Selangor Estuary requires a wider approach than only the proper management of the river discharge. However the water extraction will have consequences for the river on the long term. The main effects will be:

- A decrease in the annual average discharge with 35 m^3/s.
- A decrease in peak flows, which will affect the morphology of the river bed. The erosive power of rivers rises vary rapidly with increased flow rates [Wright, 1999]. Without peak flows, sedimentation will prevail and the bed level of the river will rise.

- A controlled discharge with a minimum base flow set to 3.47 m^3/s. During droughts the flow will be maintained at this lower limit, which will cause pollution to accumulate in the river and salinity levels to intrude further upstream.

The basis of the problems concerning the discharge in the Selangor River is the growing demand for drinking water. The solution for these problems should therefore also comprehend this aspect. A growing awareness of the necessity to save water and an improvement of the infrastructure can balance the demand and supply for fresh water in the state of Selangor. In 2006 non-revenue water was 37% of the total volume of extracted water. An estimated 26% was due to physical losses (leakage) and 11% due to commercial losses (illegal taps).

5.6 Model simulations of the effects

Salt intrusion is a problem which is difficult to solve by human intervention. Fresh water is the solution but in the developing world the value of this resource is rising. With the millions of people in the state of Selangor demanding drinking water, the Selangor River will continue to be used for water supply. At the moment water is already a scarce good in Kuala Lumpur during droughts. The best case scenario for the ecosystem in the Selangor River is that water extraction comes to a hold. A decrease in water extraction to save the ecosystem is a politically unfeasible wish. The real solution for the problem would be to create infrastructure to treat sewage water from Kuala Lumpur and pump this water back in the Selangor River system. This requires high investments and is considered not possible in the short term.

The effect of the lower average discharge for the ecosystem can be reduced with good water management. Because of the major dams in the upstream parts of the river and the barrage 50 kilometres upstream the discharge in the Selangor River is very well controllable. Good management of the discharge can keep salinity levels within an acceptable range for the ecosystem. The key features to successfully manage the Selangor River are to know the relation between river discharge, tide and salinity and the maximum levels of salinity which can occur without damaging the ecosystem. Although the latter issue is still surrounded by uncertainties, this study will predict the effects of the current management on the salinity levels with the developed Selangor Estuary Model.

To generalise the model results an average tidal cycle is selected with an average tidal range of 2.7 metres. The boundary conditions of this average tidal cycle are combined with various discharges, ranging from 3.5 till 60 m^3/s. All of these simulations were continued until a stabilised situation was established. For all of the simulations the maximum salt intrusion was calculated. For the same values as Othman (see 5.3.1) the maximum intrusion was determined at the surface and near the bottom [Kheong, 2002b]. The results are plotted in figure 5.4. The figure shows that salt intrusion is not a linear function with the discharge. The maximum salt limits advances faster when discharges are lowest. The bottom and surface lines approach each other when the discharge decrease which means the stratification becomes less. Table 5.1 lists all results and includes the maximum retreat of the saline water.

Figure 5.5 compares the maximum salt intrusion for an average dry period before water extraction (discharge 30 m^3/s) and for the lowest base flow of 3.5 m^3/s. The figure shows that especially at stratification nearly disappears when the discharge is very low. The maximum salt levels in the surface layer advance between 2 and 3 kilometres upstream.

Figure 5.6 shows the possible harm to the ecosystem. According to Othman a permanent salinity level of 6.5 will severely affect the growth of a Berembang Tree [Kheong, 2002b]. The figure shows the percentage of time this value is exceeded for an average tidal cycle. The limit where salinity is more than half of the time below this value is for a discharge of 30 m^3/s 6.5 kilometres upstream from the mouth and for a discharge of 3.5 m^3/s this limit shift to more than 11 kilometres upstream. This zone is home to the Berembang Tree and possible harm can be caused to the ecosystem. However the reaction of Berembang Trees to variable salt levels is not yet known. The simulations are only run for an average tidal cycle. A higher tidal range will certainly advance the salt limit further upstream.

5.7 Future scenarios

For the long term development of the ecosystem in the Selangor Estuary, two likely scenarios are simulated.

- All over the world people become aware of the global climate change. One of the results of this change is a rise in the average air temperature of the earth. Increases in sea level are consistent with the global warming. The global average sea level rises with a rate between 1.3 and 3.8 mm per year [IPCC, 2007]. The local sea level rise in Malaysia over the last decade is estimated at rates between 6.3 and 14.7 mm [Omar, 2005]. However in this decade a global increase in the rate was noticed and it is unclear whether this is caused by decadal variation or an increase in the long term trend [IPCC, 2007]. Calculations of sea level rise are highly uncertain and predictions are even more difficult. The Selangor Estuary is simulated with a rise of the MSL with 0.25 meter, which equals an average rate of 5 mm per year for 50 years. The results are plotted in figure 5.7 and show that the maximum salt intrusion advances upstream with a few hundred metres. Relatively little compared to the effect of the change in discharge regime.
- As mentioned in chapter 5.5 the long term effect of the change of discharge regime will cause the bed level of the river to rise. To determine the effects of this development on the salt intrusion a model with a bed level rise will be simulated. The bed level rise is implemented as a levelling off the bed level in the lower stretch of river to 4 meters below sea level. The effect of this bed level rise is shown in figure 5.8. A bed level rise will have no significant effect on the salt intrusion in the estuary.

6 Conclusions & Recommendations

6.1 Conclusions

The modelling strategy applied in this research comprehended a very accurate but time-consuming method to derive boundary conditions for the Selangor Estuary. Although the Malaysia Overall Model was developed to generate boundary conditions, it appeared to be not very well suitable for a detailed, small scale model like the Selangor Estuary. The effort to create and optimise two intermediate tidal flow models does not balance out against the advantages of the method. When the focus is solely on the estuary, boundary conditions derived from surrounding tidal stations could provide a fast alternative. The process of nesting did however produce some valuable spin-offs. The Malacca Strait is one of the major seaways in the world and an accurate tidal flow model can proof its value in many ways. The Malacca Strait Model could generate boundary conditions for other detailed flow models, provide flow velocity fields, water level predictions, morphodynamic behaviour, pollution spills, navigation optimisation etc. For the Northern Approach Model the same is applicable. This was already demonstrated during this study when the Forest Research Institute of Malaysia communicated their interest in water levels of the Selangor Estuary for the years 2006 and 2007. As a courtesy these water levels were calculated with the Northern Approach Model and provided to FRIM for their research in the Selangor Estuary.

The calibration technique for the Malacca Strait Model is capable of generating a very accurate tidal flow model. The common calibration of tidal flow models with Delft3D includes only one manual correction for the boundary conditions. The adjustments made in this one step should lead to the optimised boundary condition. In reality this requires very much experience with tidal models, knowledge of tidal waves and a good portion of luck. Furthermore the manual adjustments of the boundary conditions are time consuming. The calibration technique applied in this research can adjust the boundary conditions within minutes. The exact diagnosis of how the flow parameters should be adjusted is also only possible with the applied technique. When the model is manually corrected, it is often difficult to say whether the deviations of the observed and calculated tides are caused by inaccurate boundary conditions or by inaccurate flow parameters. In theory the calibration technique could be applied to every Delft3D tidal flow model. However, this requires some more generalisation and optimisation of the technique.

The tide model for the Malacca Strait is capable of predicting the water levels with an accuracy of a few tens of centimetres and with a time lag of a few tens of minutes. The Northern Approach Model is more accurate and predicts with an accuracy of several centimetres and a time lag of several minutes.

The modelling of the Selangor Estuary was complicated by the lack of reliable data. During the two months stay in Malaysia a lot of effort led to the collection of sufficient data for the modelling of the Estuary. The only flaw in the data remained an accurate bathymetry of the whole modelled area. The available cross-sections did provide a good indication but for numerical modelling more dense depth measurements are required. Considering this deficit the created model showed very well results. Simulations and measurements agree well on the time of high water and turning flow and salt levels are simulated with an accuracy of a few ppt. Stratification is also simulated in agreement with the measurements.

With the validated Selangor Estuary Model a relation between discharge and salt intrusion is derived for an average tidal range. The advance of the maximal salt intrusion shows an increasing rate with a declining discharge. Stratification reduces for small discharges. Before water extraction the average flow in the dry season (jul/aug) was about 30 m^3/s. Nowadays a base flow is guaranteed of 3.5 m^3/s, which will be the prevailing discharge in the dry season. This causes the maximum salt limit of 6.5 ppt at the surface to advance 3.4 kilometres further upstream for an average tidal range. The part of the river with a salinity higher than 6.5 more than 50% of an average tidal cycle shift even 4.5 kilometres upstream. The limit of 6.5 ppt is known to have a negative effect on the growth of Berembang Trees under constant conditions. How Berembang Trees are affected by variable salt levels is not yet known and needs to be investigated in order to determine whether the shift in salt intrusion harms the ecosystem. However it is clear that higher salt levels will prevail and last for a longer period of the tidal cycle. All of the simulations are based on an average tidal cycle with a tidal range of 2.7 metres. The tidal range in the Selangor Estuary varies between 0.6 and 5 metres. It is clear that the salt intrusion is related to the tidal range. A high tidal range will cause the salt intrusion further upstream.

In the long run two scenarios are likely to occur. The sea level will rise because of the global warming and the bed level of the Selangor River will rise because of the change in discharge regime. Simulations showed that the sea level rise will cause the salt intrusion to advance further by several hundreds of metres, while a bed level rise has no significant effect.

Each of the models demonstrated the importance of a reliable bathymetry. Accurate depth measurements with a high density are one of the keys for success for the hydrodynamic modeller. With the certainty of an accurate bathymetry the modeller can focus on the real calibration parameters as bottom roughness and turbulence. The process of adjusting depths to fit measurements with model results leads to an endless process of calibration.

6.2 Recommendations

Water as a natural resource is becoming a scarce good in many parts of the world. Traditionally, Malaysia has an abundant supply of fresh water. However the demand for fresh water in the state Selangor is growing at such a rate that these quantities of water can no longer be extracted from the river without affecting the natural environment. Although the downgrade of the firefly population cannot be contributed to just one cause, it is clear the advance of the salt intrusion will have an effect. Considered the sensitivity of the eco-system to salt there will be consequences in the long term. Further research is needed to fully assess the impact on the ecosystem. The Forest Research Institute of Malaysia is currently involved in a study of the fireflies. Hopefully this study will contribute to their research and in the understanding of the complex ecosystem in the Selangor Estuary.

Sustainable development is a term which has not yet been widely spread in Malaysia. The conservation of fragile natural ecosystems is not yet been accepted as a common responsibility of society. Although the attitude is slowly changing there is still a long road ahead. To get to a point where natural resources are being used in a sustainable way requests a raise in the consciousness of the problem. People, from the local village in Selangor to the urban areas in Kuala Lumpur, and businesses, from the palm oil plantations to the drinking water company, should be aware of the limits of the use of natural resources and be willing to contribute to a sustainable solution. A feasible, short term solution to reduce the salt intrusion in the Selangor Estuary does not exist.

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Appendix A

Calibration of boundary conditions for the Malacca Strait Model

The Malacca Strait Model has two open boundaries where the water level is enforced by astronomical constituents. Each of these constituents consists of an amplitude and a phase. The tidal wave has to propagate within the limits of these boundaries. This means that for every partial tide the phase difference between the two boundaries is fixed and the top of each wave has to travel from one boundary to the other within the enforced time. The same is applicable for the amplitudes of the partial wave. Because of the length-width ratio of the model area, the propagation of the tidal wave in the middle part will be controlled by the bathymetry and the flow parameters.

The boundaries of the Malacca Strait Model are divided in sections. The northwest boundary consists of five sections and the southeast boundary consists of six sections. For each of the sections the water level is determined by the average of two points on the edges of the sections. In these points the water level is determined for each time step based on the tidal amplitudes and phases of the included tidal constituents. Summarised the model consists of 11 boundary sections, 22 boundary points and 21 constituents. Note that some of the boundary points overlap because boundary sections adjoin.

The difficulty of the adjustments of the boundaries is the fact that a change in phase will affect the amplitude and vice versa. For example: if for any partial tide the phase difference between the boundaries becomes smaller, this partial tide will propagate faster trough the model and an increased shoaling effect will cause an increase of the average amplitude of this partial tide in the model. These effects complicate the establishment of a perfect fit of the boundaries. Moreover the results of a tidal analysis for a period of 33 days should be interpreted with care. The reliability of a tidal analysis depends on the period of the constituent, the period of the time series of water levels and the amplitude of the constituent. Moreover the accuracy of the coupling relations is involved. The calibration of the tidal wave in the Malacca Strait Model does not only require a lot of insight in the behaviour of tidal waves but also in the reliability of results.
Initially the problem was faced by visualising the deviations between measurements and model results for each partial tide. This resulted in maps of the Malacca Strait Model which showed the deviations of amplitudes and phases for each partial tide. Based on these maps the boundaries were adjusted to improve the fit of the model with the measurements. However this leads to a labour-intensive process because there are 22 boundary points and 21 constituents with an amplitude and a phase. Additionally the adjustment of the boundary conditions is complicated by the fact that a change in the phase affects the amplitude and vice versa.

The manual adjustment of boundary conditions led to an improvement of the model results but it appeared to be nearly impossible to obtain a perfect fit. To solve this issue a program was written with the Matlab Software (page B-4). The program could be applied after a model simulation and a tidal analysis of the results. The Matlab script is included at the end of this Appendix. The following steps are taken:

1. The boundary conditions, the results of tidal analysis, locations of boundary points and locations of observation points are read. The tidal analysis with TRIANA includes the deviations between measured and calculated amplitudes and phases. The first is included as calculated amplitude divided by the observed amplitude (Hc/Ho). The latter is included as calculated phase minus observed phase (Gc-Go).
2. For each of the constituents two multiple regression analyses are carried out for the deviation between measured and calculated amplitude (Hc/Ho) and phase (Gc-Go). The predictor variables are longitude and latitude. The results are functions that describe the deviations of the partial tides for the area of the Malacca Strait Model.

3. With locations of the boundary points and the created functions, the deviations are extrapolated to the boundary points. These extrapolated deviations will be used to correct the boundary conditions.
4. For each constituent the amplitude is corrected by dividing the original amplitude of the boundary by the extrapolated deviation for the amplitude. The phase is corrected by subtracting the extrapolated deviation for the phase.
5. The new values for the phases of the constituents are checked and corrected for the transition from 360 to zero degrees.
6. When two boundary points of the same boundary section have phases of over zero and just below 360, the Delft3D software will calculate a phase of about 180 degrees. The new values for the phases are checked for these phase transitions within a boundary section.
7. When calculated and observed values differ considerably, the result can be that the correction factor at the boundary becomes negative or zero. The new amplitudes are checked for negative and zero values.
8. The new boundary conditions are written in a file which is compatible with the Delft3D software.

The new boundary conditions lead to a better fit of the calculated and observed tidal wave. However the adjustments to the phases affect the amplitude and vice versa. The process improves the boundary conditions but should be repeated to obtain a perfect fit of the observed and calculated tide. Depending on the correctness of the initial boundary conditions it can take up to five iterative steps before the perfect fit is obtained. The iteration process is ended when the new Matlab-generated boundary conditions are equal to the boundary conditions of the last simulation. This generally leads to an average value for Gc-Go close to zero and for Hc/Ho close to one. Because of the multiple regression not all locations weigh the same and the process will not lead to exact values of respectively zero and one.

The aforementioned process appeared to work effectively. The disadvantage is that several simulations have to be made to obtain a perfect fit. With a simulation time of 14 hours for one run, this can easily take a week.

The technique can be applied to other tidal flow models in general. However it can be further optimised and a few aspects require attention.

- Long term constituents cannot be analysed accurately in a simulation of just 33 days.
- The smaller the amplitude of a constituents, the less reliable a tidal analysis. For the smallest amplitudes the technique did not work with a simulation time of 33 days.
- The Delft3D output file (tba-file) includes only four digits.
- Coupling relations disturb the optimisation of the model and should be avoided.

When a simulation time of 33 days is applied the calibration should be restricted to the dominant constituents in an area. For small and long term constituents a simulation time of a year is recommended.

Matlab Script to optimise boundaries for a tidal flow model

```
run = 72;
dir = ['C:\Delft3D\Nested_70_serie\Nested_',num2str(run),'\'];
mkdir(['C:\Delft3D\Nested_70_serie\Nested_',num2str(run+1),'\']);
newdir = ['C:\Delft3D\Nested_70_serie\Nested_',num2str(run+1),'\'];

mapfile = vs_use('c:\Delft3D\Nested_70_serie\Nested_70_mapgenerator\trim-MS.dat');
xz  = squeeze(vs_let(mapfile,'map-const','XZ','quiet')); xz(xz==0)=NaN;
yz  = squeeze(vs_let(mapfile,'map-const','YZ','quiet')); yz(yz==0)=NaN;

tba = qpfopen([dir,'MSTrianaM.tba']);  nr_st = 21; %Number of stations included

%Multiple regression with x and y as variables for the corrections for amplitude and
phases for all constituents
for k=1:21
    eval([    'DataAm',num2str(k),' =
[tba.Field(1,k).Data(:,3),tba.Field(1,k).Data(:,4),tba.Field(1,k).Data(:,11)];'     ]);
    eval([    'for m= 1:nr_st; if DataAm',num2str(k),'((nr_st+1-m),3)==999.999;
DataAm',num2str(k),'((nr_st+1-m),:)=[]; end; end;' ]);
    eval([    'MatrixAm',num2str(k),' = [ones(size(DataAm',num2str(k),'(:,1),1),1)
DataAm',num2str(k),'(:,1)  DataAm',num2str(k),'(:,2)];']);
    eval([    'CorrAm',num2str(k),' =
MatrixAm',num2str(k),'\DataAm',num2str(k),'(:,3);'    ]);

    eval([    'DataPh',num2str(k),' =
[tba.Field(1,k).Data(:,3),tba.Field(1,k).Data(:,4),tba.Field(1,k).Data(:,10)];'     ]);
    eval([    'for m= 1:nr_st; if DataPh',num2str(k),'((nr_st+1-m),3)==999.999;
DataPh',num2str(k),'((nr_st+1-m),:)=[]; end; end;' ]);
    eval([    'MatrixPh',num2str(k),' = [ones(size(DataPh',num2str(k),'(:,1),1),1)
DataPh',num2str(k),'(:,1)  DataPh',num2str(k),'(:,2)];']);
    eval([    'CorrPh',num2str(k),' =
MatrixPh',num2str(k),'\DataPh',num2str(k),'(:,3);'    ]);
end

%Reading of the grid locations from the bnd-file
[BND_M_A, BND_N_A, BND_M_B, BND_N_B] = textread([dir,'MS.bnd'],'%*s%*s%*s %u%u%u%u
%*s%*s%*s');

%Correction for each boundary poind, calculated with the multiple regression relation
and location of the boundary point (11 boundary sections, each two boundary points, 21
constituents)
BND_6_B_17_Am = Correction for the amplitude of boundarypoint 6B for constituent 17
(=M2, see prt-Triana-file)
for k=1:21
    for m=1:11
        eval([  'BND_',num2str(m),'_A_',num2str(k),'_Am = CorrAm',num2str(k),'(1) +
CorrAm',num2str(k),'(2)*xz(BND_N_A(m),BND_M_A(m))+ '...
            'CorrAm',num2str(k),'(3)*yz(BND_N_A(m),BND_M_A(m)) ;'  ]);
        eval([  'BND_',num2str(m),'_B_',num2str(k),'_Am = CorrAm',num2str(k),'(1) +
CorrAm',num2str(k),'(2)*xz(BND_N_B(m),BND_M_B(m))+ '...
            'CorrAm',num2str(k),'(3)*yz(BND_N_B(m),BND_M_B(m)) ;'  ]);
        eval([  'BND_',num2str(m),'_A_',num2str(k),'_Ph = CorrPh',num2str(k),'(1) +
CorrPh',num2str(k),'(2)*xz(BND_N_A(m),BND_M_A(m))+ '...
            'CorrPh',num2str(k),'(3)*yz(BND_N_A(m),BND_M_A(m)) ;'  ]);
        eval([  'BND_',num2str(m),'_B_',num2str(k),'_Ph = CorrPh',num2str(k),'(1) +
CorrPh',num2str(k),'(2)*xz(BND_N_B(m),BND_M_B(m))+ '...
            'CorrPh',num2str(k),'(3)*yz(BND_N_B(m),BND_M_B(m)) ;'  ]);
    end
end

%Reading of the current boundary conditions from the bnd-file
fid = fopen([dir,'MS_XY_MR.bca'],'rt');
k=1; while 1;  tline = fgetl(fid);   if ~ischar(tline),   break,   end;   BCA(k) =
textscan(tline,'%s');    k=k+1;  end;    fclose(fid);

for m=1:22; for k=1:21; bca_ampl(k + 21*(m-1),1) = str2num(BCA{1,(2 + k + 23*(m-
1))}{2,1}); end; end;
for m=1:22; for k=1:21; bca_phase(k + 21*(m-1),1) = str2num(BCA{1,(2 + k + 23*(m-
1))}{3,1}); end; end;

%Sequence of constituents in Triana (only when different from bca-file)
SeqTr = [6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 5 4 1 2 3];
```

```
%Applying the correction to the current boundary condition
for k= 1:21 % k=1:21 = all constituents, in this study only the main constituents are
optimised, for example: k=[2 4 9 12 14], sequence of the bca-file
    for m=1:11
        eval([  'bca_ampl(k+42*(m-1),1)  = bca_ampl(k+42*(m-1),1)  /
BND_',num2str(m),'_A_',num2str(SeqTr(k)),'_Am;'  ]);
        eval([  'bca_phase(k+42*(m-1),1) = bca_phase(k+42*(m-1),1) -
BND_',num2str(m),'_A_',num2str(SeqTr(k)),'_Ph;'  ]);

        eval([  'bca_ampl(k+21+42*(m-1),1)  = bca_ampl(k+21+42*(m-1),1)  /
BND_',num2str(m),'_B_',num2str(SeqTr(k)),'_Am;'  ]);
        eval([  'bca_phase(k+21+42*(m-1),1) = bca_phase(k+21+42*(m-1),1) -
BND_',num2str(m),'_B_',num2str(SeqTr(k)),'_Ph;'  ]);
    end
end

%Check for phases smaller than 0 or greater than 360
for k=1:16
    for m=1:11
        if bca_phase(k+42*(m-1),1) < 0
            bca_phase(k+42*(m-1),1) = bca_phase(k+42*(m-1),1) + 360;
        end
        if bca_phase(k+42*(m-1),1) > 360
            bca_phase(k+42*(m-1),1) = bca_phase(k+42*(m-1),1) - 360;
        end
        if bca_phase(k+21+42*(m-1),1) < 0
            bca_phase(k+21+42*(m-1),1) = bca_phase(k+21+42*(m-1),1) + 360;
        end
        if bca_phase(k+21+42*(m-1),1) > 360
            bca_phase(k+21+42*(m-1),1) = bca_phase(k+21+42*(m-1),1) - 360;
        end
    end
end

%Check for phase transitions within a section (between A and B boundary points)
for k=1:21
    for m=1:11
        if bca_ampl(k+42*(m-1),1) < 0.001
            fprintf(['Warning: Negative or no amplitude in
bnd_',num2str(m),'_A_const_',num2str(k),'\n'])
            %bca_num(k+1+46*(m-1),1) = 0.001;
        end
        if bca_ampl(k+21+42*(m-1),1) < 0.001
            fprintf(['Warning: Negative or no amplitude in
bnd_',num2str(m),'_B_const_',num2str(k),'\n'])
            %bca_num(k+24+46*(m-1),1) = 0.001;
        end
        if abs( bca_phase(k+42*(m-1),1) - bca_phase(k+21+42*(m-1),1) ) > 200
            fprintf(['Warning:
Phase_transition_in_bnd_',num2str(m),'_const_',num2str(k),'\n'])
        end
    end
end

%Creating a new, optimised boundary condition file (bca-file) in a new directory
fid=fopen([newdir,'MS_XY_MR.bca'],'w');
for k=1:22
    fprintf(fid,'%s\n',BCA{1,(1+23*(k-1))}{1,1});
    fprintf(fid,'%s     %6.5f\n',[BCA{1,(2+23*(k-1))}{1,1}],[str2num(BCA{1,(2+23*(k-
1))}{2,1})]);
    for m=1:21
        fprintf(fid,'%s    %6.3f    %6.3f\n',BCA{1,(m+2+23*(k-))}{1,1},bca_ampl(m+21*(k-
1),1),bca_phase(m+21*(k-1),1));
    end
end
```

	ATT No.	Place	Translation	MHWS	MHWN	MLWN	MLWS	MSL
				Waterlevels in meter (Z0 = LAT)				
MALAYSIA SE <- NW	4676	Pulau Jarak	Jarak island	2.3	1.7	1.1	0.5	1.4
	4674	Lumut Pier		3	2.3	1.5	0.7	1.87
	4675	Pulau Katak	katak Island	3	2.3	1.5	0.8	1.9
	4678	Bagan Datuk		2.9	2.1	1.3	0.5	1.67
	4679	Teluk Intan	Intan Bay	4.3	2.9	2.4	1.1	2.65
	4680	Kuala Bernam	Bernam Estuary	3.6	2.7	1.6	0.7	2.17
	4690	Pulau Jemur	Jemur Island	4.3	3.1	1.8	0.5	2.44
	4683	Sungai Selangor	Selangor River	4.6	3.4	2	0.7	2.7
	4684	Pulau Angsa	Angsa Island	5.1	3.8	2.5	1.2	3.13
	4689	Permatang Sedepa	One Fathom Bank	4.3	3.1	1.8	0.6	2.44
	4686	Pelabuhan Klang	Kelang Harbor	5.3	3.9	2.5	1.1	3.21
	4688	Pintu Gedong	Gedong Passage	4.6	3.3	2.1	0.9	2.71
	4693	Tanjung Gabang	Cape Gabang	3.4	2.3	1.3	0.3	1.83
	4695	Port Dickson		2.7	1.9	1.1	0.3	1.5
	4696	Cape Rachado		2.6	1.9	1.1	0.4	1.53
	4698	Tanjung Keling	Cape Keling	2.4	1.8	1.2	0.6	1.48
	4699	Melaka		2.1	1.5	0.9	0.3	1.22
SUMATRA SE <- NW	4795	Kualatanjung		2.8	2.1	1.2	0.5	1.6
	4794	Tanjungtiram		2.3	1.7	0.9	0.3	1.3
	4792	Bagan		3.6	2.6	1.6	0.6	2.1
	4789	Berombang		3.9	2.9	1.5	0.5	2.2
	4790	Labuan Bilik		4.1	2.8	1.6	0.4	2.2
	4785	Bagan Si Api Api		5.3	3.5	1.9	0.1	2.7
	4784	Tanjung Sinaboi	Cape Sinaboi	4.0	2.9	1.7	0.6	2.32
	4783	Tanjung Ketam	Cape Ketam	3.9	2.7	1.6	0.3	2.1
	4782	Tanjung Medang	Cape Medang	2.9	2.1	1.3	0.6	1.7
	4781	Dumai		2.9	2.1	1.3	0.5	1.71
	4780	Tanjung Lebang	Cape Lebang	3.1	2.1	1.3	0.3	1.7

Project location
UHSLC-station

LAT	Lowest Astronomical Tide
MHWS	Mean High Water Springs
MHWN	Mean High Water Neaps
MLWN	Mean Low Water Neaps
MLWS	Mean Low Water Springs
MSL	Mean Sea Level

Tabel 3.1 ATT tidal stations and waterlevels (relative to the lowest astronomical tide)
Both Malaysian as Sumatran stations are sorted from NW at the top to SE at the bottom, which is the direction of the tidal wave

	ATT No.	Place	Translation	M2 Ampl.	M2 Phase	S2 Ampl.	S2 Phase	K1 Ampl.	K1 Phase	O1 Ampl.	O1 Phase
MALAYSIA SE <- NW	4674	Lumut Pier*		0.75	241	0.35	276	0.22	247	0.03	161
	4678	Bagan Datuk*		0.83	269	0.37	310	0.19	258	0.04	158
	4679	Teluk Intan	Intan Bay	0.93	279	0.64	320	0.24	269	0.09	28
	4690	Pulau Jemur	Jemur Island	1.28	270	0.62	307	0.25	232	0.04	72
	4683	Sungai Selangor	Selangor River	1.33	284	0.62	331	0.16	283	0.1	347
	4684	Pulau Angsa	Angsa Island	1.3	275	0.66	322	0.21	273	0.01	223
	4689	Permatang Sedepa	One Fathom Bank	1.25	282	0.62	324	0.17	267	0.05	49
	4686	Pelabuhan Klang*	Port Kelang	1.37	284	0.68	326	0.19	265	0.04	45
	4688	Pintu Gedong	Gedong Passage	1.22	293	0.6	335	0.13	275	0.05	88
	4693	Tanjung Gabang	Cape Gabang	1.01	304	0.51	346	0.08	288	0.13	38
	4695	Port Dickson		0.83	320	0.42	1	0.05	334	0.17	37
	4696	Cape Rachado		0.74	325	0.36	7	0.09	348	0.21	47
	4698	Tanjung Keling*	Cape Keling	0.61	356	0.3	36	0.09	35	0.22	33
	4699	Melaka		0.6	7	0.28	46	0.06	24	0.21	32
SUMATRA SE <- NW	4795	Kualatanjung		0.8	236	0.35	277	0.17	256	0.03	109
	4794	Tanjungtiram		0.71	243	0.33	288	0.19	261	0	NA
	4792	Bagan		1.08	256	0.5	294	0.22	236	0	NA
	4789	Berombang		1.2	281	0.51	328	0.17	278	0	NA
	4790	Labuan Bilik		1.24	292	0.61	334	0.17	271	0	NA
	4785	Bagan Si Api Api		1.7	291	0.9	334	0.18	283	0.04	100
	4784	Tanjung Sinaboi	Cape Sinaboi	1.18	300	0.58	343	0.12	281	0.1	39
	4783	Tanjung Ketam	Cape Ketam	1.2	318	0.6	18	0.1	308	0.2	9
	4782	Tanjung Medang	Cape Medang	0.75	328	0.37	8	0.05	3	0.19	36
	4781	Dumai		0.84	339	0.52	19	0.12	8	0.21	35
	4780	Tanjung Lebang	Cape Lebang	0.9	345	0.5	47	0.1	329	0.2	4

Project location

UHSLC-station

* Data from 2008 Tide Tables Malaysia

Tabel 3.2 ATT tidal stations and harmonic constituents

Amplitude in meter, phase in degree (converted to GMT)

Both Malaysian as Sumatran stations are sorted from NW at the top to SE at the bottom which is the direction of the tidal wave

		Station (analysed period)					
		Lumut (99-01)		Kelang (93-95)		Keling (99-01)	
NAME	FREQUENCY	AMPL. ↓	PHASE	AMPL.	PHASE	AMPL.	PHASE
M2*	28.98	0.741	240.9	1.380	284.6	0.607	355
S2*	30.00	0.348	275.1	0.689	326.7	0.295	34.2
K1*	15.04	0.218	246.1	0.185	265.5	0.088	32.7
N2*	28.44	0.144	233.8	0.268	277.6	0.107	344.8
K2*	30.08	0.099	271.6	0.191	320.9	0.084	28.9
P1*	14.96	0.078	252.4	0.073	273.4	0.027	10.2
SSA*	0.08	0.054	114.5	0.060	120.7	0.042	118.3
O1*	13.94	0.031	157.6	0.039	45.9	0.217	34.3
NU2*	28.51	0.029	232.5	0.048	270.7	0.024	343.1
SA*	0.04	0.028	165.4	0.057	157.5	0.044	236.7
L2*	29.53	0.026	244.9	0.053	261.3	0.026	3.2
S1	15.00	0.024	40.9	0.028	68.7	0.038	117.7
2N2*	27.90	0.023	216.6	0.035	263.2	0.017	327.6
T2*	29.96	0.022	278	0.042	327.4	0.018	35.1
M1*	14.50	0.022	257.5	0.007	323.8	0.016	290.8
J1*	15.59	0.021	290.8	0.034	312	0.014	337.5
MU2*	27.97	0.021	265.3	0.068	316	0.014	88.7
OO1*	16.14	0.021	294.3	0.019	319.8	0.010	5
2MS6	87.97	0.013	109.5	0.079	279.3	0.016	216.7
M4	57.97	0.012	322.2	0.056	84.3	0.027	291.1
MS4	58.98	0.012	357.9	0.061	120.7	0.028	328.6
LABDA2	29.46	0.011	226.1	0.031	263.9	0.014	349.7
2SM2	31.02	0.008	100.6	0.031	143.9	0.017	225.6
MM*	0.54	0.008	8.6	0.008	65.2	0.019	20.3
Q1*	13.40	0.007	121.6	0.008	89	0.032	8.7
M6	86.95	0.007	69.6	0.056	240.5	0.012	182
MSM*	0.47	0.006	318	0.007	35.2	0.006	334.1
MNS2	27.42	0.006	247.4	0.017	314	0.004	76.9
MF*	1.10	0.005	49.4	0.016	0.7	0.009	272.1
MN4	57.42	0.005	310.1	0.022	78.1	0.011	279
MK3	44.03	0.005	214.9	0.023	67.1	0.024	267
MSN2	30.54	0.005	80.3	0.016	116.9	0.009	200.2
MPS2	28.94	0.005	130.6	0.010	187	0.005	258.2
2Q1	12.85	0.005	52.7	0.004	78.9	0.006	45.5
MSP2	29.03	0.004	168.6	0.006	102	0.005	328.6
MSK2	28.90	0.004	305.1	0.004	320.7	0.003	130.3
MSF	1.02	0.004	74.2	0.005	118.9	0.028	49.3

(yellow)	**Compound tide**
(green)	**Overtide**
...*	**Included in boundary of Malacca Strait Model**

Tabel 3.3 Tidal analysis UHSLC waterlevel data (sorted by amplitude of Lumut)
Amplitude in m, phase in degree (GMT); Location of stations are shown in figure XXX

UHSLC-analysis of period 2001-2002 for the stations Lumut Pier, Kelang and Keling.
Analysis of satellite-data based on the five locations in the deepest water.
Equilibrium tide derived from Delft3D TIDE-Manual

RAYLEIGH CRITERION	MODEL	ANALYSIS
	0.455	0.021

			UHSLC-stations		Satellite-data		Equilibrium tide
NAME	**FREQ.**	**DELTA FR.**	**AMPL.**	**PHASE**	**AMPL.**	**PHASE**	**AMPLITUDE**
SA	0.0411				0.1502	-0.3670	
		0.0411					
SSA	0.0821						
		0.3894					
MSM	0.4715				0.2145	4.8100	
		0.0729					
MM	0.5444						
		0.5537					
MF	1.0980						
		12.3006					
Q1	13.3987						
		0.5444					
O1	13.9430						
		0.5537					
M1	14.4967						
		0.4622					
P1	14.9589		0.3557	-3.8667	0.2916	-1.1738	0.3280
		0.0821					
K1	15.0411						
		0.5444					
J1	15.5854						
		0.5537					
OO1	16.1391						
		11.8291					
MU2	27.9682						
		0.4715					
2N2	27.8954		0.1396	-1.5333	0.1337	1.8992	0.1320
		0.5444					
N2	28.4397						
		0.0729					
NU2	28.5126		0.1972	-2.4000	0.1900	-0.1724	0.1940
		0.4715					
M2	28.9841						
		0.5444					
L2	29.5285						
		0.4305					
T2	29.9589		0.0651	-0.3333	0.0584	-2.1740	0.0590
		0.0411					
S2	30.0000						
		0.0821					
K2	30.0821		0.2814	-4.6667	0.2888	-3.7098	0.2840

P1	14.9589		**Coupled (sub-)constituent**
		0.08213728	**Delta frequency smaller than Rayleigh criterion of model**
K1	15.0411		**Main constituent**

Tabel 3.4 Coupling relations *Comparison between coupling relations of TIDE-analysis, satellite data and equilibrium tides*

	Discharge (m3/s)					
	3.5	10	20	30	40	60
Maximum advance of 3.25 ppt limit at bottom	16.5	14.6	13.6	12.6	11.9	11.3
Maximum retreat of 3.25 ppt limit at bottom	7.9	5.2	3.3	2.2	1.1	0.1
Maximum advance of 3.25 ppt limit at surface	16.5	14.4	13.0	12.3	11.5	10.7
Maximum retreat of 3.25 ppt limit at surface	7.9	5.2	3.3	2.1	1.1	0.1
Maximum advance of 6.5 ppt limit at bottom	14.8	13.8	12.5	12.0	11.6	11.3
Maximum retreat of 6.5 ppt limit at bottom	5.5	3.3	1.2	0.3	-	-
Maximum advance of 6.5 ppt limit at surface	14.7	13.1	12.0	11.3	10.7	10.0
Maximum retreat of 6.5 ppt limit at surface	5.5	3.3	1.2	0.2	-	-
Maximum advance of 13 ppt limit at bottom	12.8	12.1	11.5	11.3	11.1	10.9
Maximum retreat of 13 ppt limit at bottom	1.4	-	-	-	-	-
Maximum advance of 13 ppt limit at surface	12.4	11.3	10.4	10.0	9.8	9.2
Maximum retreat of 13 ppt limit at surface	1.4	-	-	-	-	-
Maximum advance of 26 ppt limit at bottom	9.2	8.6	7.7	7.0	6.4	5.6
Maximum retreat of 26 ppt limit at bottom	-	-	-	-	-	-
Maximum advance of 26 ppt limit at surface	8.8	8.3	7.6	6.9	6.3	5.2
Maximum retreat of 26 ppt limit at surface	-	-	-	-	-	-

Tabel 5.1 Salt water intrusion for various discharges and an average tide (tidal range 2.7 metres)

= Area of Aerial photograph of figure 1.2

Location of the Selangor Estuary		
SELANGOR MALAYSIA R1504	Alkyon	Fig. 1.1

Aerial photograph of the Selangor Estuary

Source: GoogleEarth

SELANGOR MALAYSIA R1504 Alkyon Fig. 1.2

SELANGOR MALAYSIA

Overview of Malacca Strait

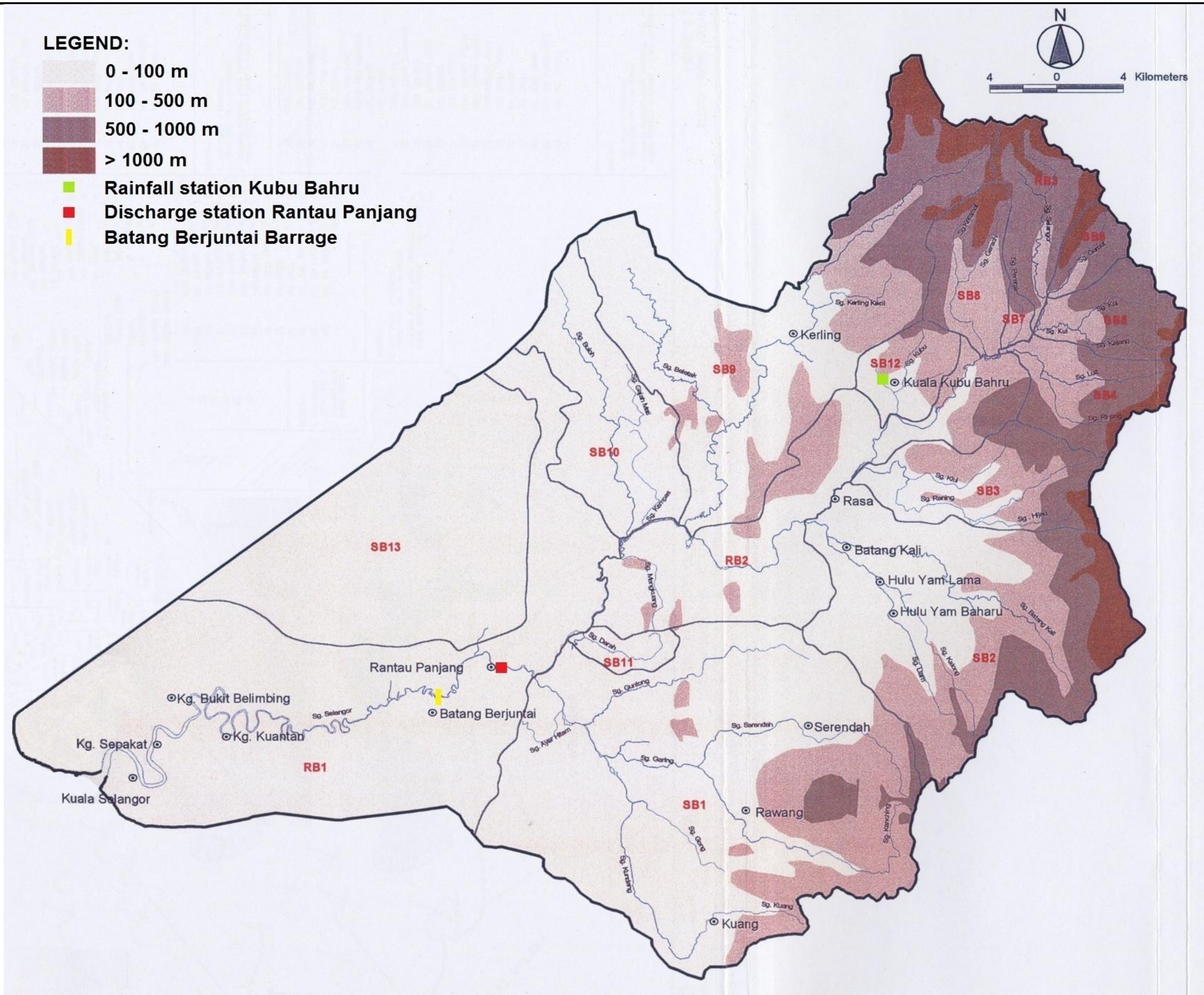
R1504

Alkyon

Fig. 1.3

C:\Selangor\[Figures3.xlsx]summary

Rev. 2: 23 Jun 2008



Contour map of the Selangor River Basin

Source: DID Masterplan Study 2002

SELANGOR MALAYSIA

R1504

Alkyon

Fig. 1.4

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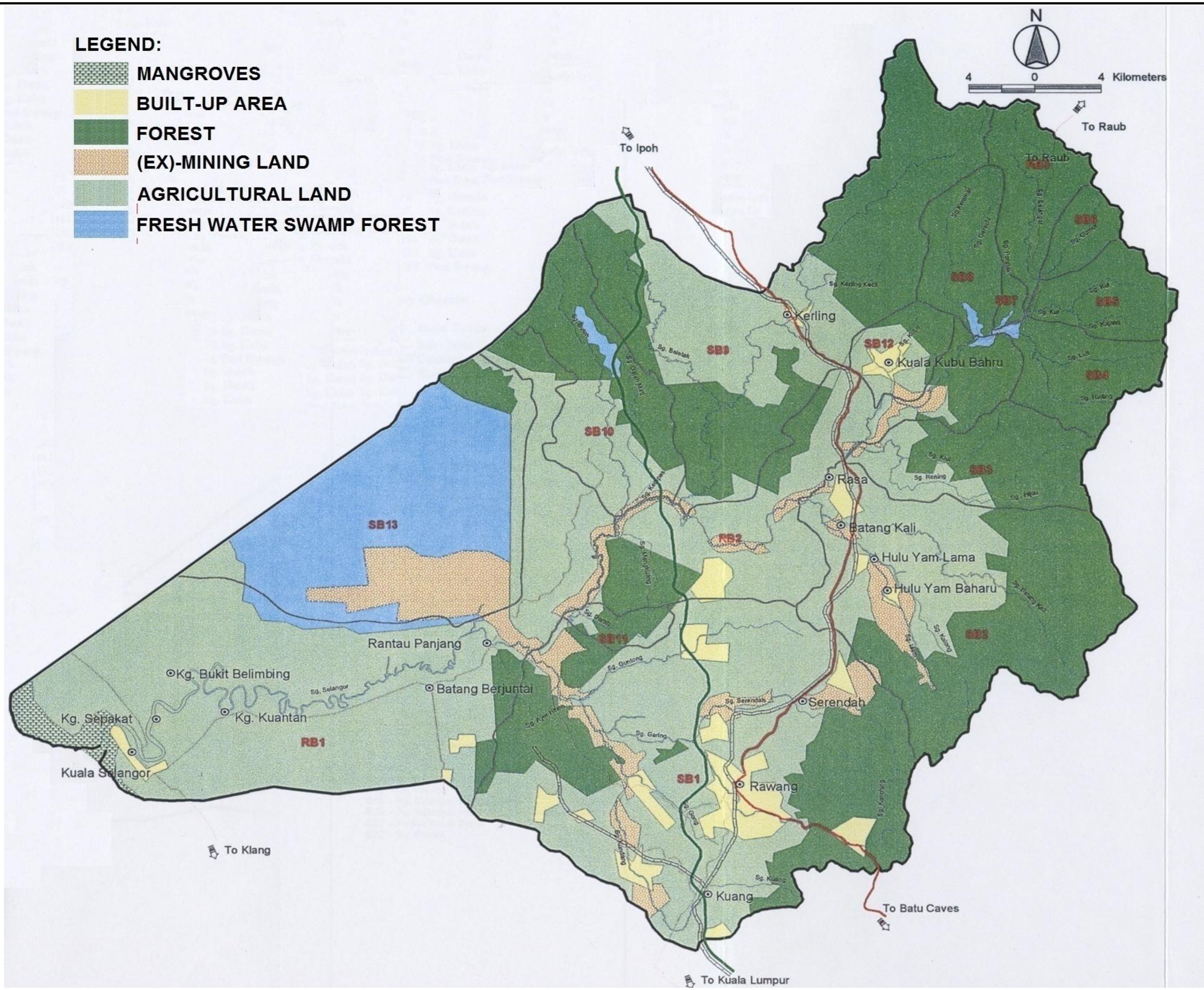
Rev. 2: 23 Jun 2008



Land use of the Selangor River Basin

Source: DID Masterplan Study 2002

SELANGOR MALAYSIA

R1504

Alkyon

Fig. 1.5

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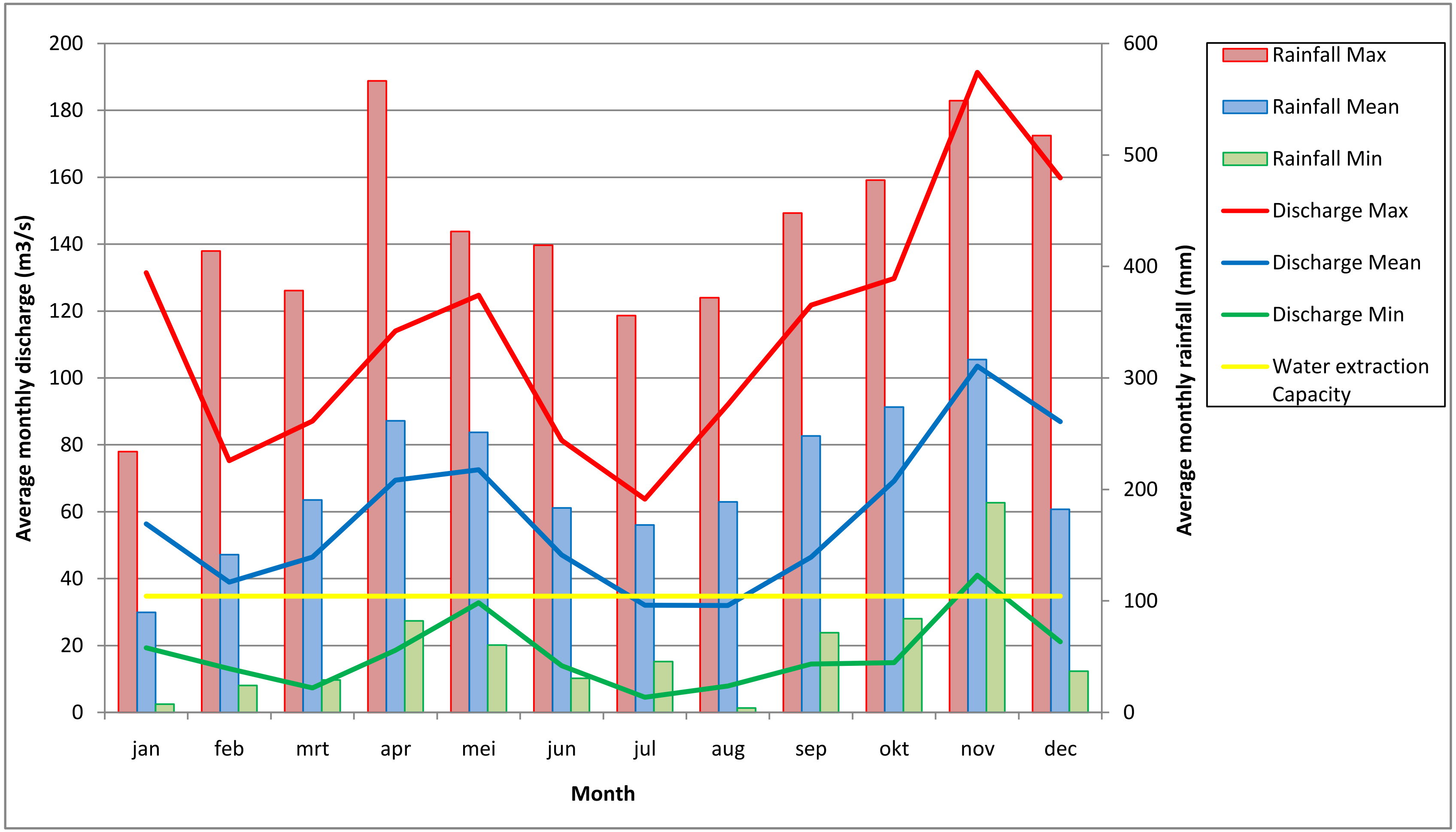
Rev. 2: 23 Jun 2008

Analysis of monthly average values of discharge for the period 1960-2000 and rainfall for the period 1970-1999. (Station locations in figure 1.4)

Source: DID (h2o.water.gov.my)



SELANGOR MALAYSIA

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Fig. 1.6

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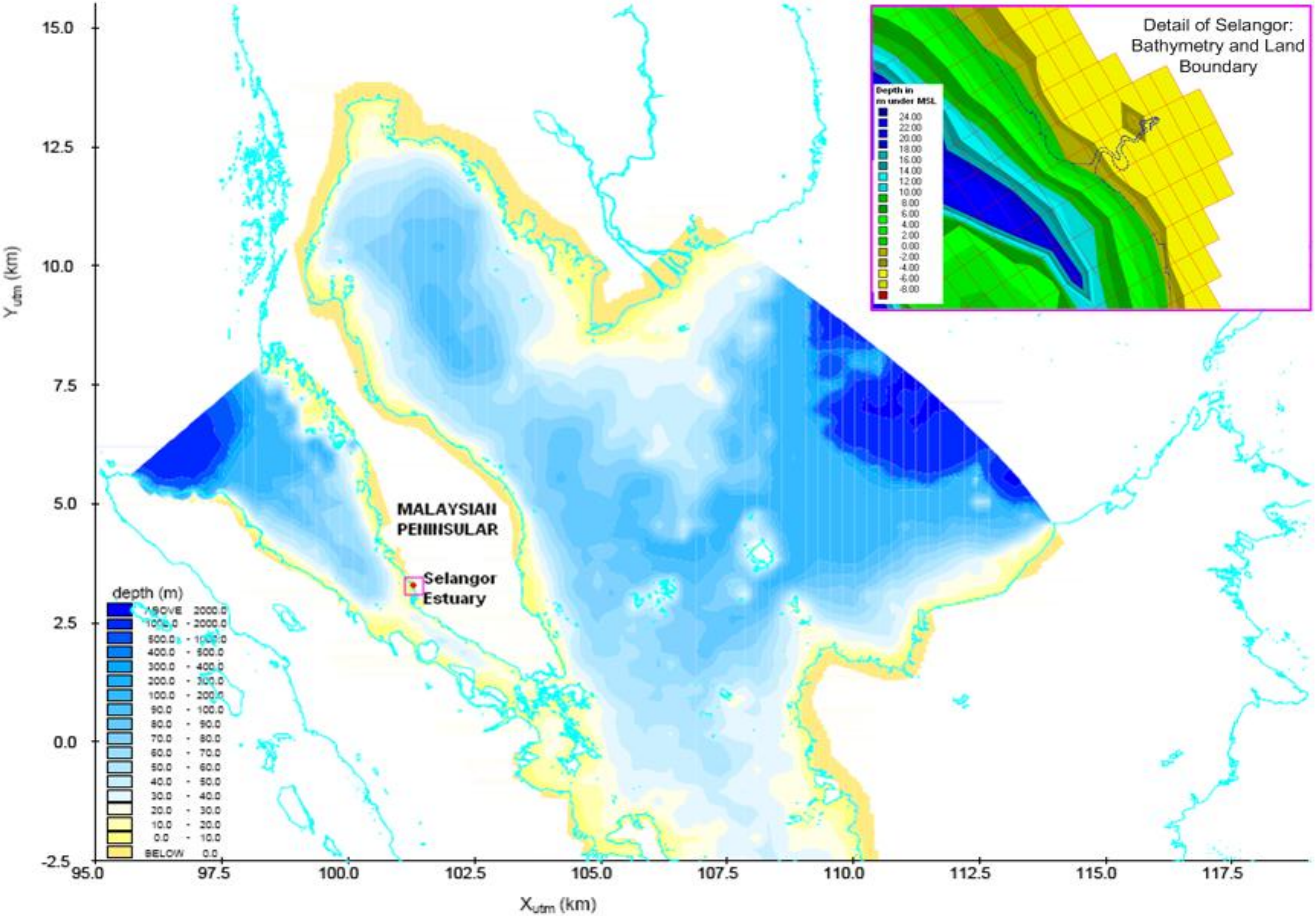
Rev. 2: 23 Jun 2008

SELANGOR MALAYSIA

Malaysia Overall Model



R1504

Alkyon

Fig. 2.1

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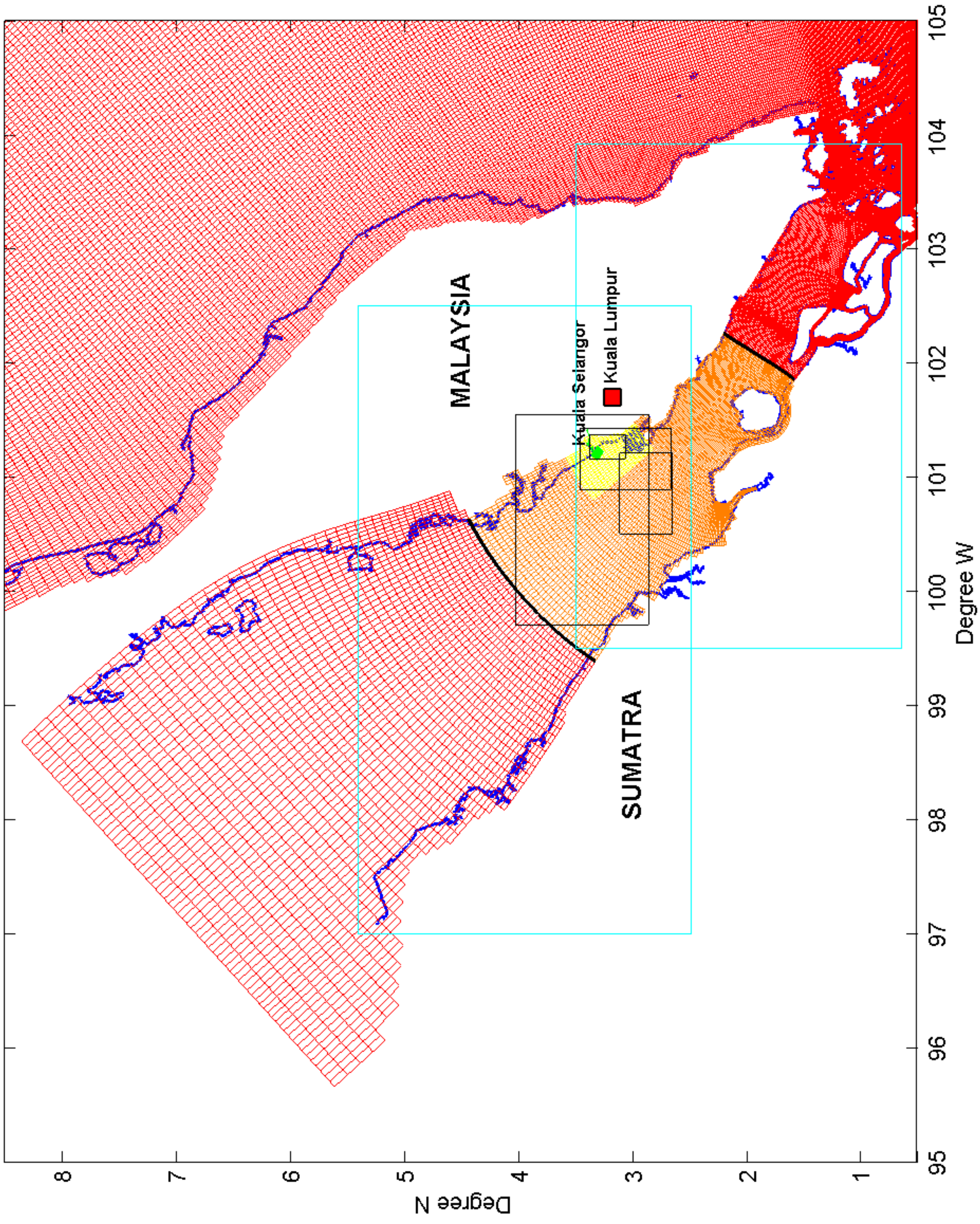
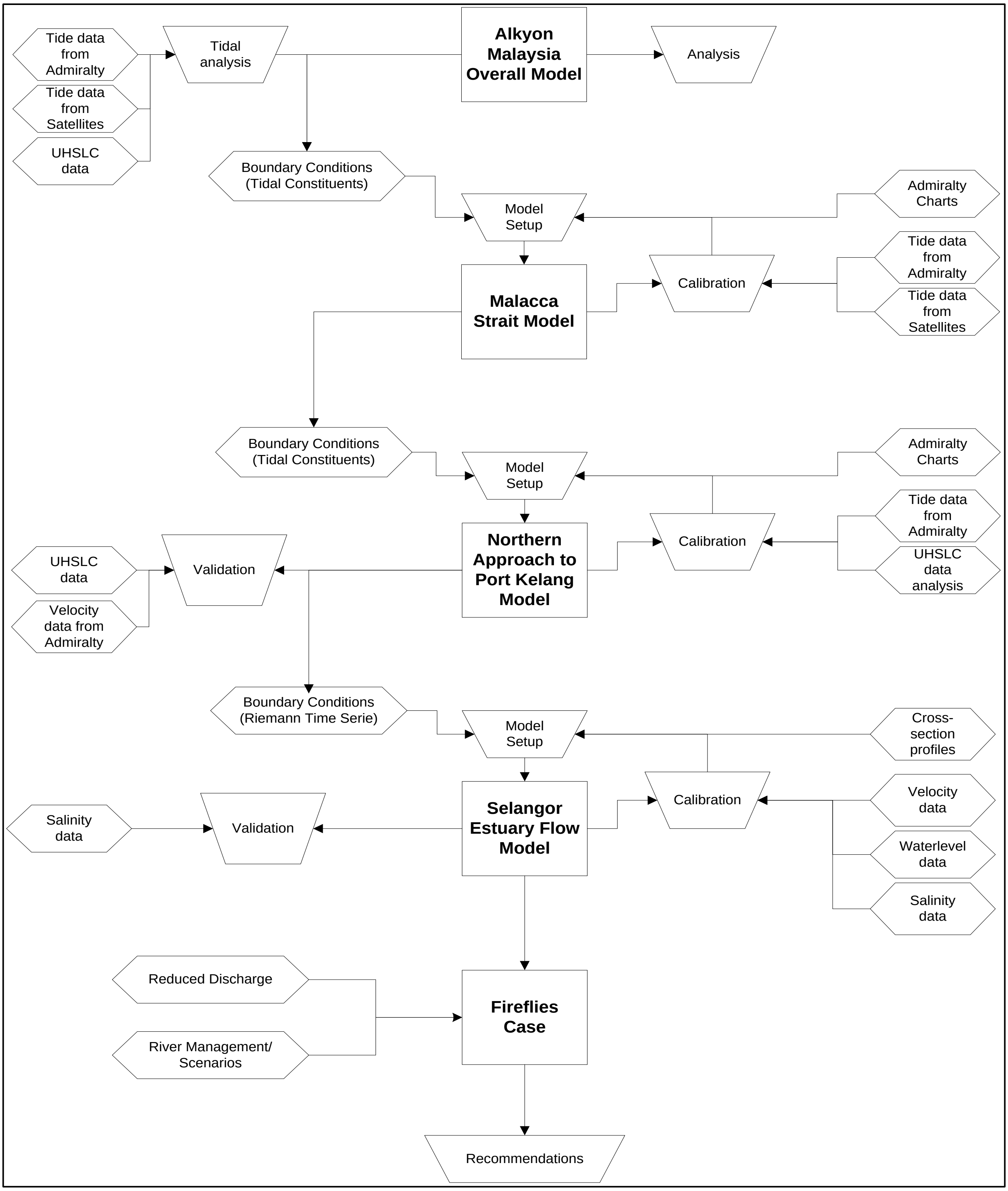
Rev. 2: 23 Jun 2008

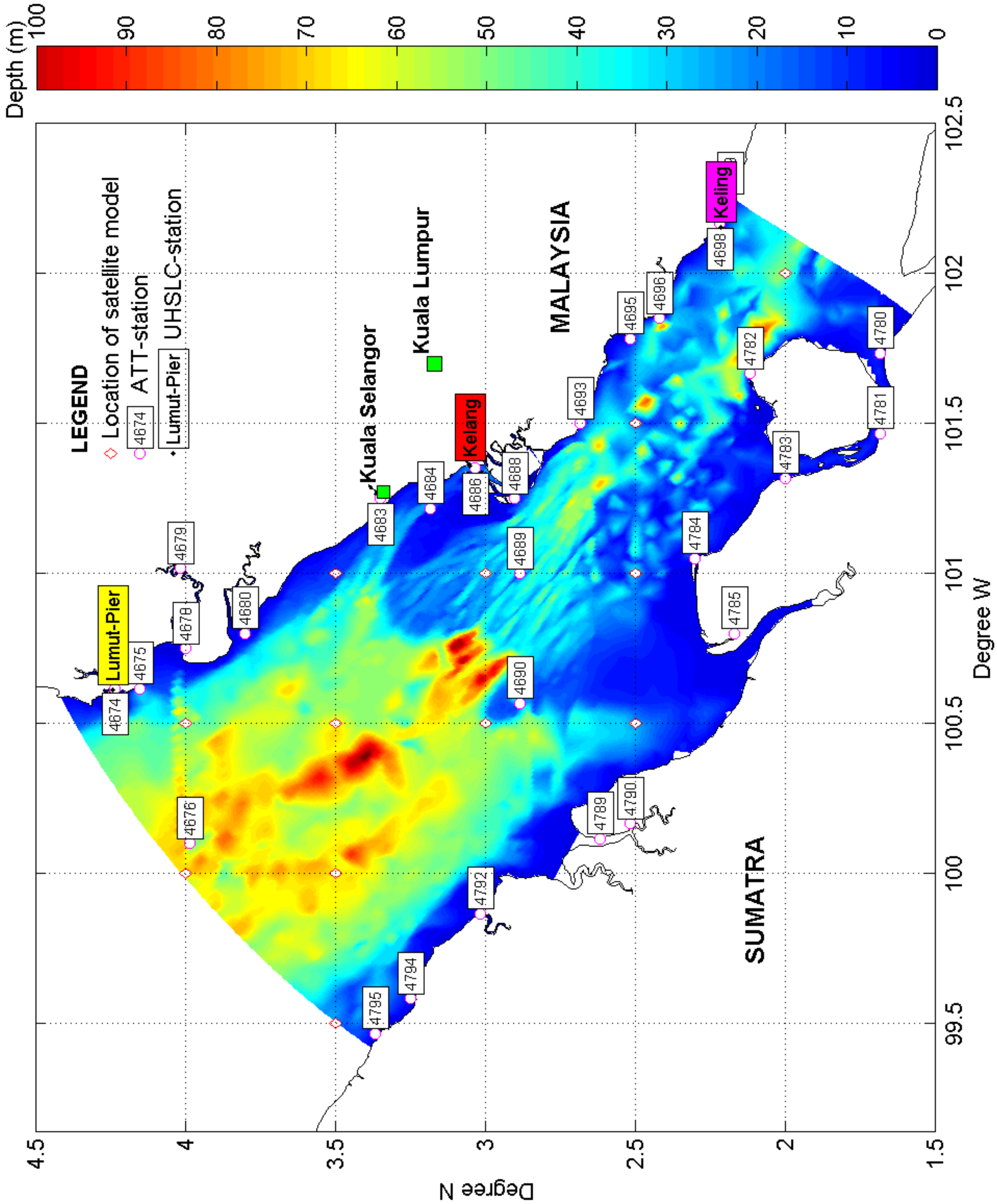


Malaysian Overall model (red), Malacca Strait Model (orange), Northern Approach Model (yellow) and Selangor Estuary Model (green) Blue and black rectangles are the Admiralty Charts of the area	Run ID:	-
Selangor Malaysia R1504	Alkyon	Fig.2.2



Flowchart of the modelling process

SELANGOR MALAYSIA | R1504 | Alkyon | Fig. 2.3



Overview of available tidal data in the Malacca Strait		Run ID:	-
Selangor Malaysia	R1504	Alkyon	Fig.2.4

Selangor Malaysia

Hindcast based on 66 constituents, water levels relative to mean sea level

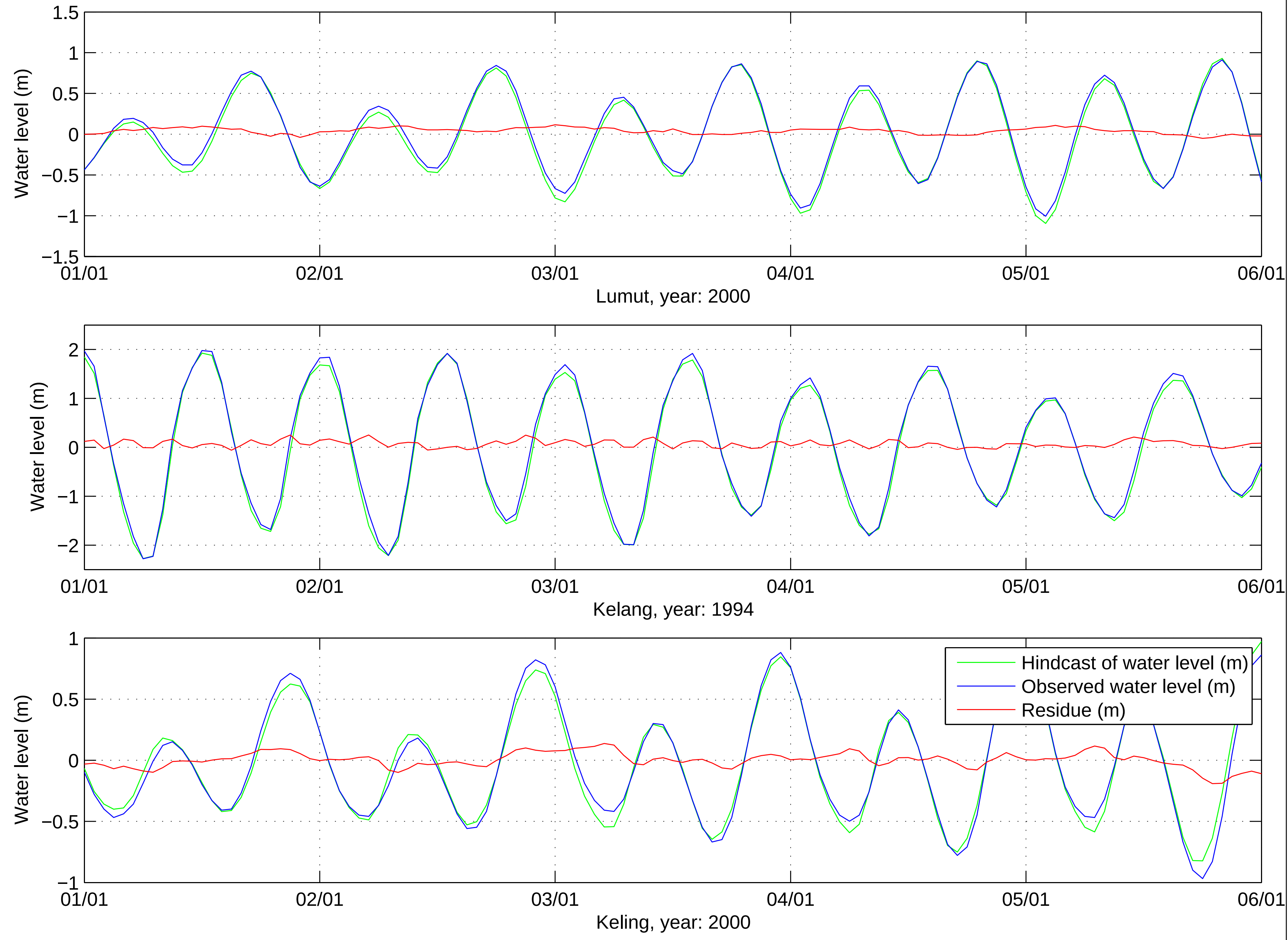
Tidal analysis of UHSLC data for three stations in the Malacca Strait

R1504

Alkyon

Fig.3.3

Run ID: -



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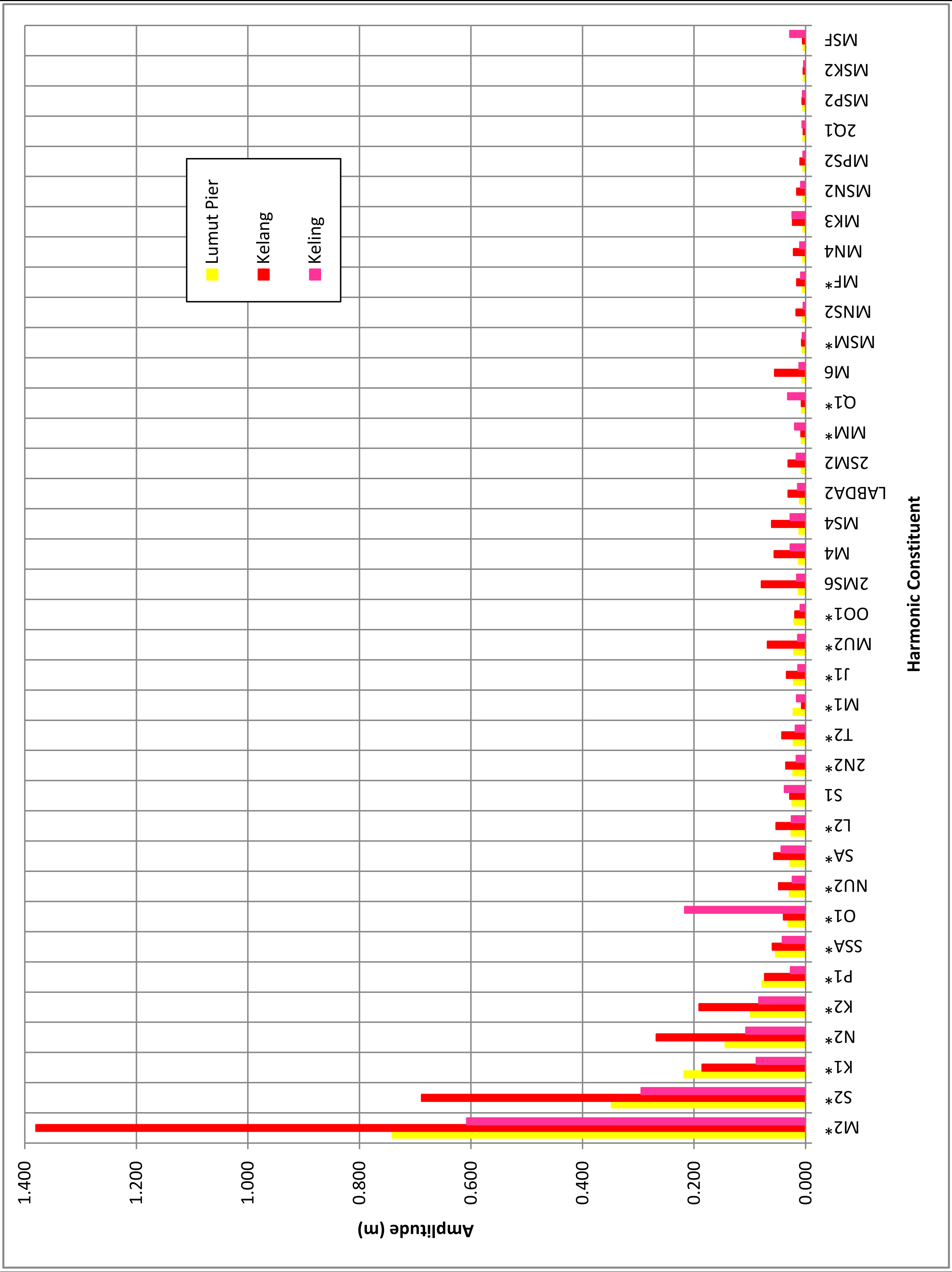
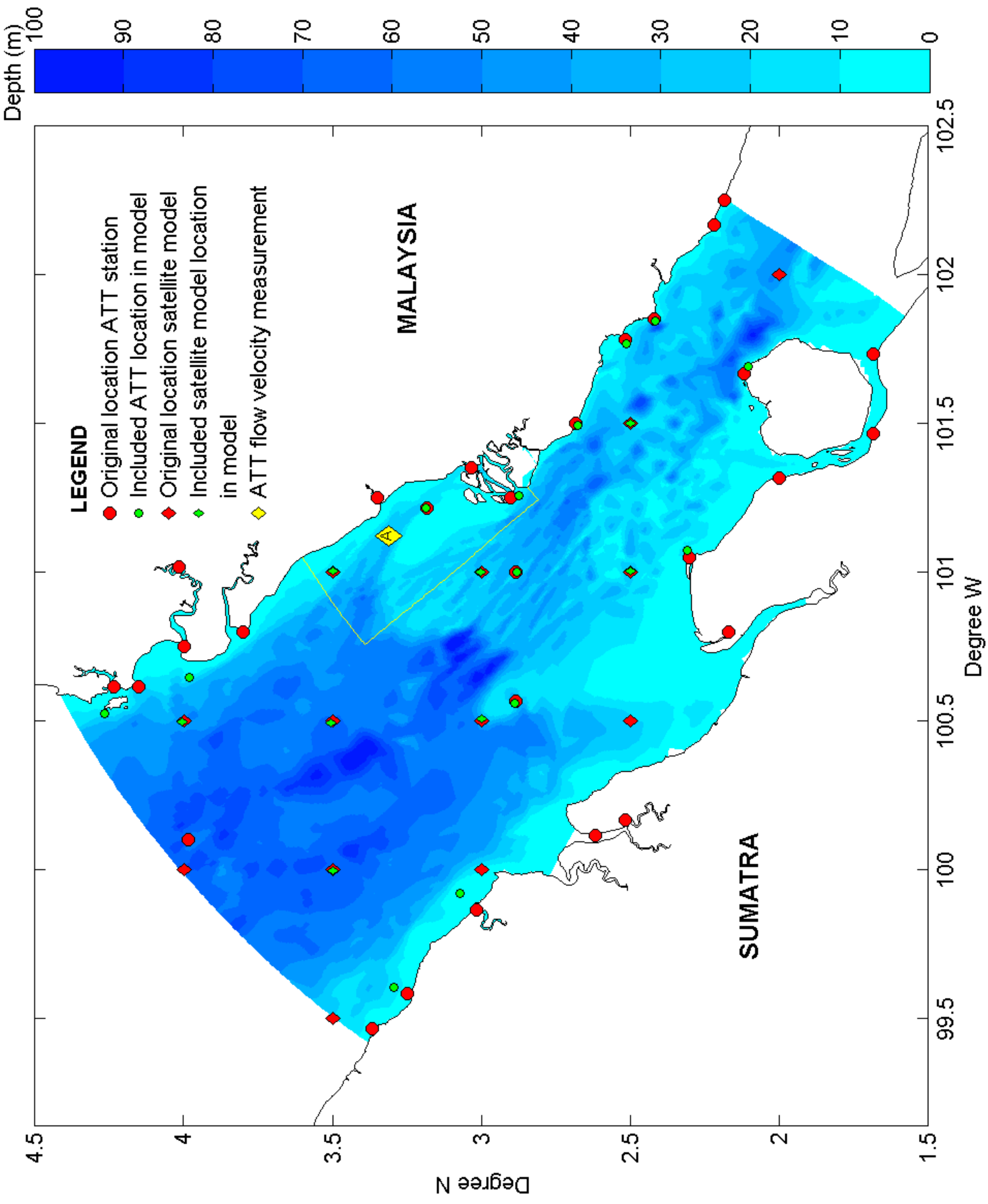
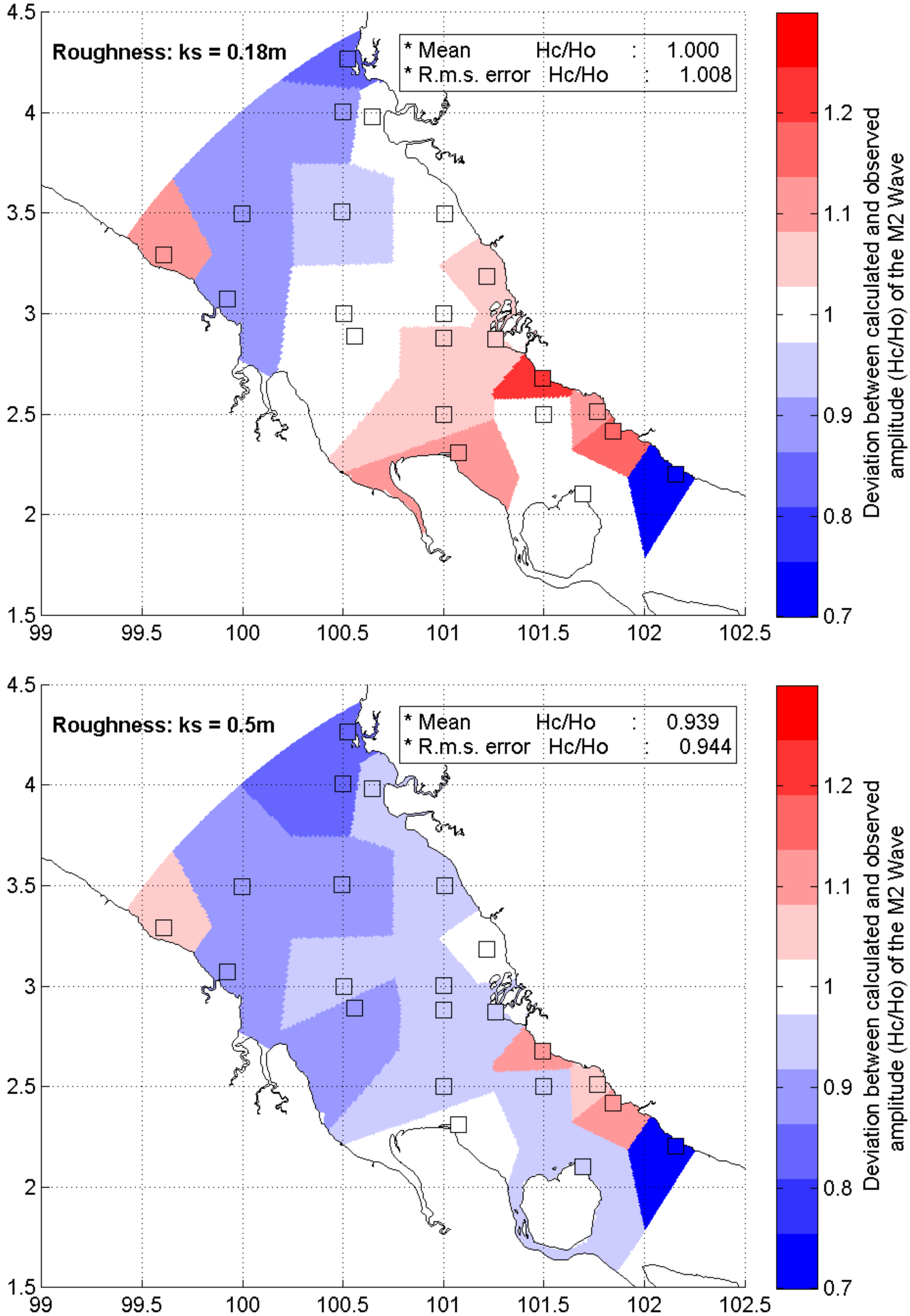


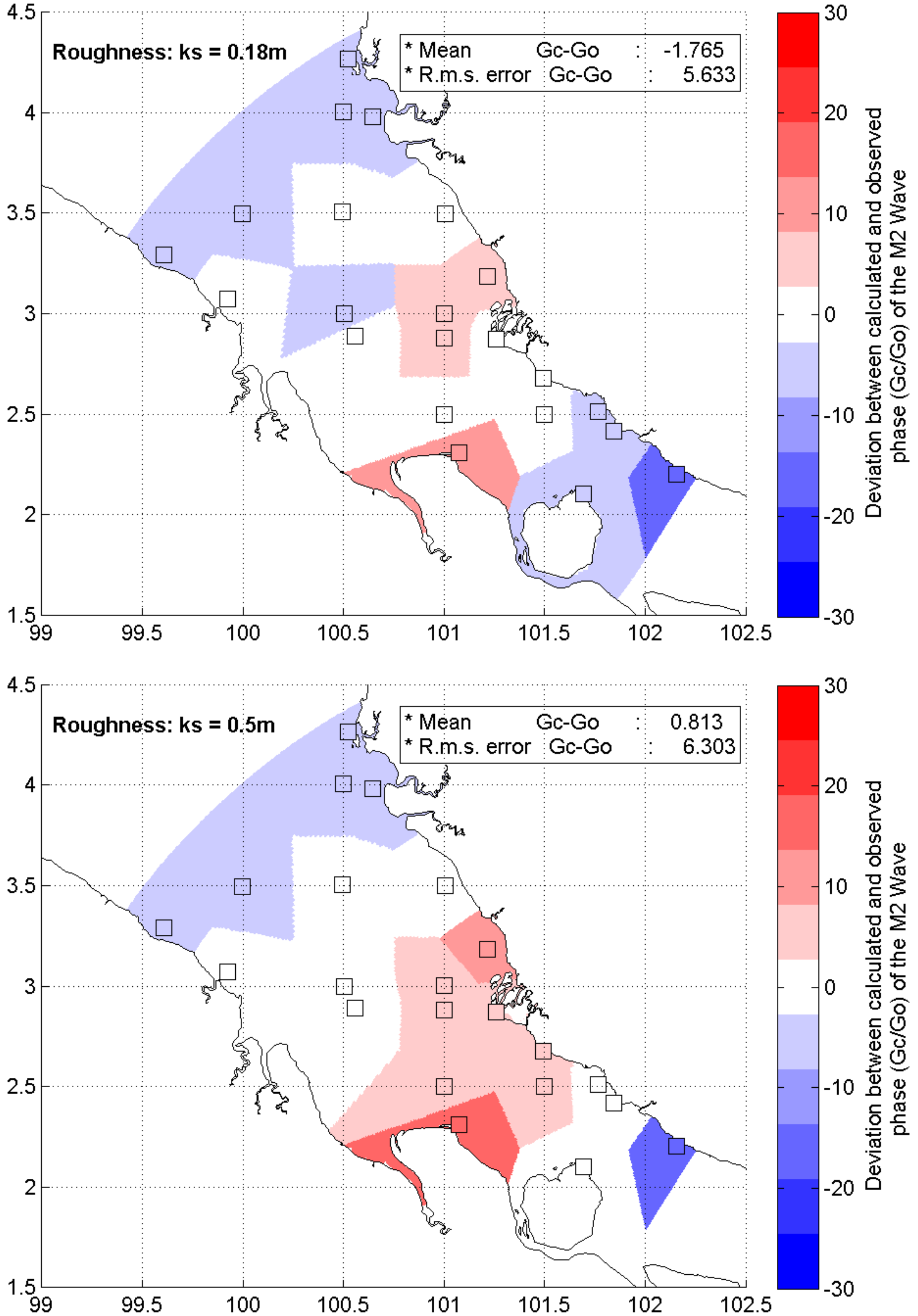
Result of tidal analyses Locations of the tidal stations are shown in figure 2.4 The constituents marked with a star (*) are included in the Malacca Strait Model		
SELANGOR MALAYSIA R1504	Alkyon	Fig. 3.4



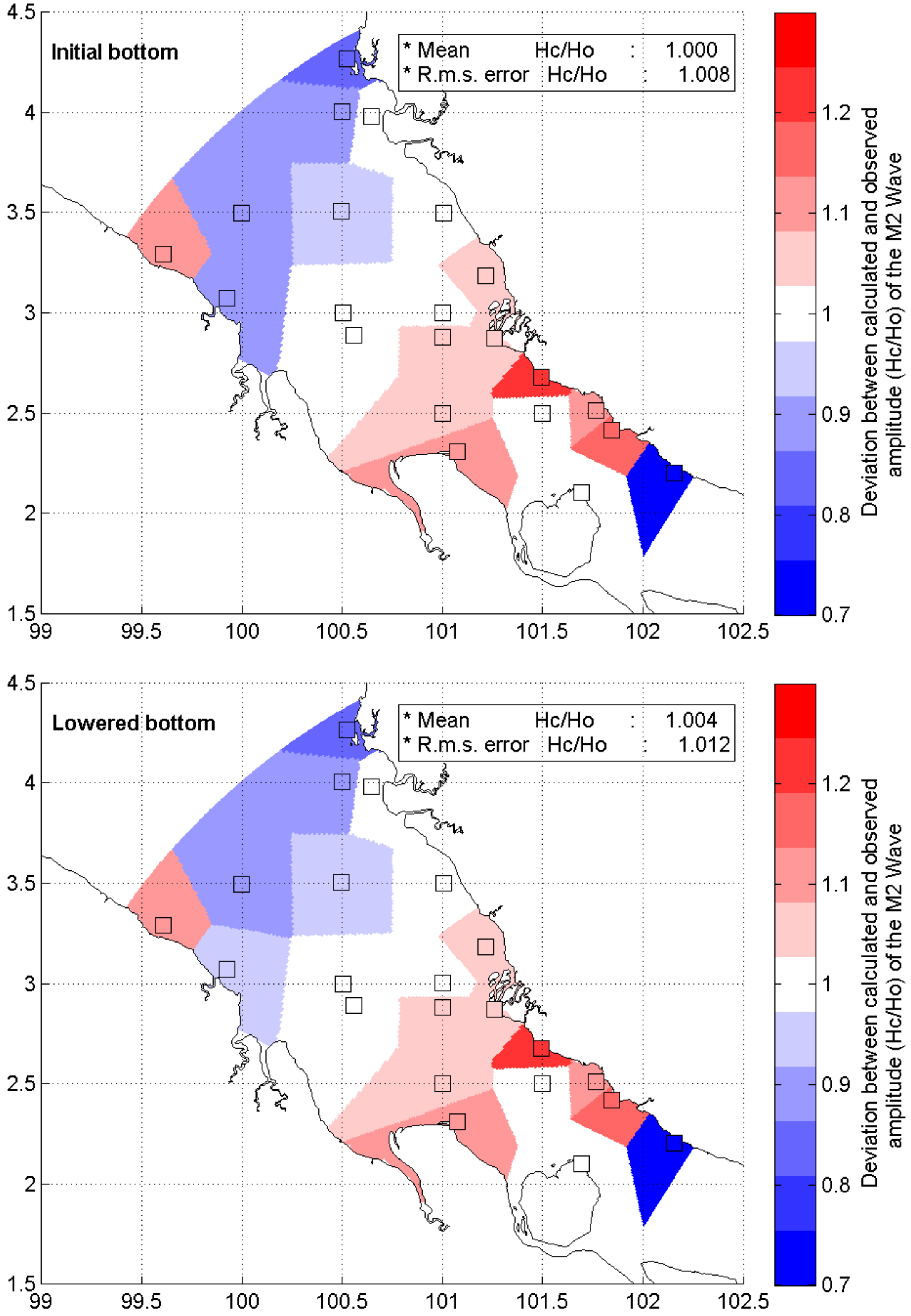
Selection of calibration locations for the Malacca Strait Model	Run ID:	MS
Selangor Malaysia R1504	Alkyon	Fig.3.6



Effect of increased roughness on the amplitude of the M2 tidal wave in the Malacca Strait Model (ks = Nikuradse Roughness Height)	Run ID:	MS
Selangor Malaysia R1504	Alkyon	Fig.3.7a

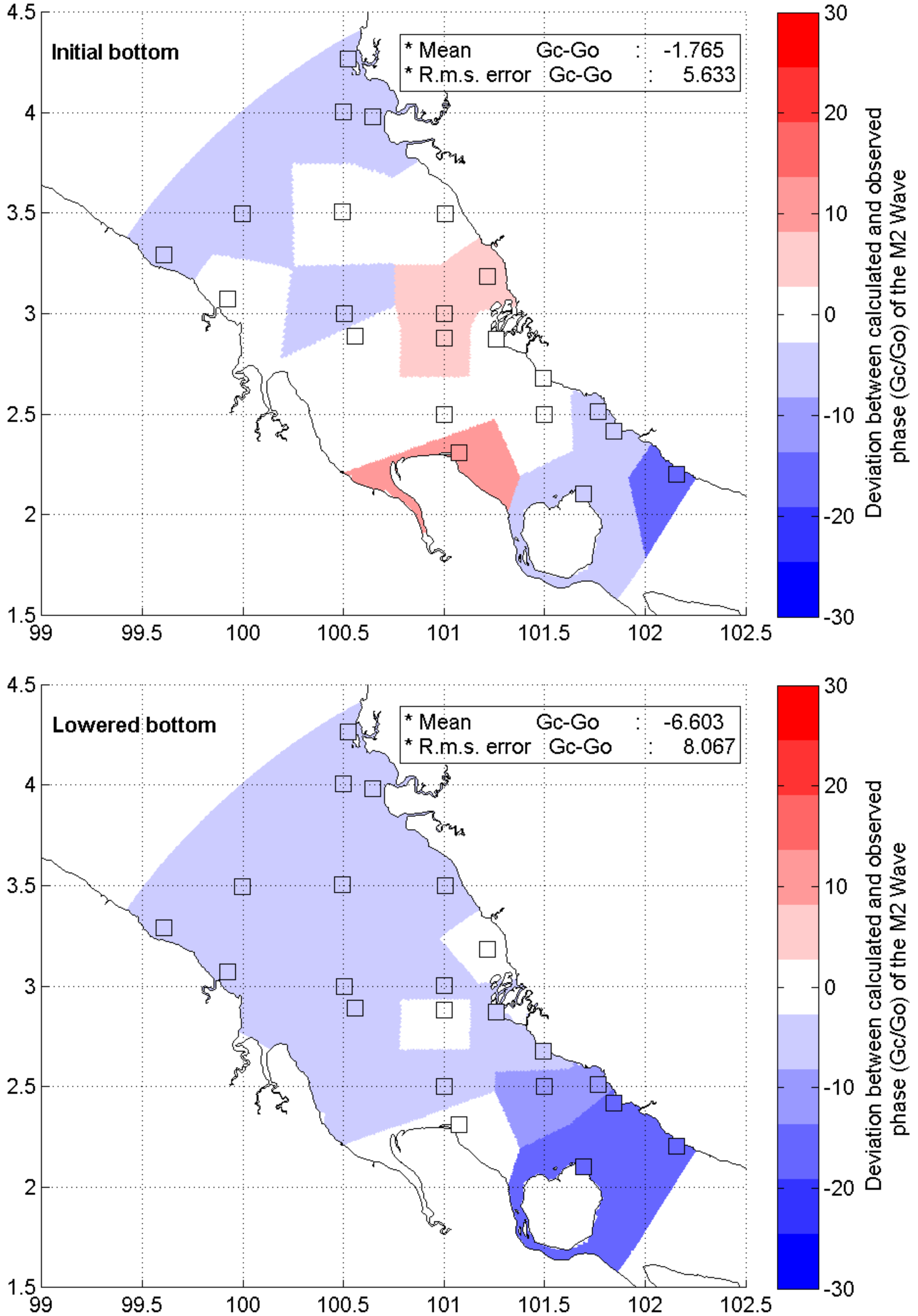


Effect of increased roughness on the phase of the M2 tidal wave in the Malacca Strait Model (ks = Nikuradse Roughness Height)	Run ID:	MS
Selangor Malaysia R1504	Alkyon	Fig.3.7b

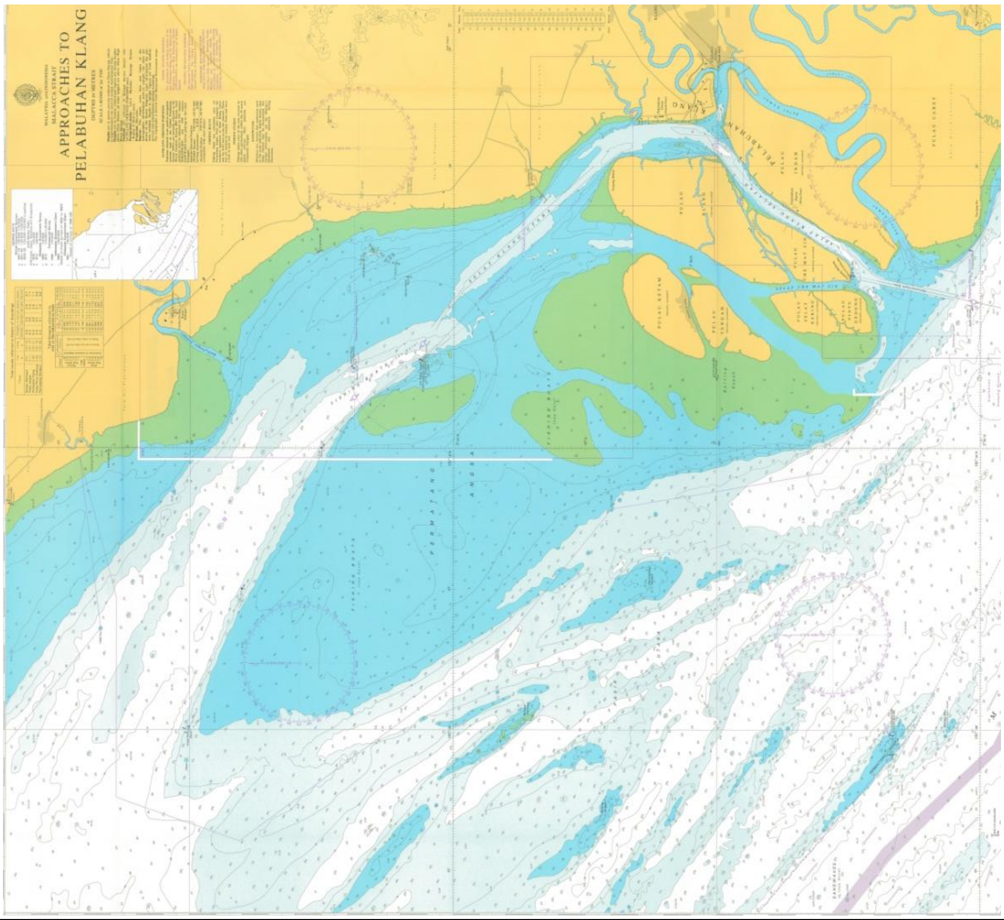


Effect of a uniform bed level lowering of 2 meter on the amplitude of the M2 tidal wave in the Malacca Strait Model

		Run ID:	MS
Selangor Malaysia	R1504	Alkyon	Fig.3.8a



Effect of a uniform bed level lowering of 2 meter on the phase of the M2 tidal wave in the Malacca Strait Model	Run ID:	MS
Selangor Malaysia R1504	Alkyon	Fig.3.8b



Implementation of depth in Delft3D

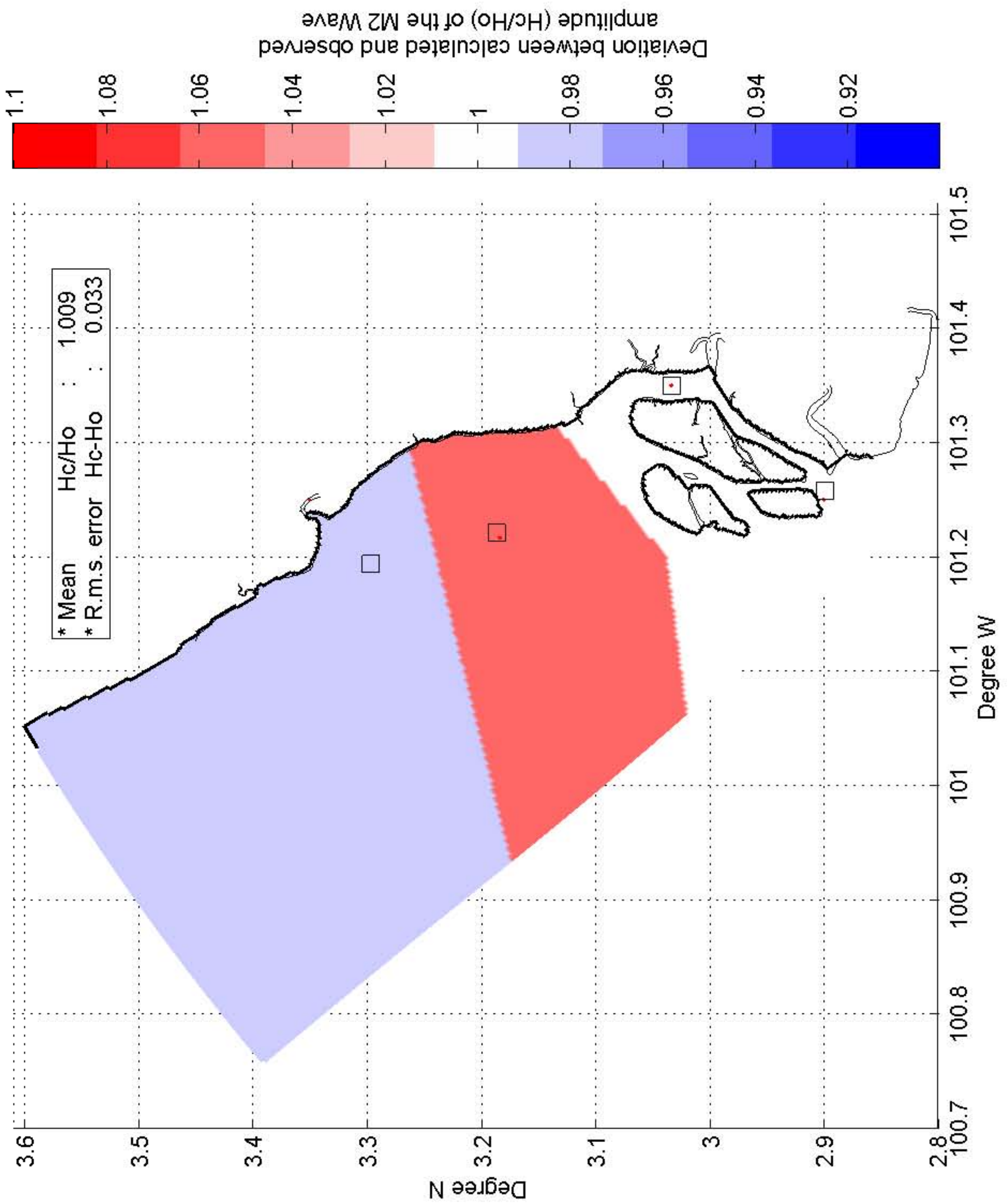
Comparison between Admiralty Chart 2139 and Delft3D-bathymetry

SELANGOR MALAYSIA

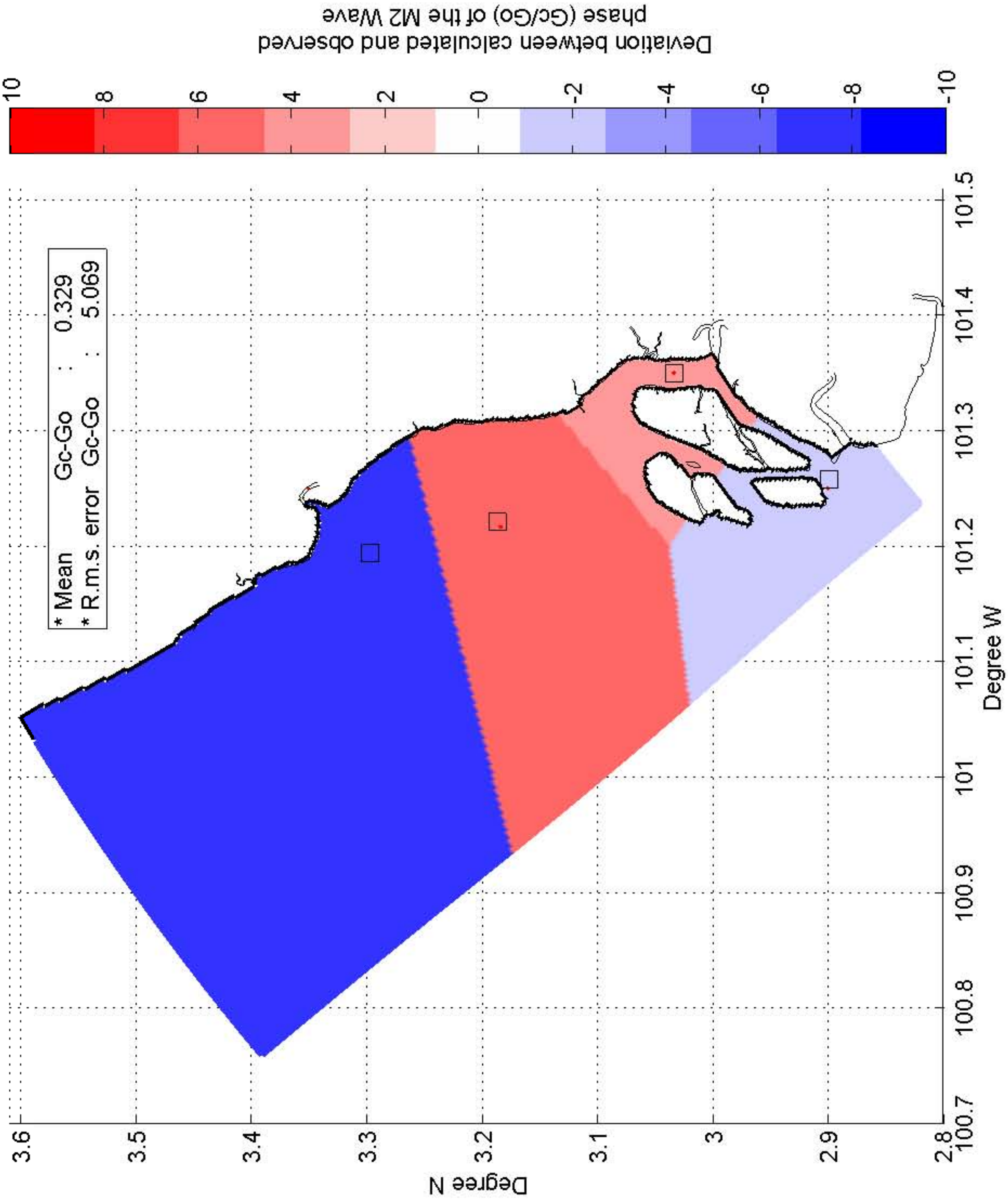
R1504

Alkyon

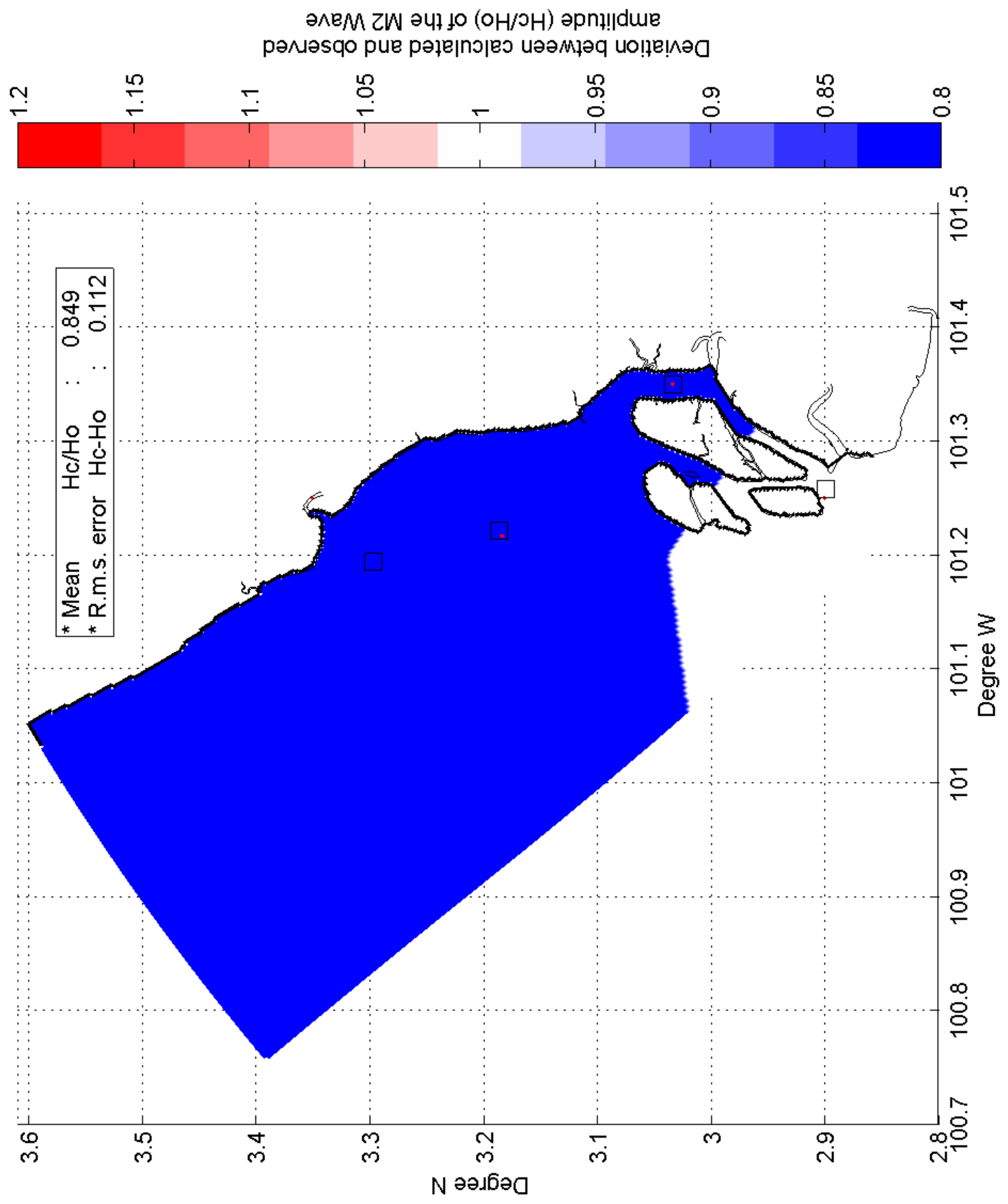
Fig. 3.9



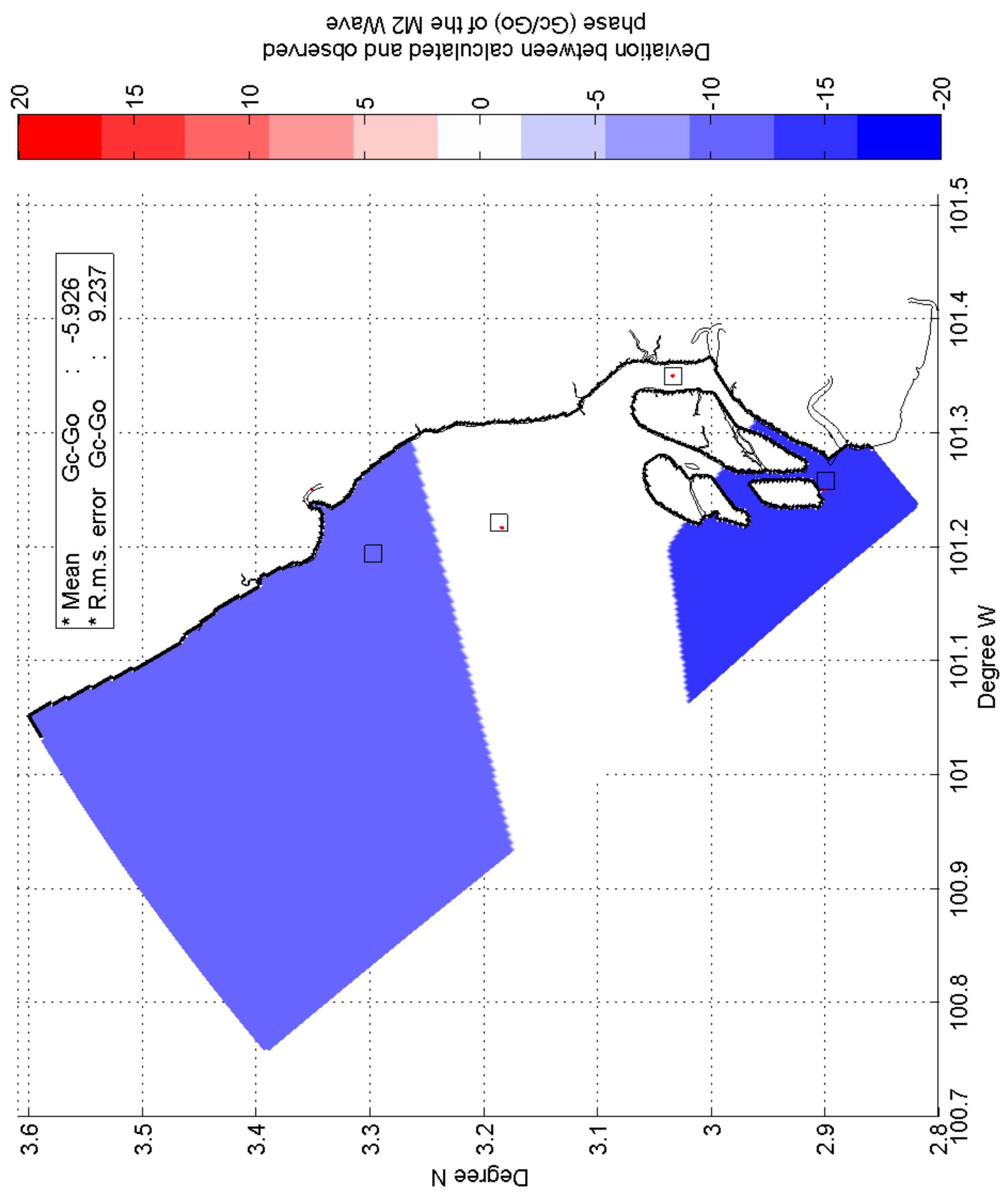
Results of Northern Approach Model compared to ATT values for the Ampli of the M2 constituent	Run ID:	NA
Selangor Malaysia R1504	Alkyon	Fig.3.10a



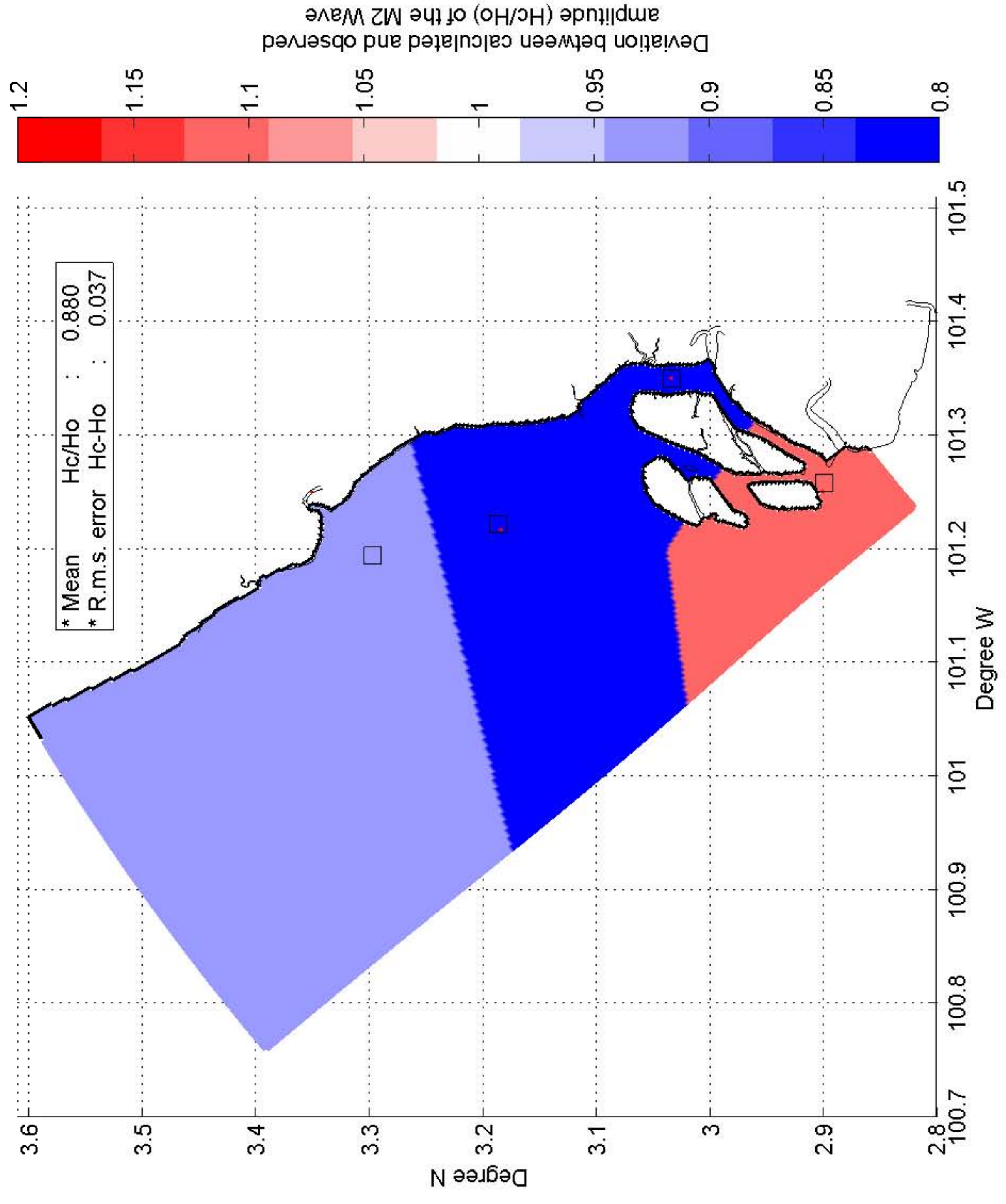
Results of Northern Approach Model compared to ATT values for the Phase of the M2 constituent		Run ID:	NA
Selangor Malaysia	R1504	Alkyon	Fig.3.10b



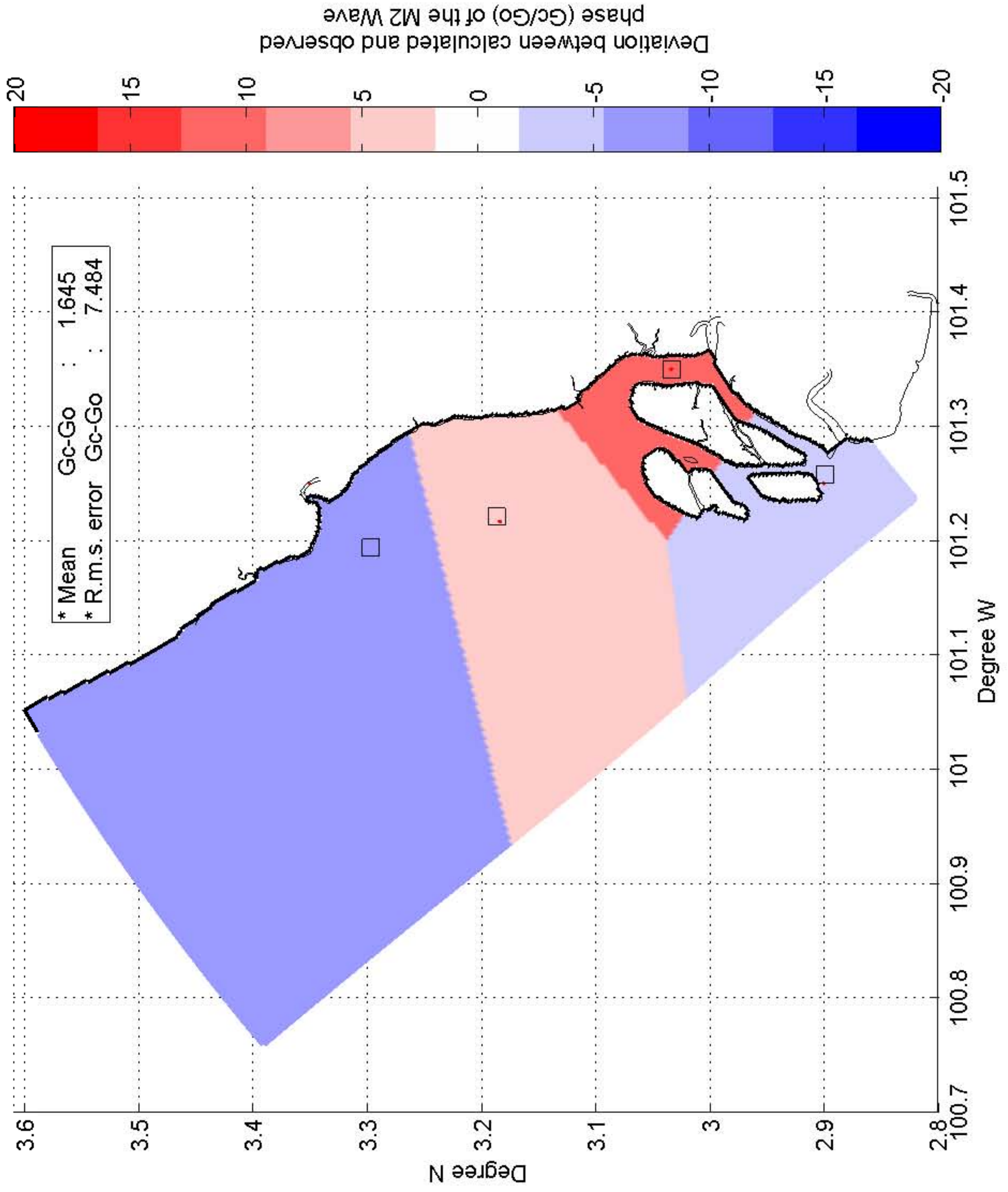
Results of Northern Approach Model compared to ATT values for the Ampli of the S2 constituent	Run ID:	NA
Selangor Malaysia R1504	Alkyon	Fig.3.10c



Results of Northern Approach Model compared to ATT values for the Phase of the S2 constituent	Run ID:	NA
Selangor Malaysia R1504	Alkyon	Fig.3.10d



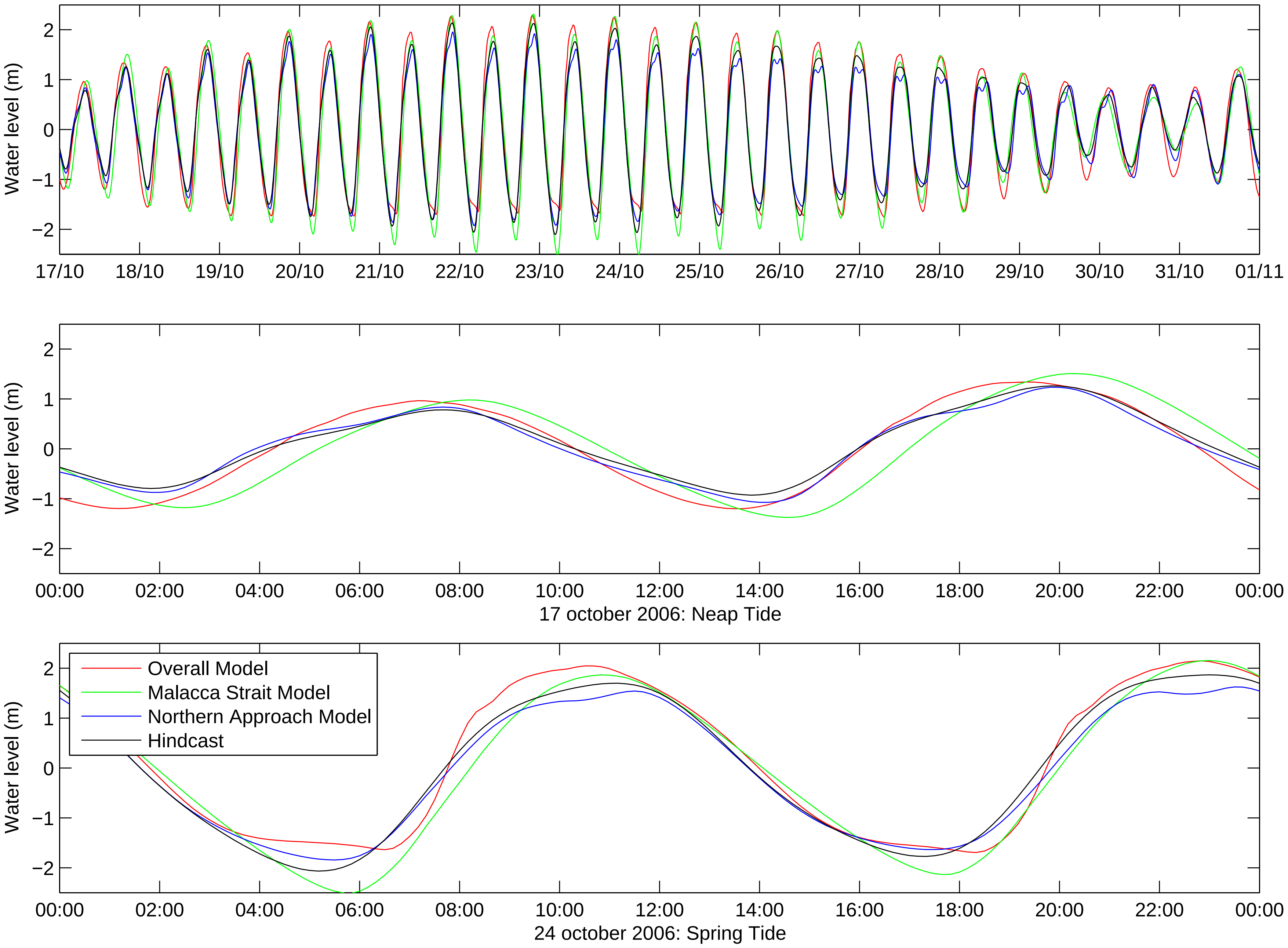
Results of Northern Approach Model compared to ATT values for the Ampli of the K1 constituent	Run ID:	NA
Selangor Malaysia R1504	Alkyon	Fig.3.10e



Results of Northern Approach Model compared to ATT values for the Phase of the K1 constituent	Run ID:	NA
Selangor Malaysia R1504	Alkyon	Fig.3.10f

Selangor Malaysia

Validation of used models for Port Klang



R1504

Alkyon

Run ID:

–

Fig.3.11

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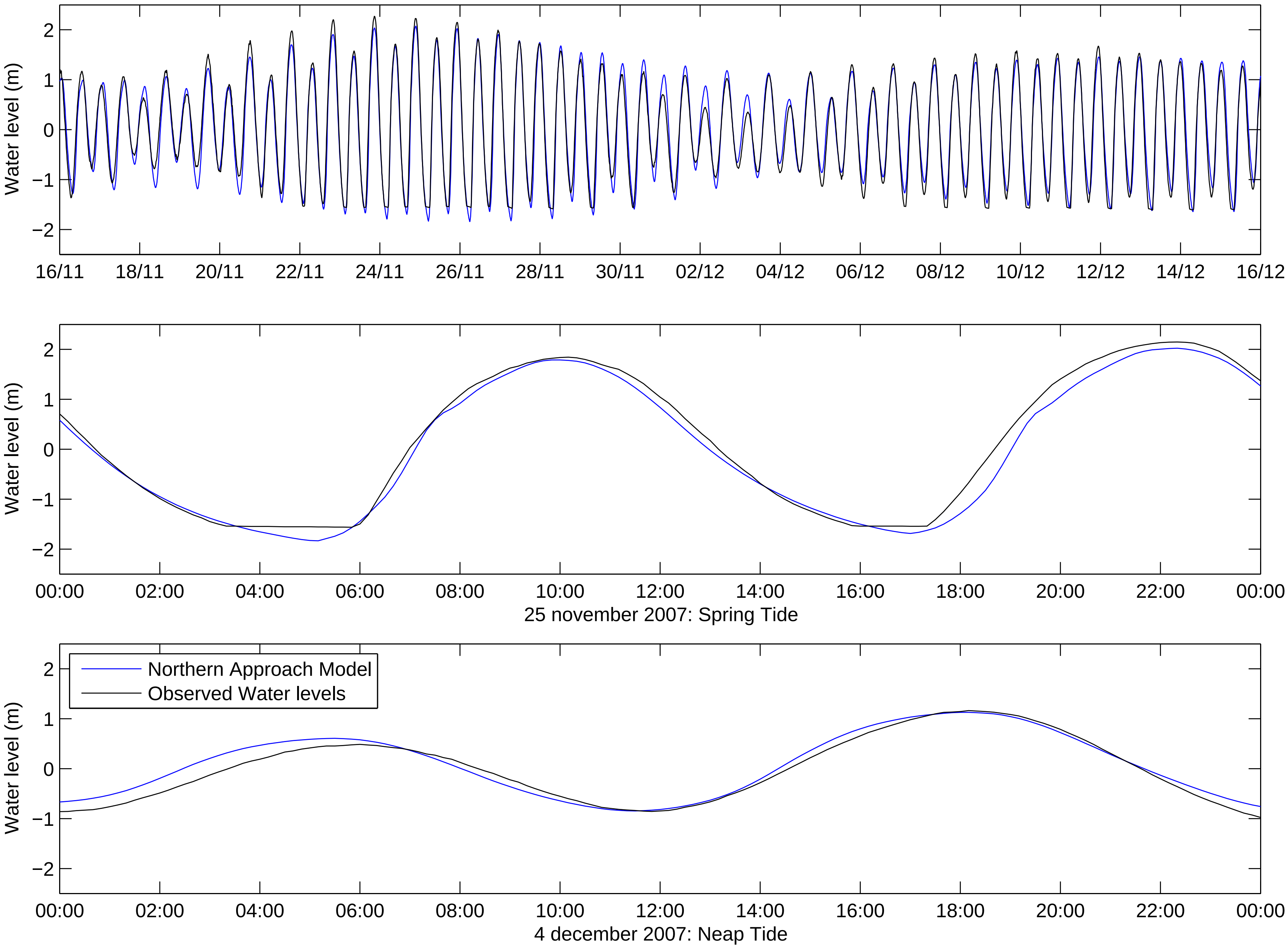
Selangor Malaysia

Validation of Northern Approach Model for the Selangor Estuary



R1504

Alkyon

Run ID:

NA

Fig.3.12

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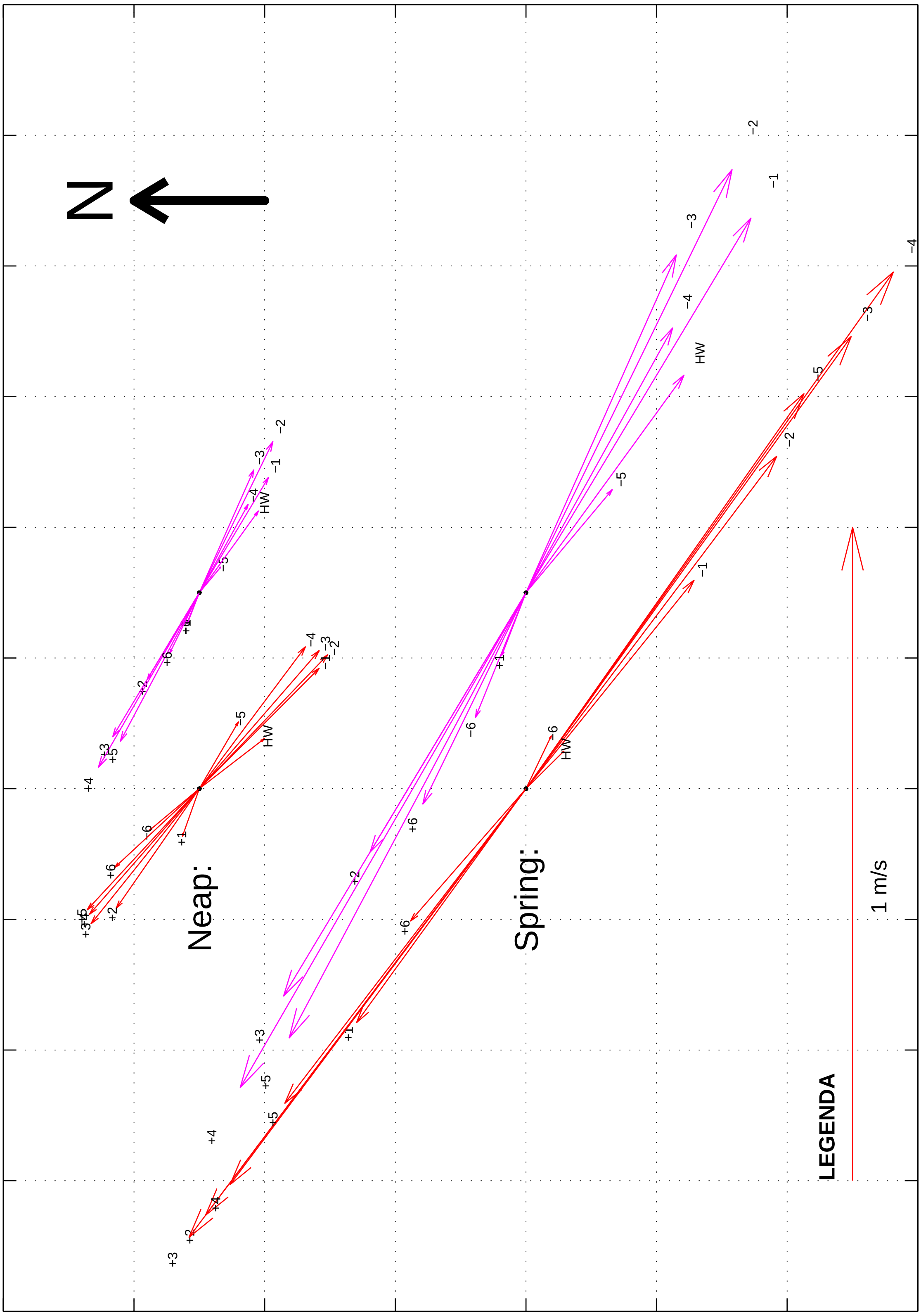
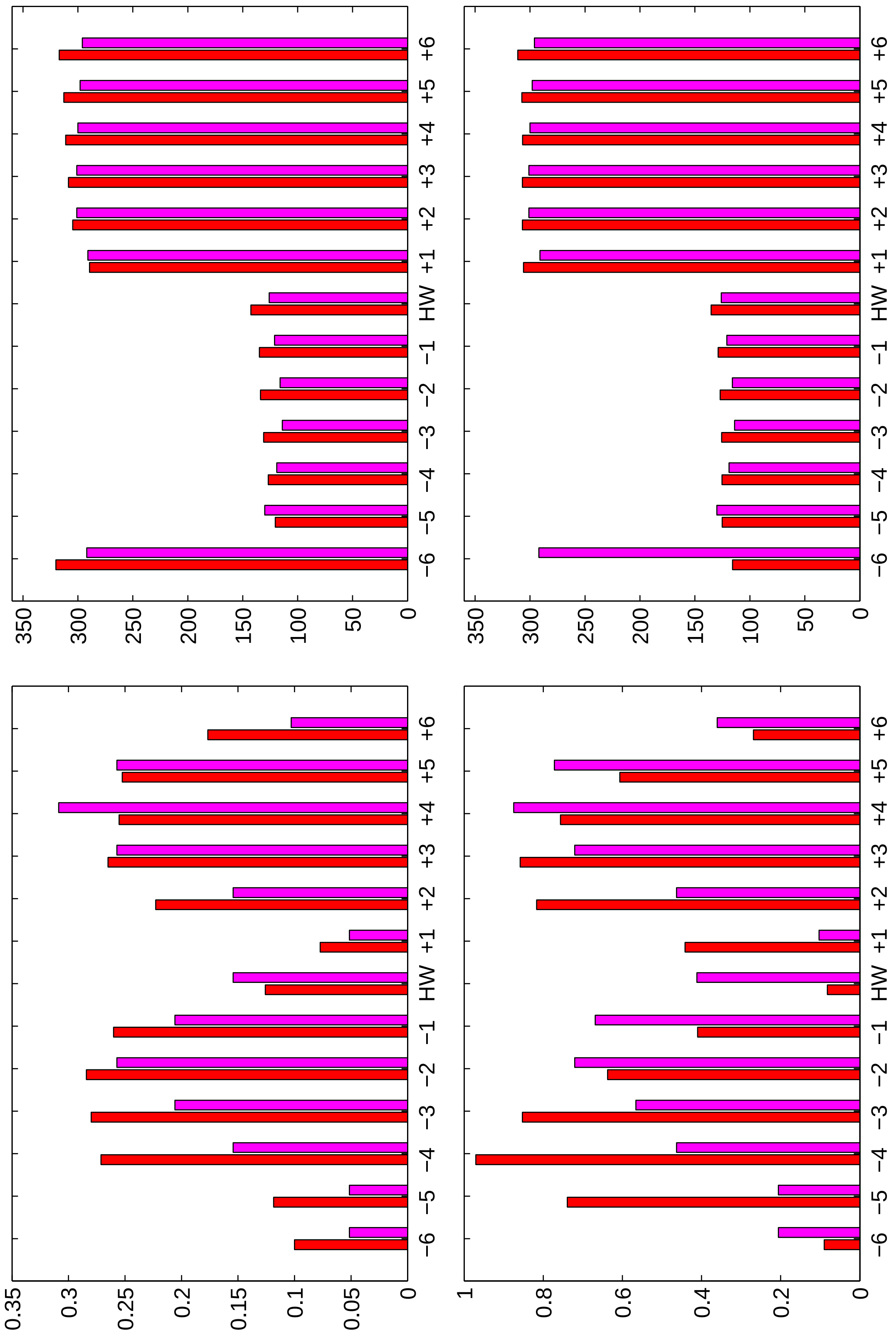
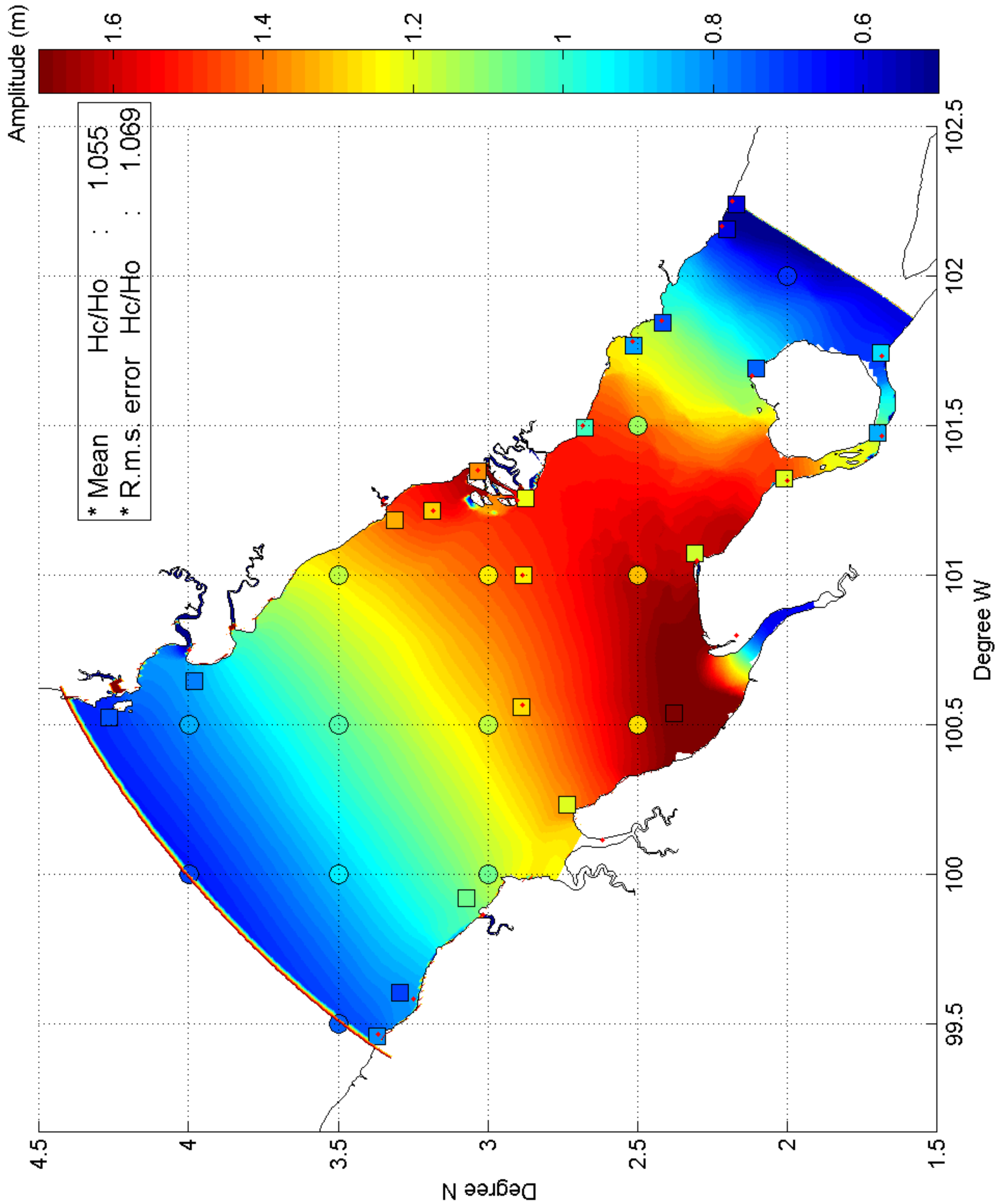


Comparison of velocities for location 'diamond A' in figure 3.6 calculated (red) versus measured (purple) velocities for neap and spring conditions	Run ID:	NA
Selangor Malaysia R1504	Alkyon	Fig.3.13a



Comparison of velocities for location 'diamond A' in figure 3.6 calculated (red) versus measured (purple) velocities for neap and spring conditions	Run ID:	NA
Selangor Malaysia R1504	Alkyon	Fig.3.13b

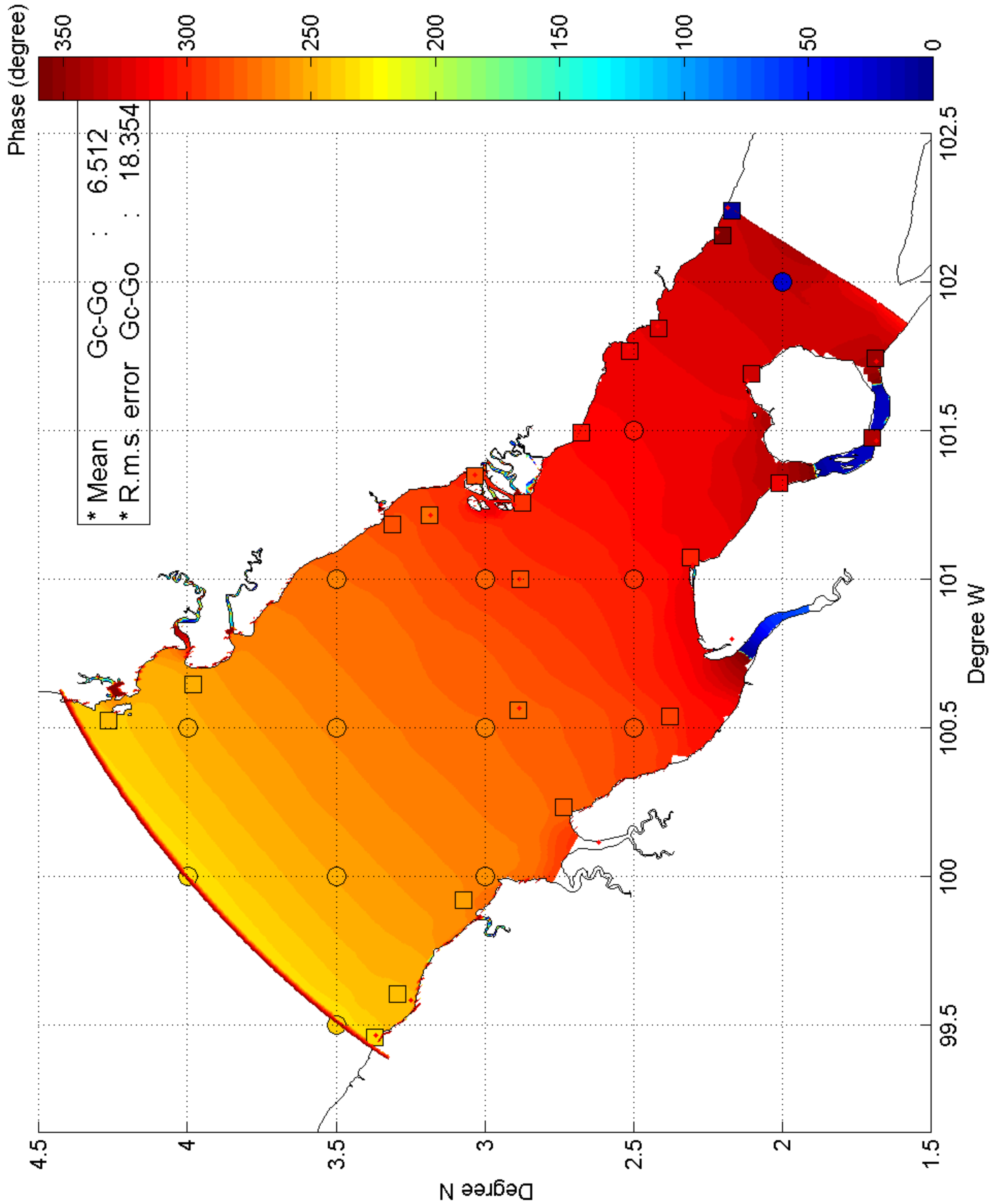


Delft3D model output compared to satellite-data (circles) and ATT-data (squares) for the Ampli of the M2 constituent

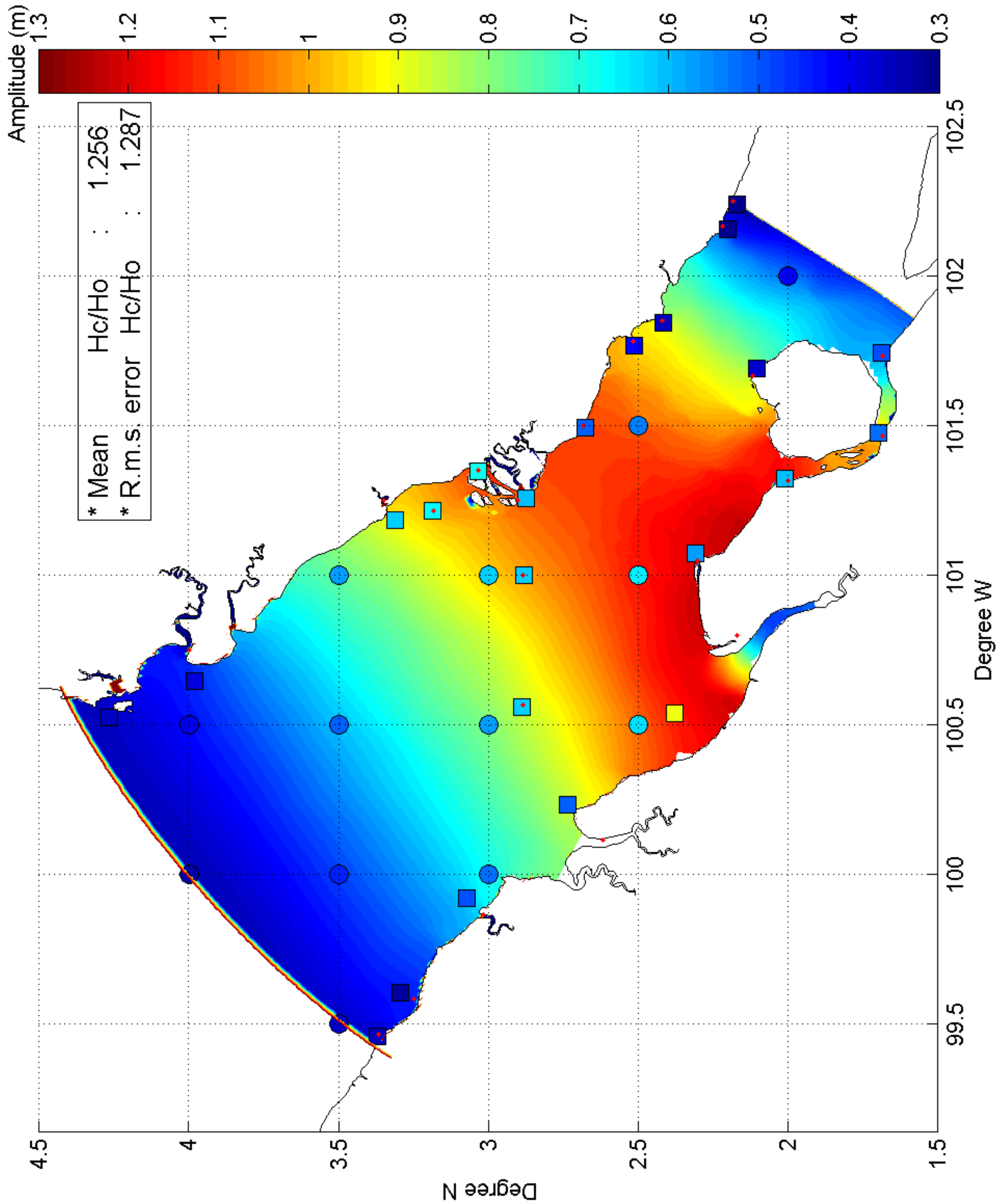
Run ID:	MS

Selangor Malaysia R1504

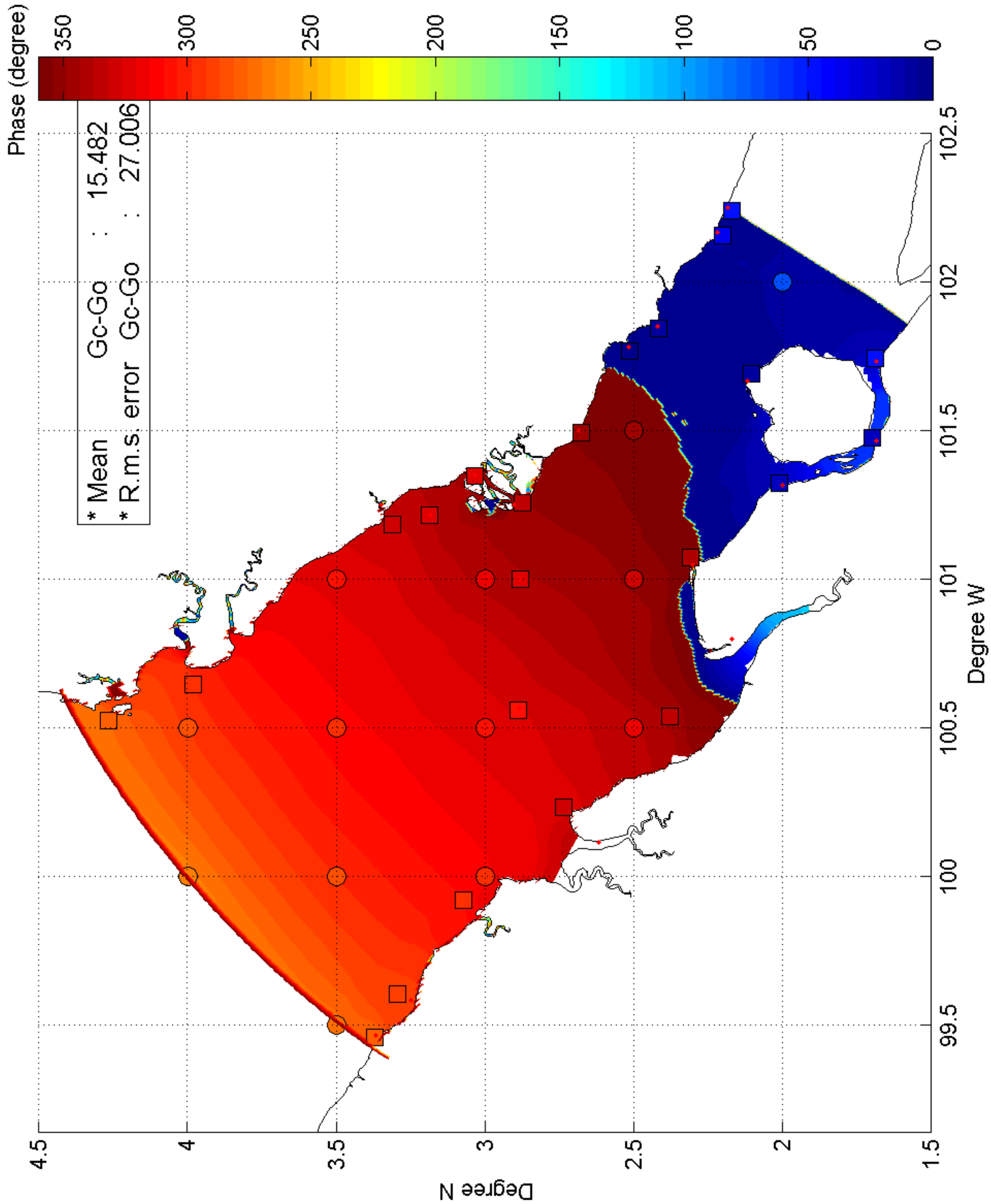
Alkyon Fig.3.14a



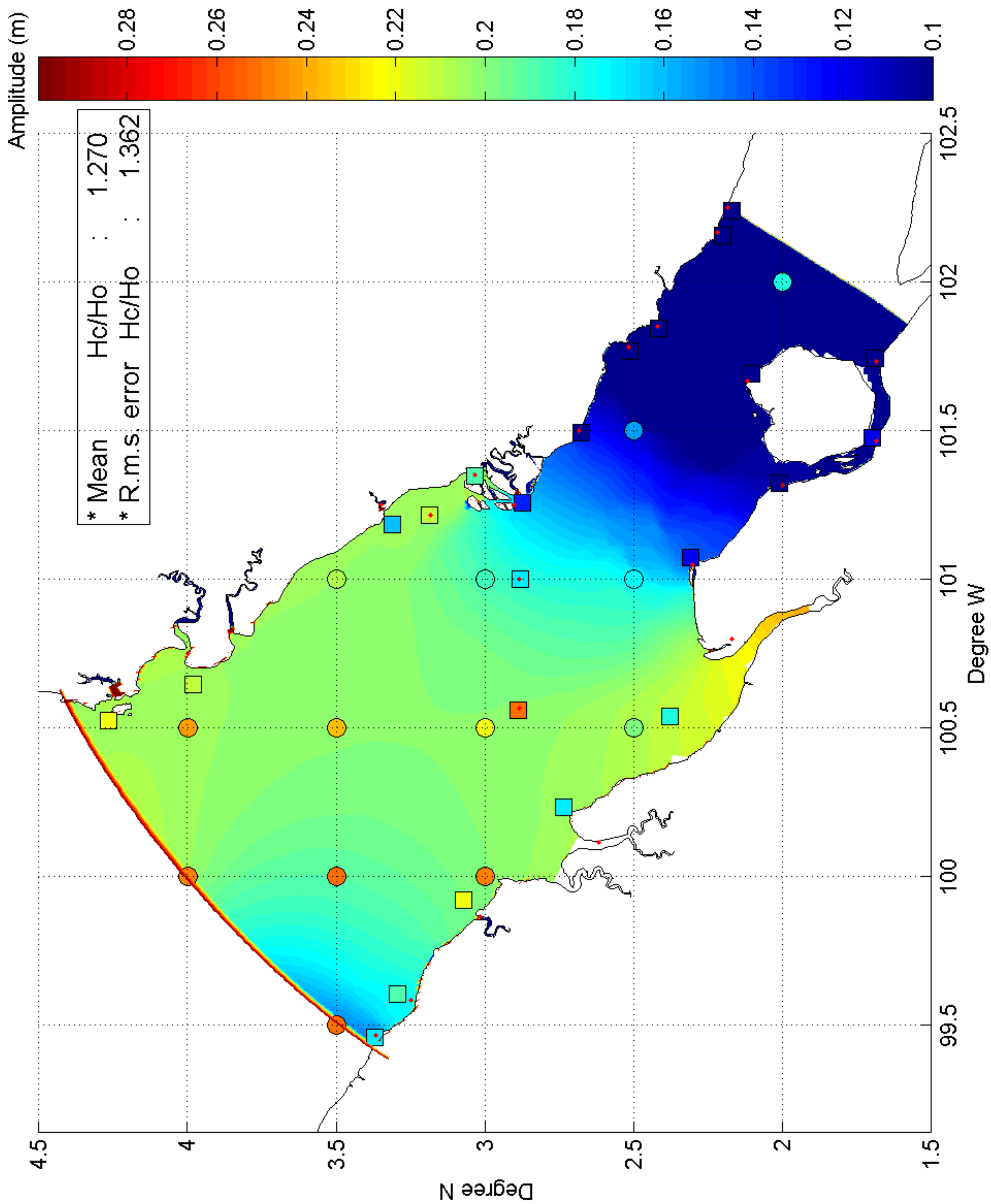
Delft3D model output compared to satellite-data (circles) and ATT-data (squares) for the Phase of the M2 constituent	Run ID:	MS
Selangor Malaysia R1504	Alkyon	Fig.3.14b



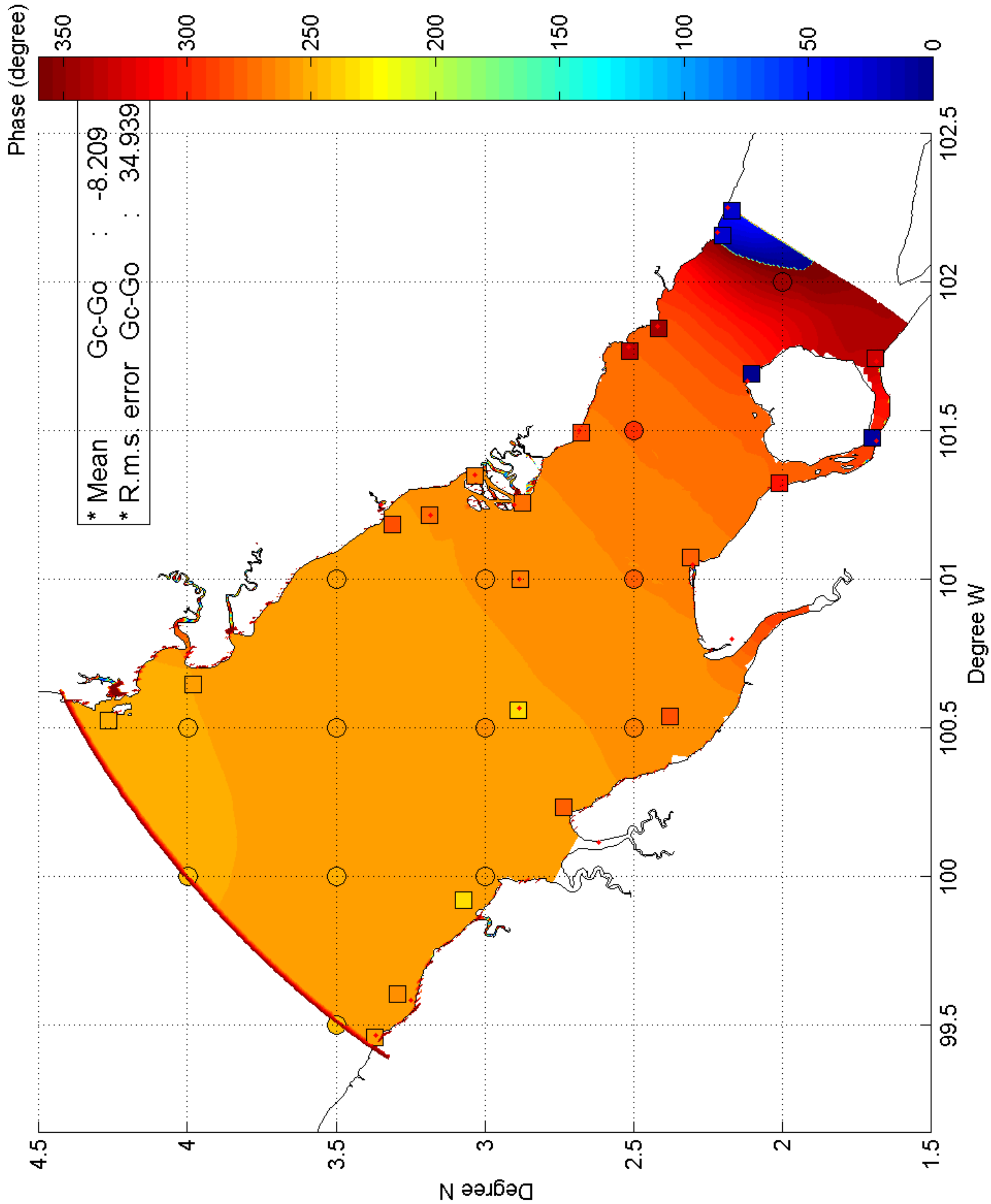
Delft3D model output compared to satellite-data (circles) and ATT-data (squares) for the Ampli of the S2 constituent	Run ID:	MS
Selangor Malaysia R1504	Alkyon	Fig.3.14c



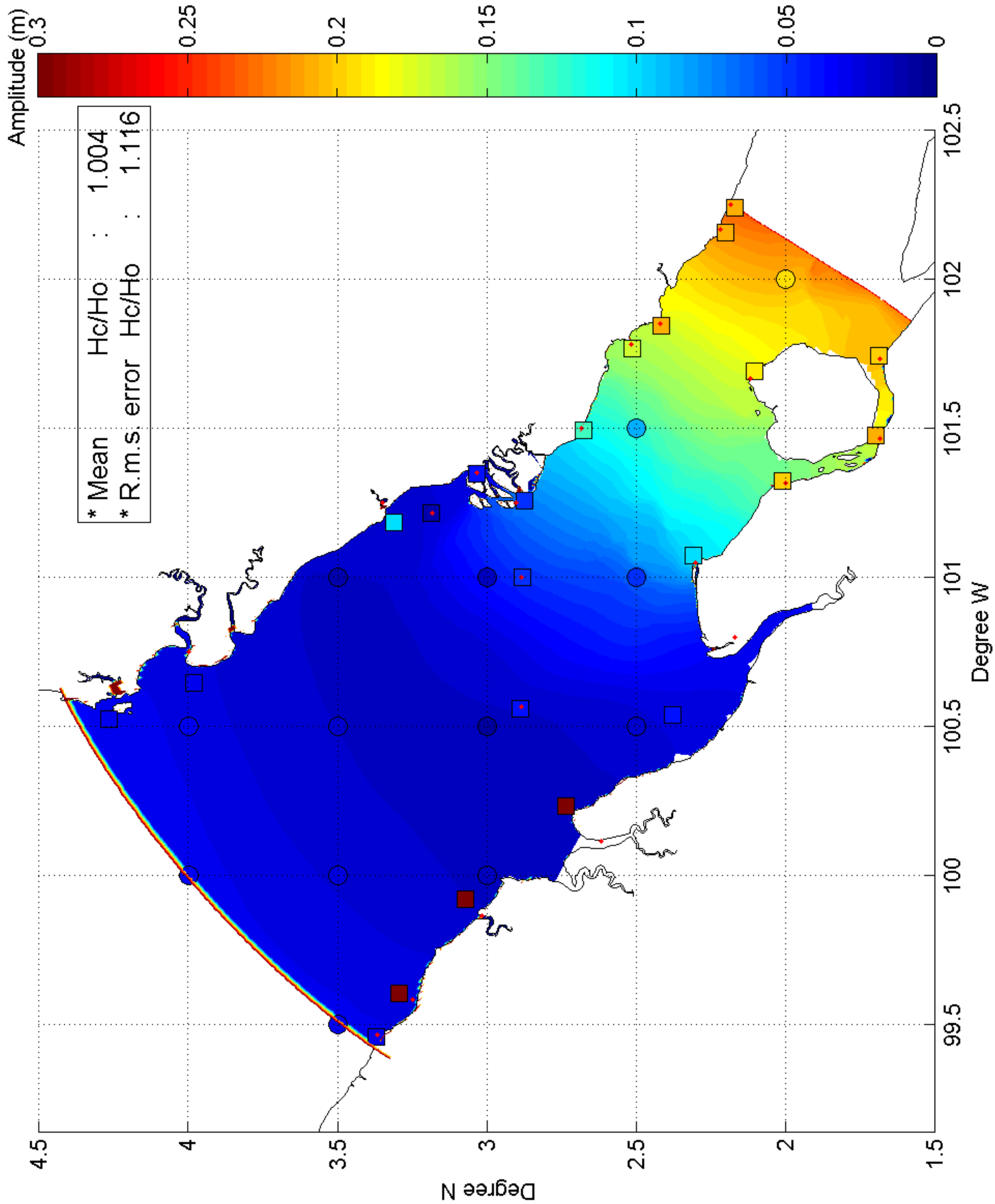
Delft3D model output compared to satellite-data (circles) and ATT-data (squares) for the Phase of the S2 constituent	Run ID:	MS
Selangor Malaysia R1504	Alkyon	Fig.3.14d



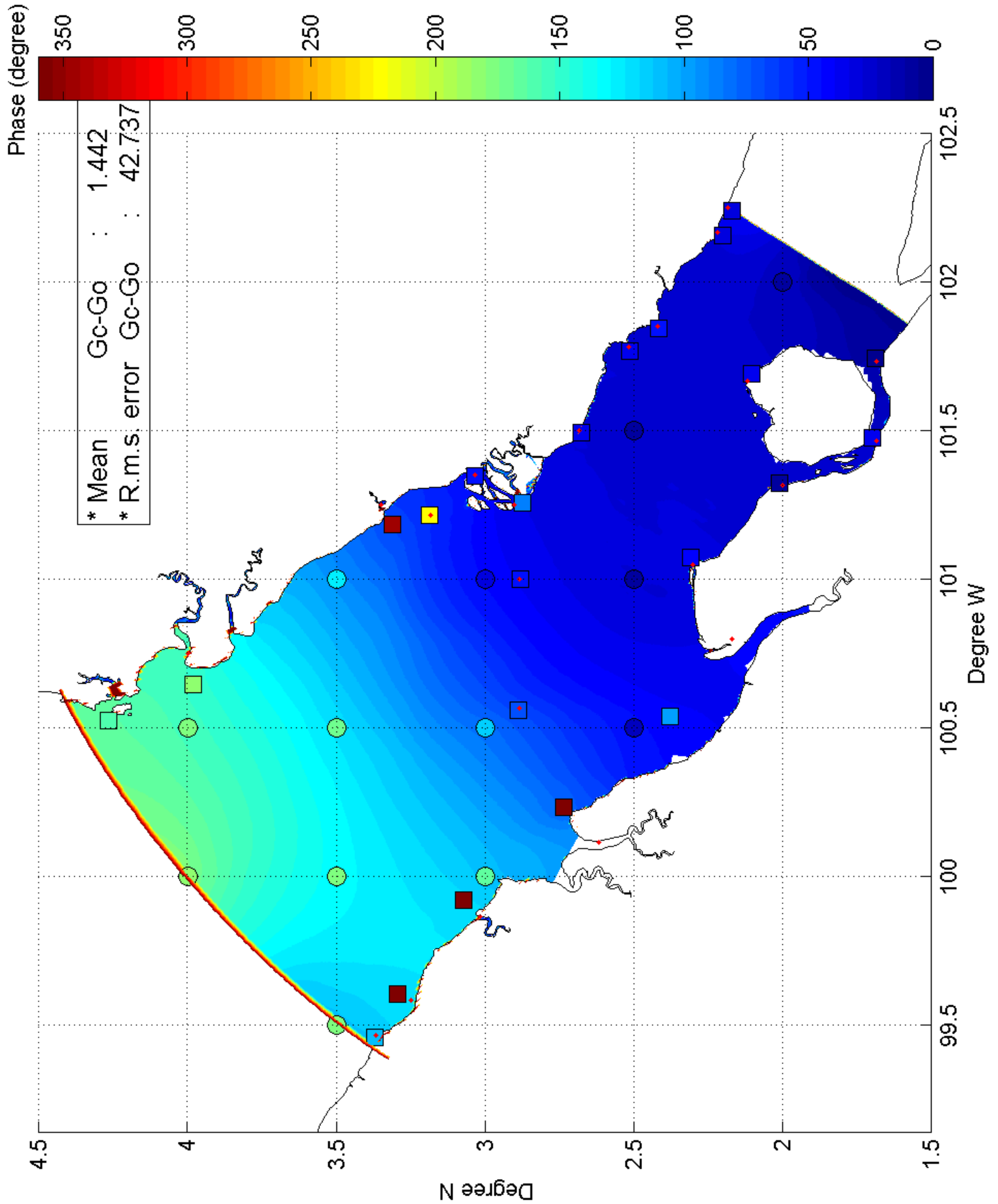
Delft3D model output compared to satellite-data (circles) and ATT-data (squares) for the Ampli of the K1 constituent	Run ID:	MS
Selangor Malaysia R1504	Alkyon	Fig.3.14e



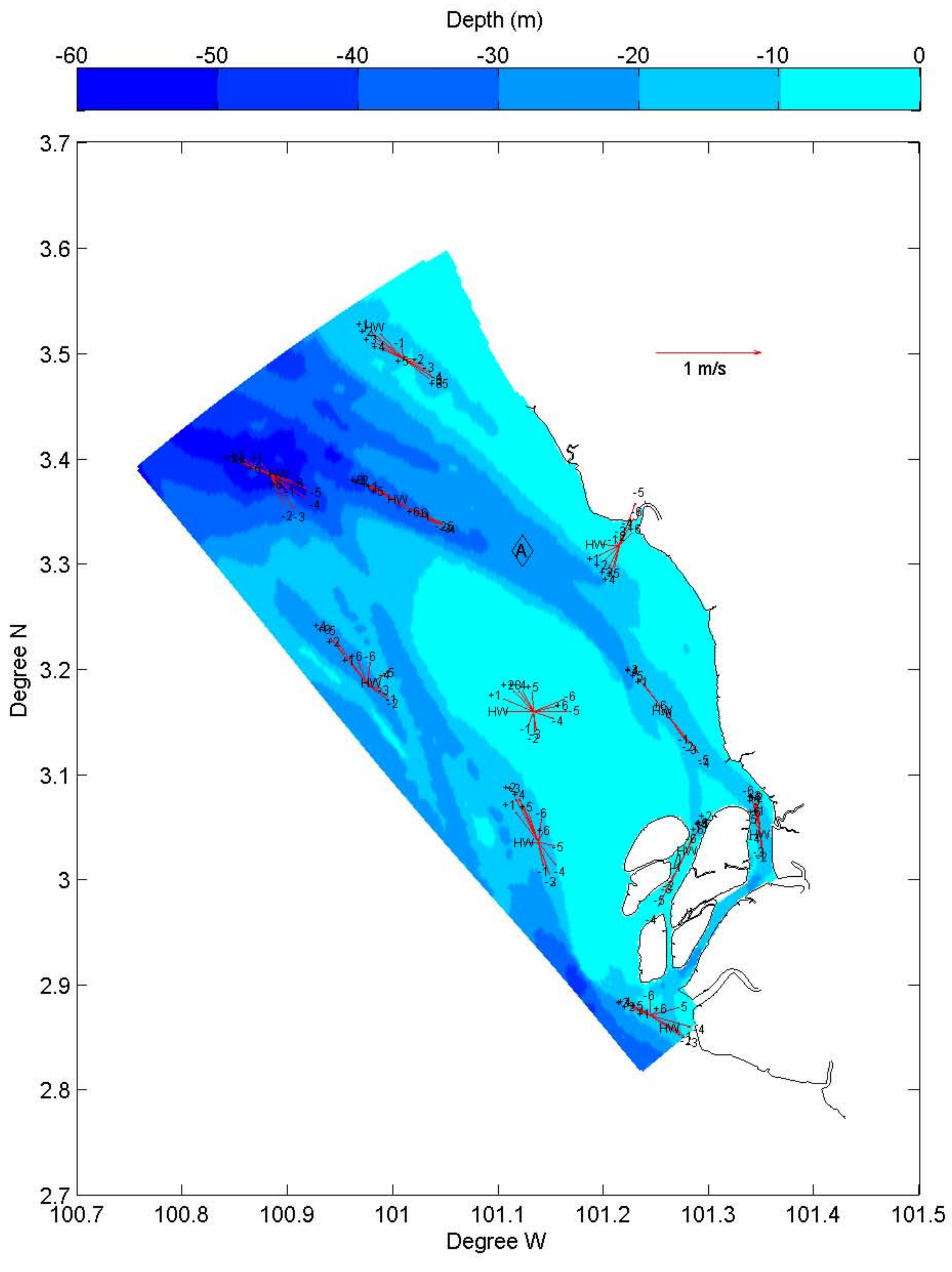
Delft3D model output compared to satellite-data (circles) and ATT-data (squares) for the Phase of the K1 constituent	Run ID:	MS
Selangor Malaysia R1504	Alkyon	Fig.3.14f



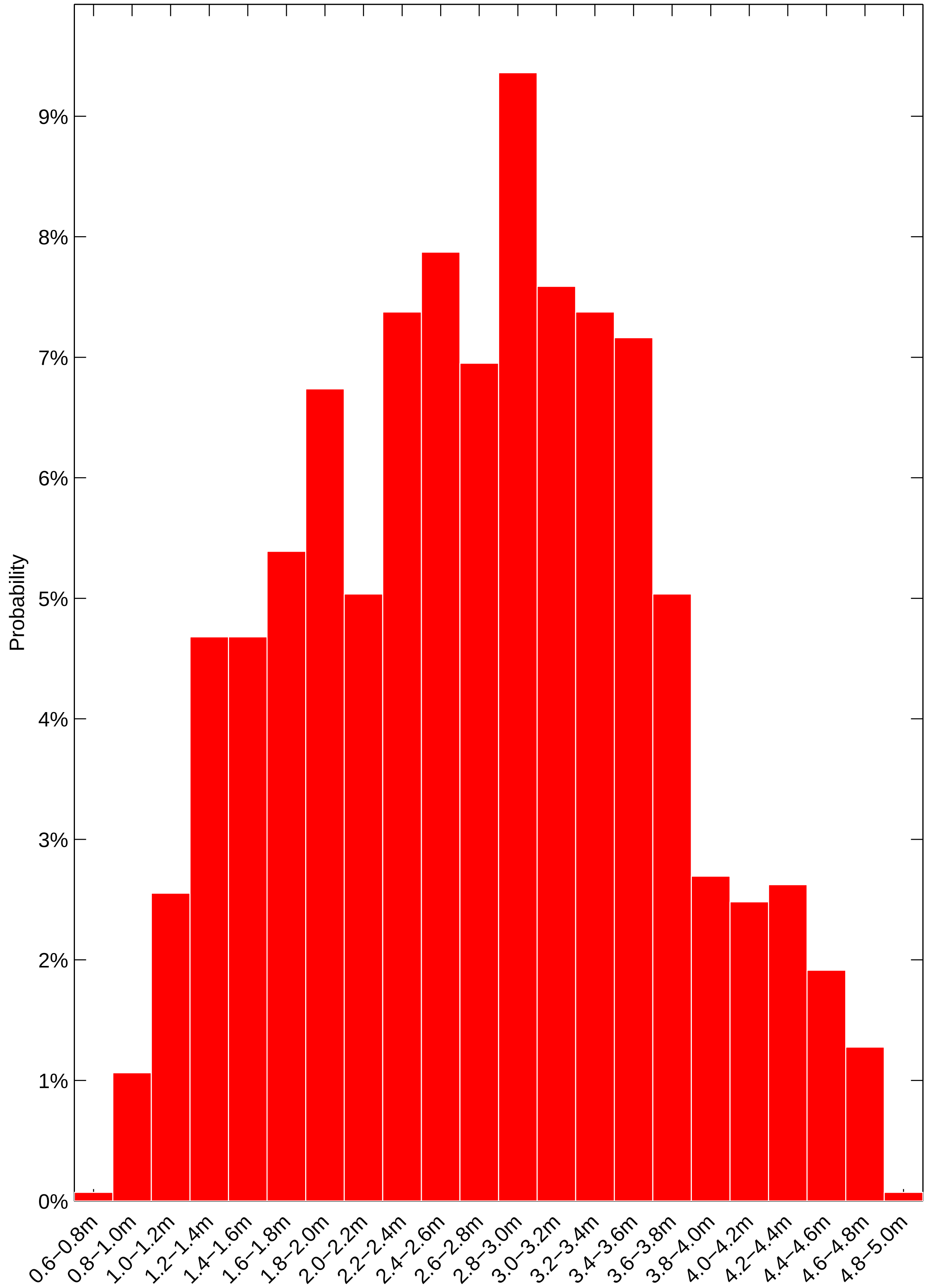
Delft3D model output compared to satellite-data (circles) and ATT-data (squares) for the Ampli of the O1 constituent	Run ID:	MS
Selangor Malaysia R1504	Alkyon	Fig.3.14g



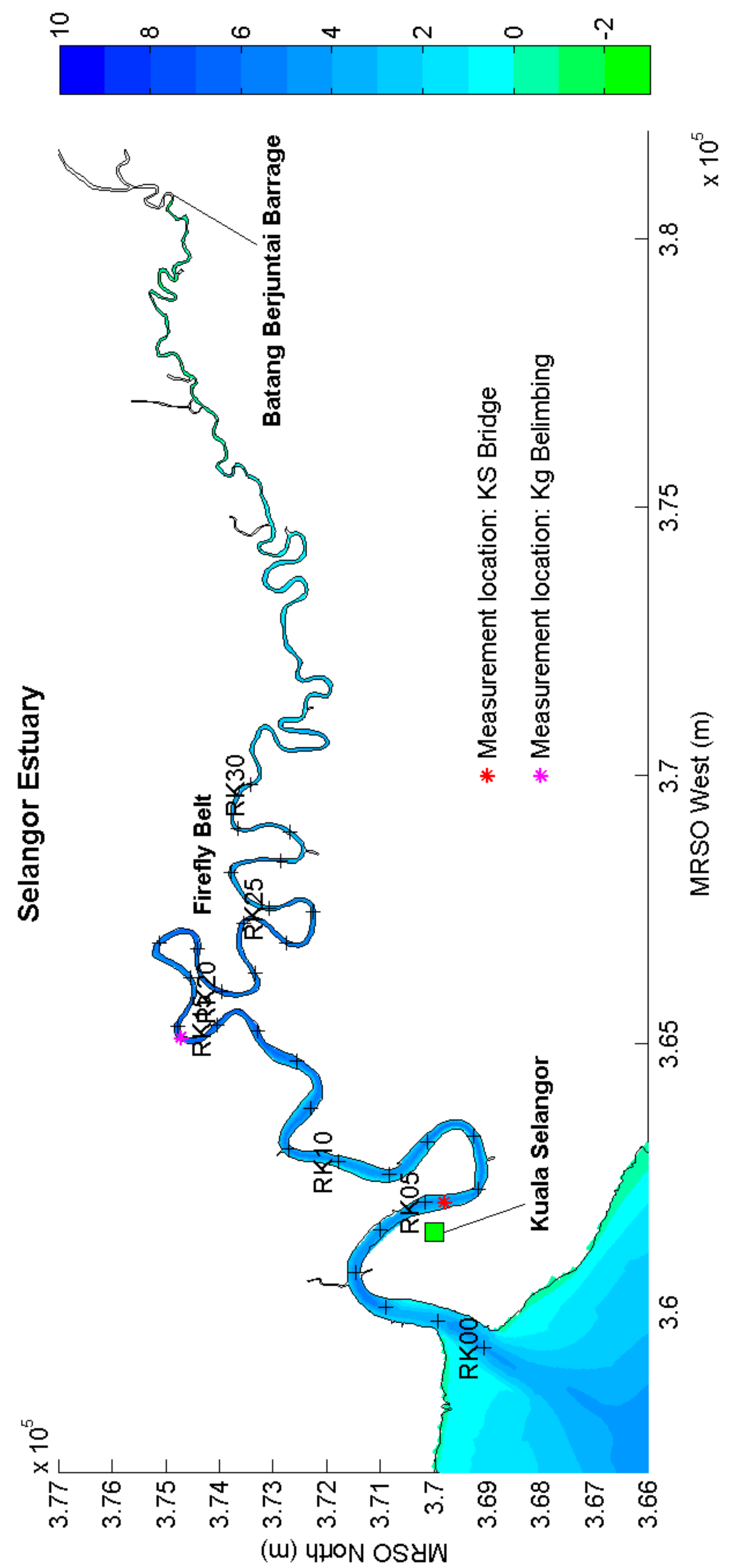
Delft3D model output compared to satellite-data (circles) and ATT-data (squares) for the Phase of the O1 constituent	Run ID:	MS
Selangor Malaysia R1504	Alkyon	Fig.3.14h



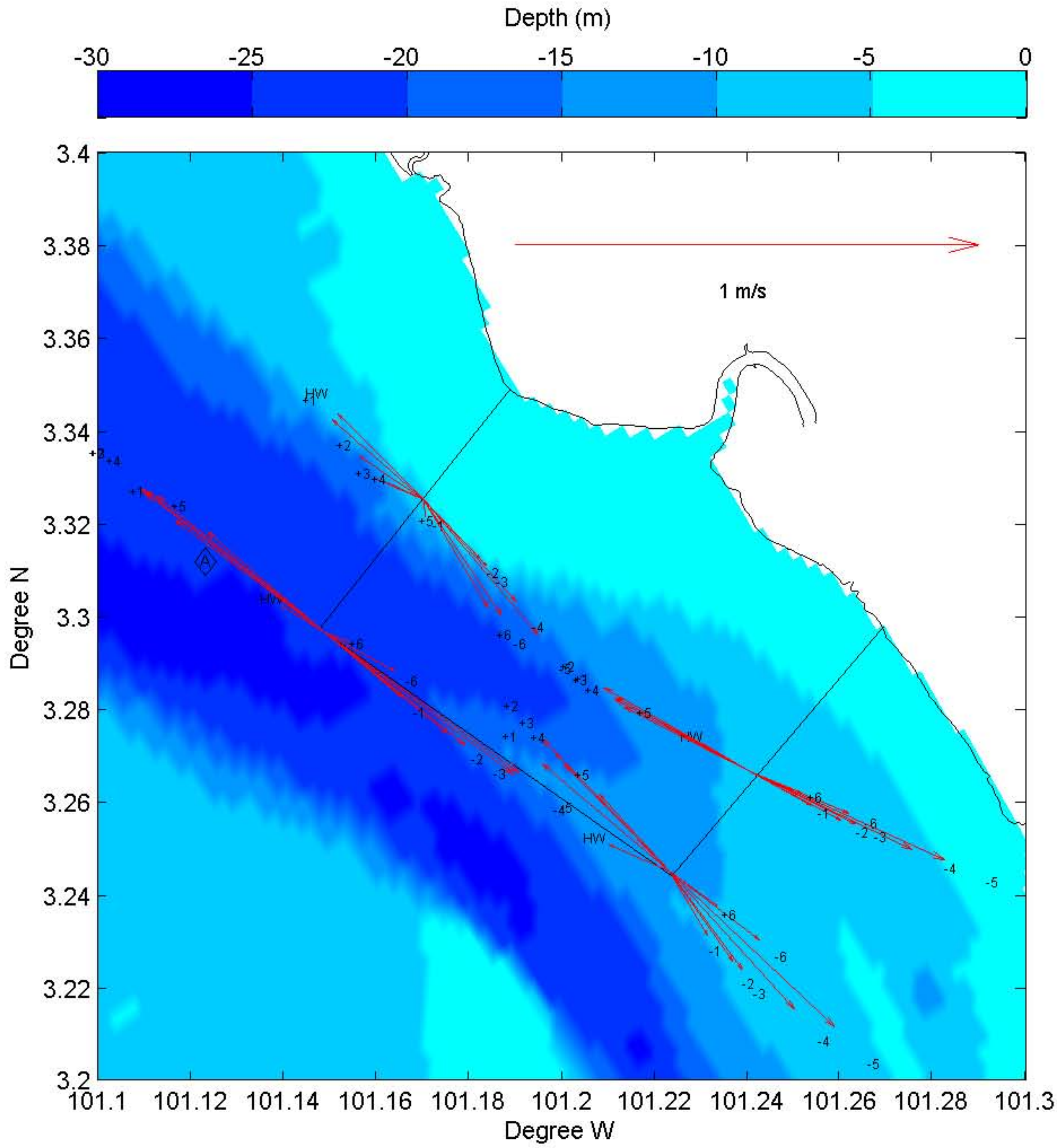
Flow velocities of the Northern Approach Model	Run ID:	NA
Selangor Malaysia R1504	Alkyon	Fig.3.15



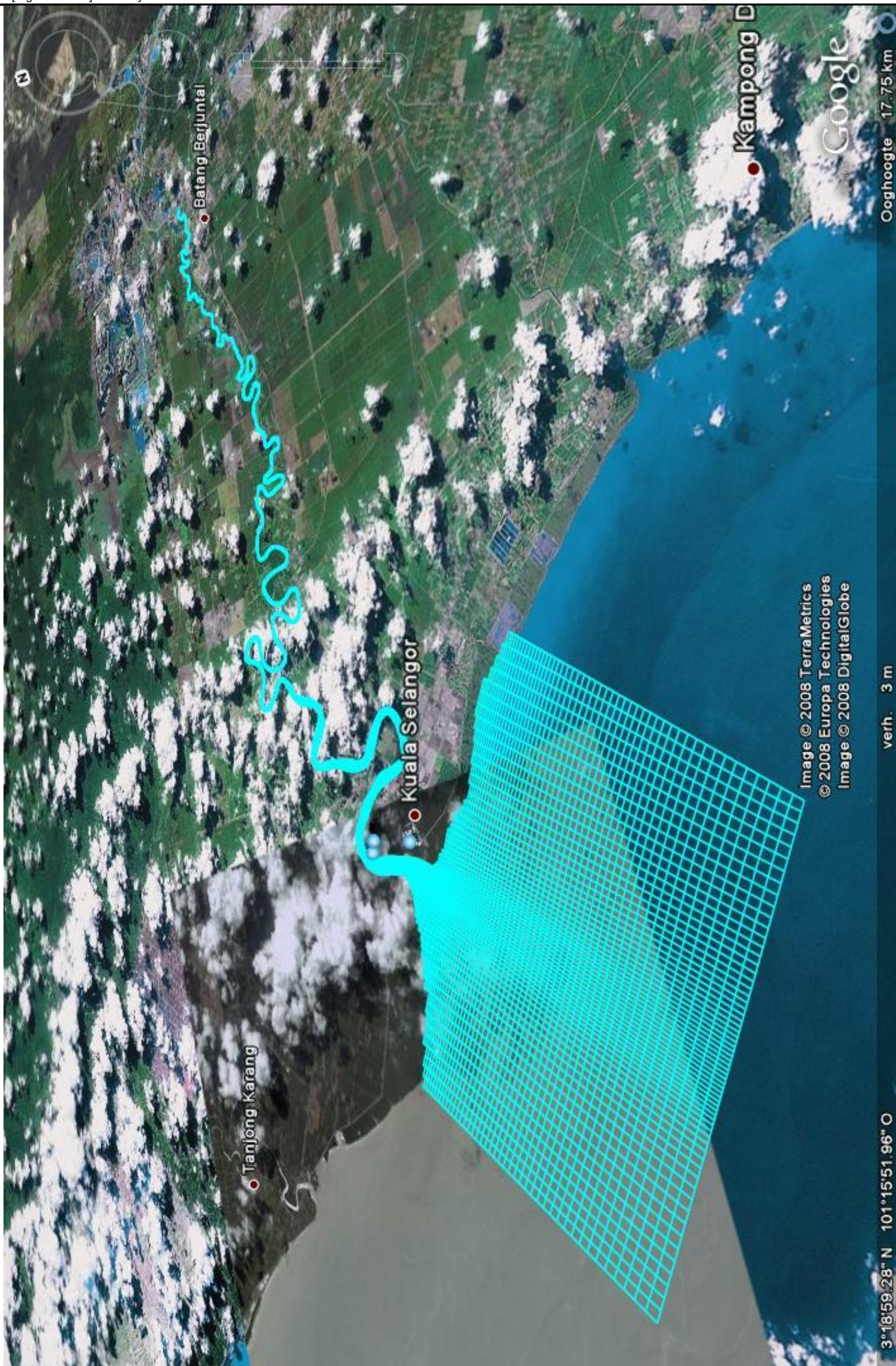
Distribution of tidal ranges in the Selangor Estuary (Tidal range = High Water Level − Subsequent Low Water Level) The analysed period is 2006−2007 which covers 1410 tidal cycles	Run ID:	NA
Selangor Malaysia R1504	Alkyon	Fig.3.16



Overview of the Selangor Estuary	Run ID:	SEM
Selangor Malaysia R1504	Alkyon	Fig.4.1



Flow velocities along the boundaries of the Selangor model (Black line = the boundary of Selangor Estuary Model)	Run ID: NA
Selangor Malaysia R1504	Alkyon Fig.4.2

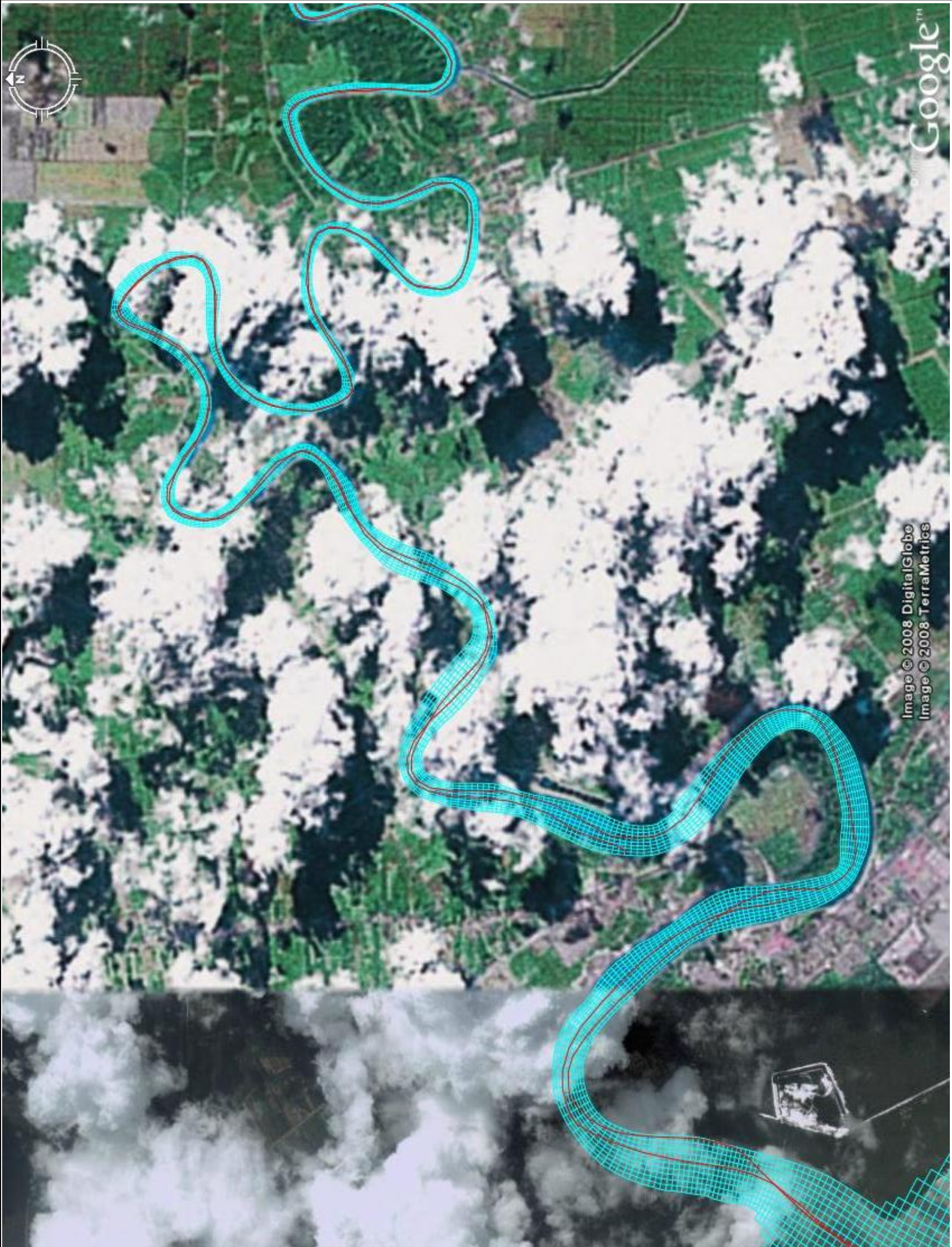


3D View of the grid of the Selangor Estuary Model

(Note: The color differences in the sea are caused by different aerial photographs

Source: GoogleEarth

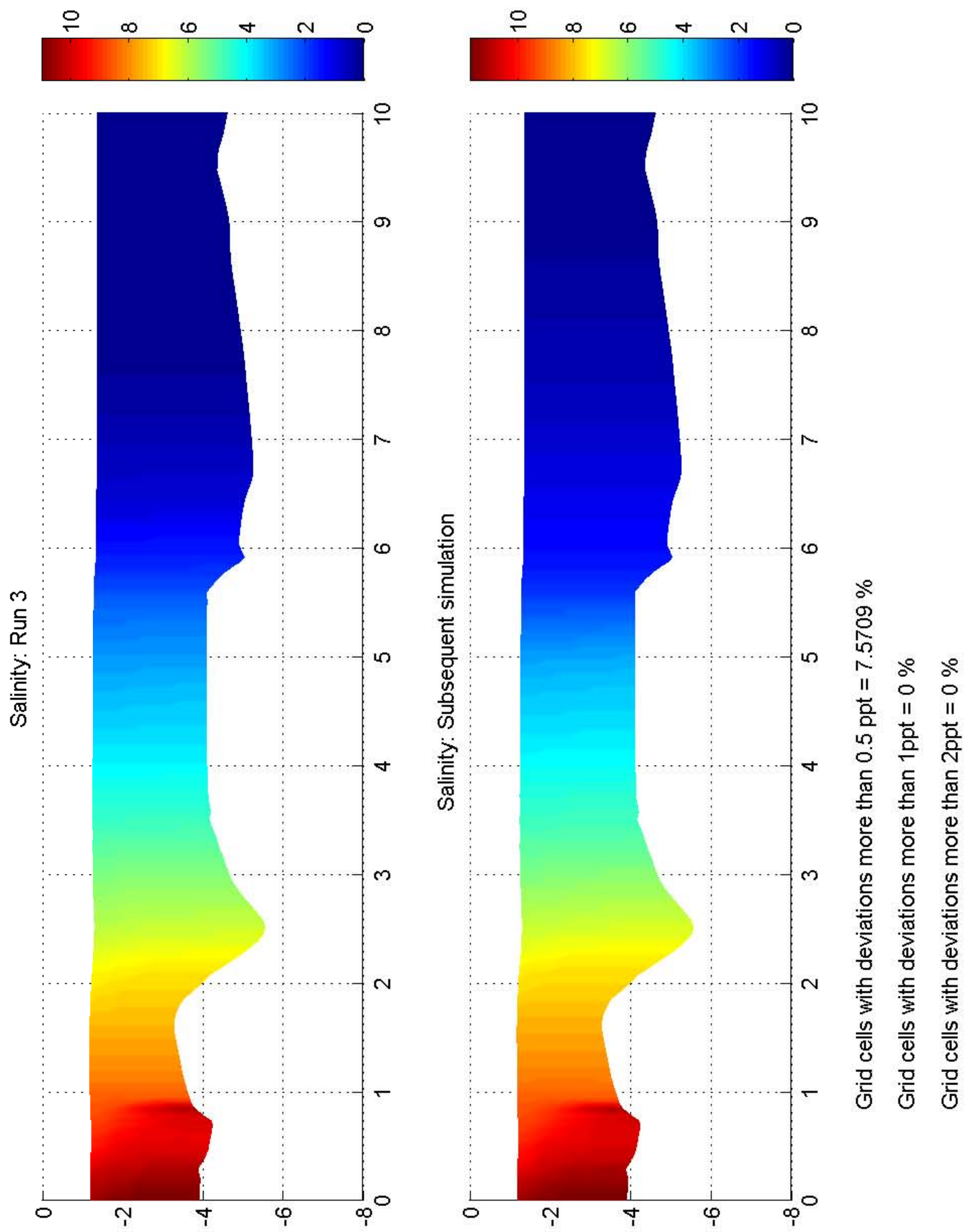
SELANGOR MALAYSIA R1504 Alkyon Fig. 4.3



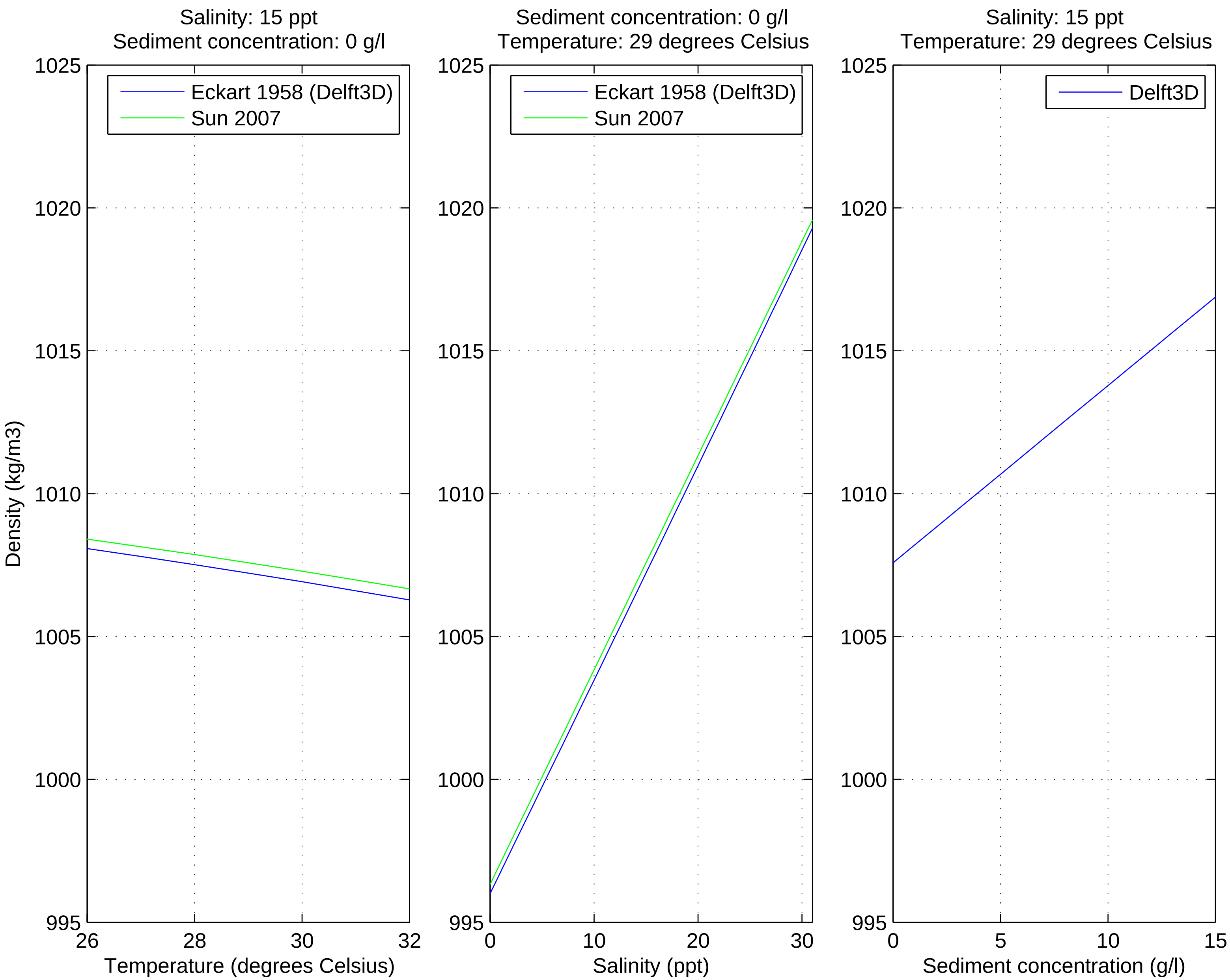
Top-down perspective of the grid of the Selangor Estuary Model; detail of the first 30 kilometres of the river. The red line is the GPS-run of the sitevisit.

Source: GoogleEarth

SELANGOR MALAYSIA | R1504 | Alkyon | Fig. 4.4



Stabilisation of salinity levels in the Selangor Estuary	Run ID:	SEM
Selangor Malaysia R1504	Alkyon	Fig.4.5



Effect of temperature, salinity and sediment concentration on density as implemented in Delft3D (Eckart) and according to the equation of Sun 2007

Run ID: -

Selangor Malaysia

R1504

Alkyon

Fig.4.6

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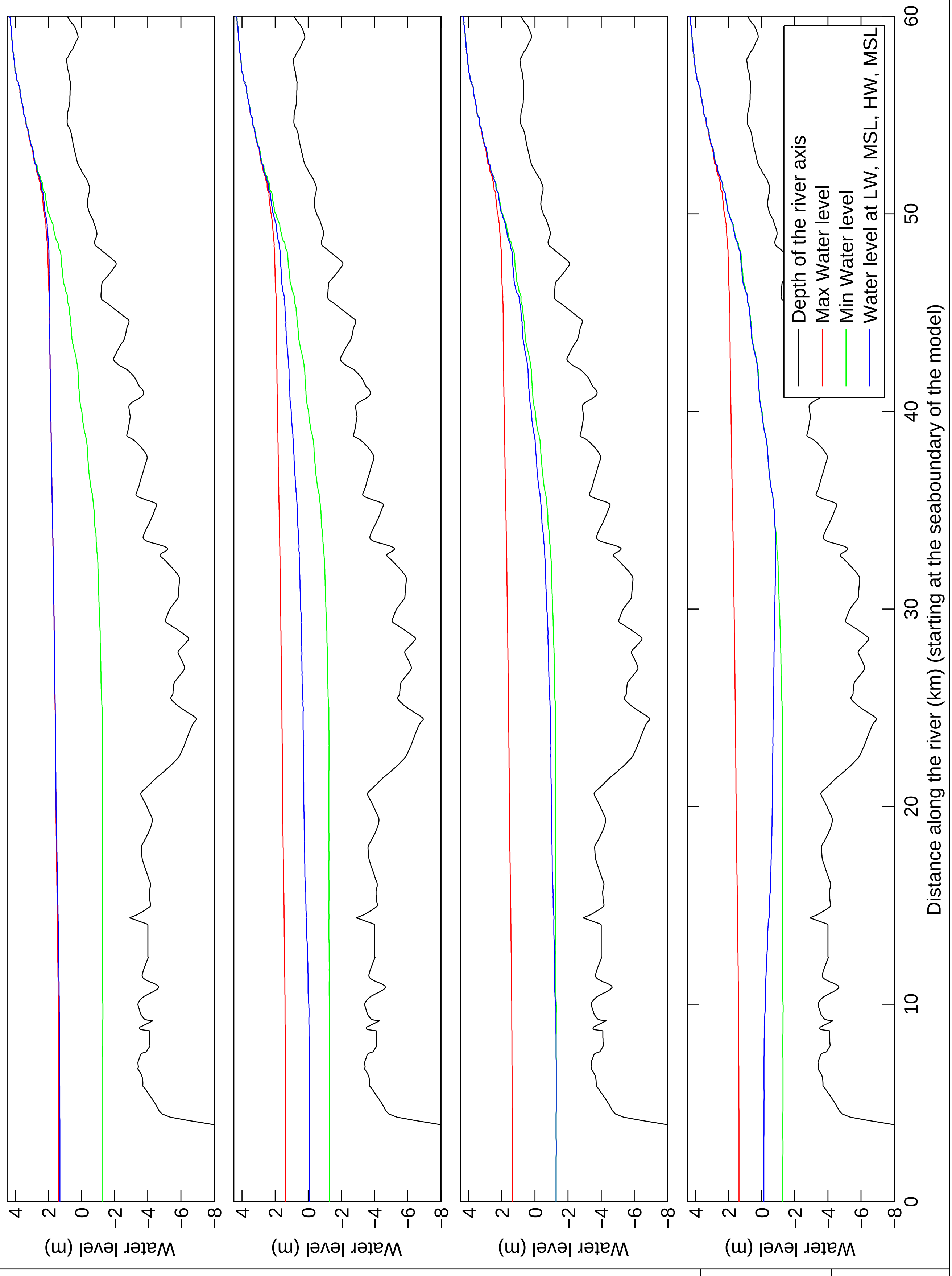
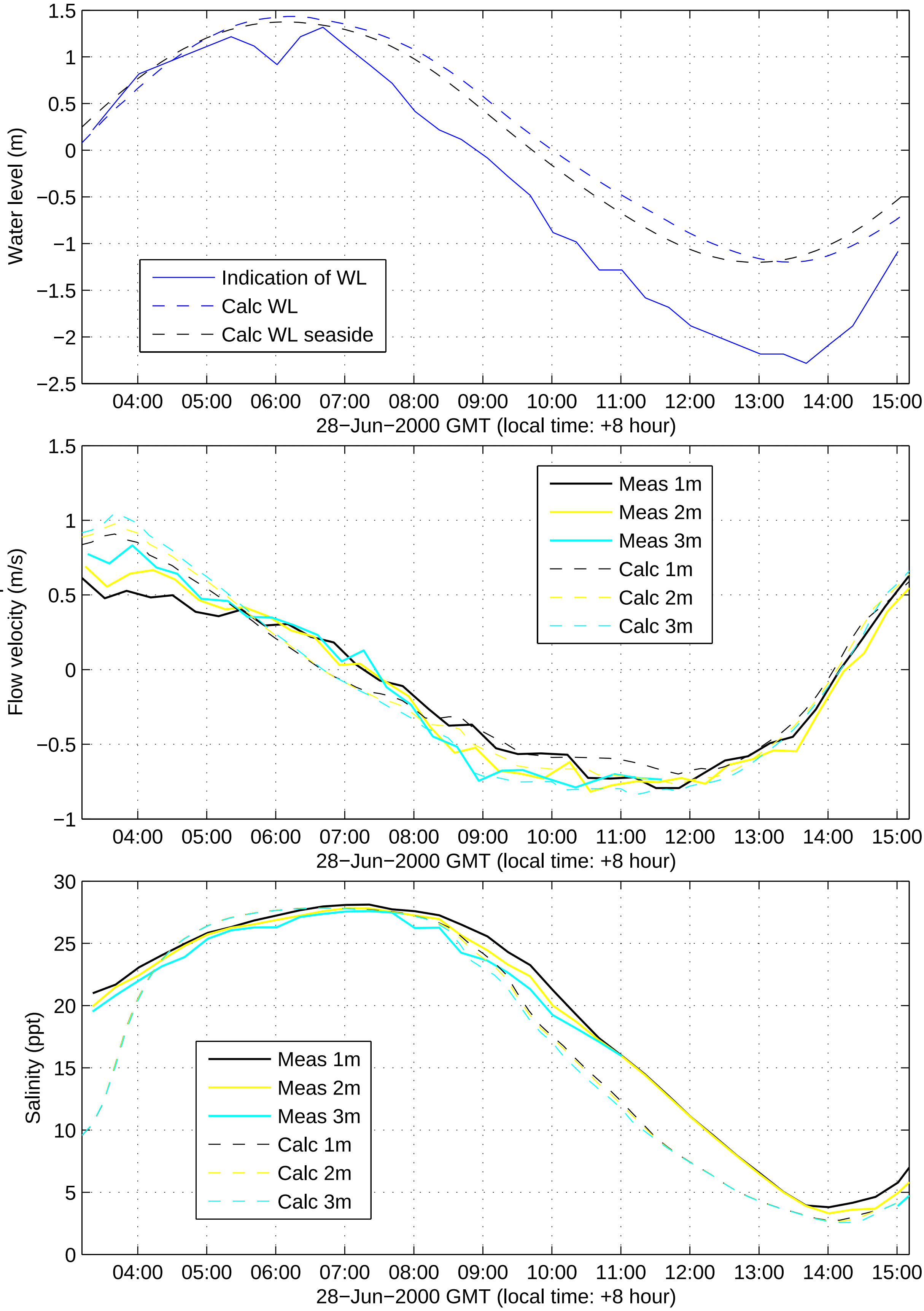
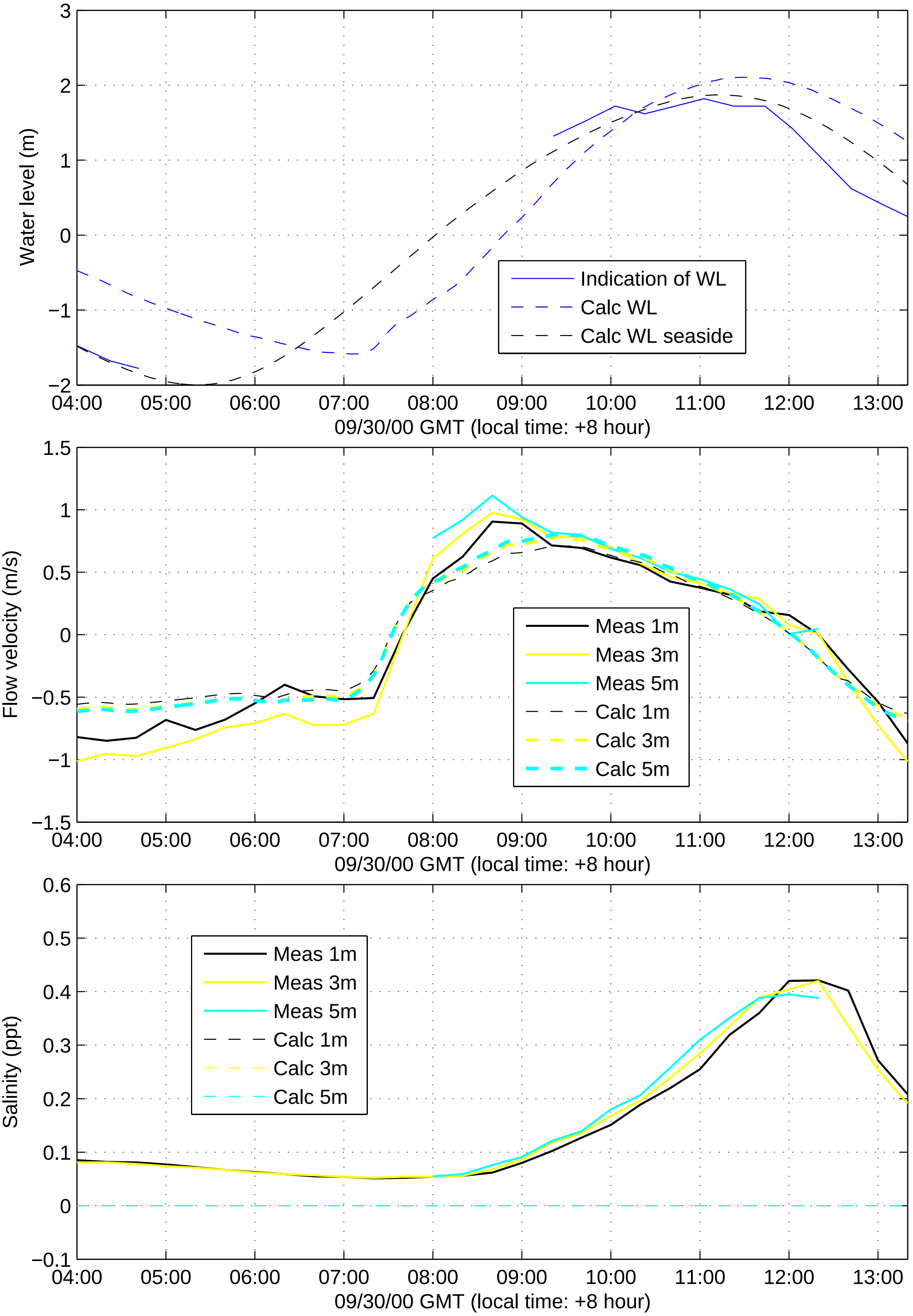


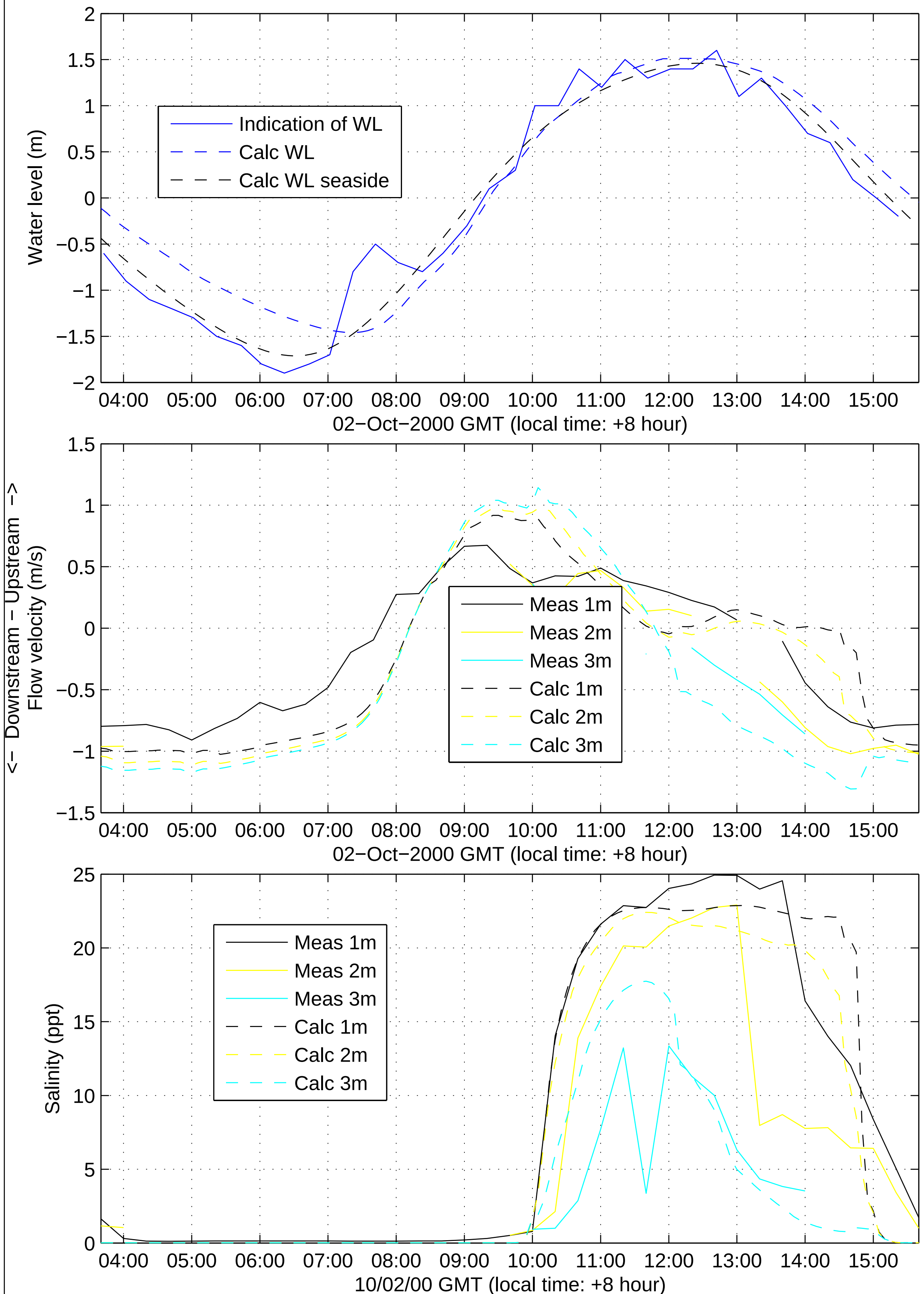
Tidal intrusion (water levels) in the Selangor Estuary for 4 time steps, from top to bottom: HW, MSL, LW, MSL (at sea) Conditions: average tide (2.7m) and average discharge (60m3/s)	Run ID:	SEM
Selangor Malaysia R1504	Alkyon	Fig.4.8



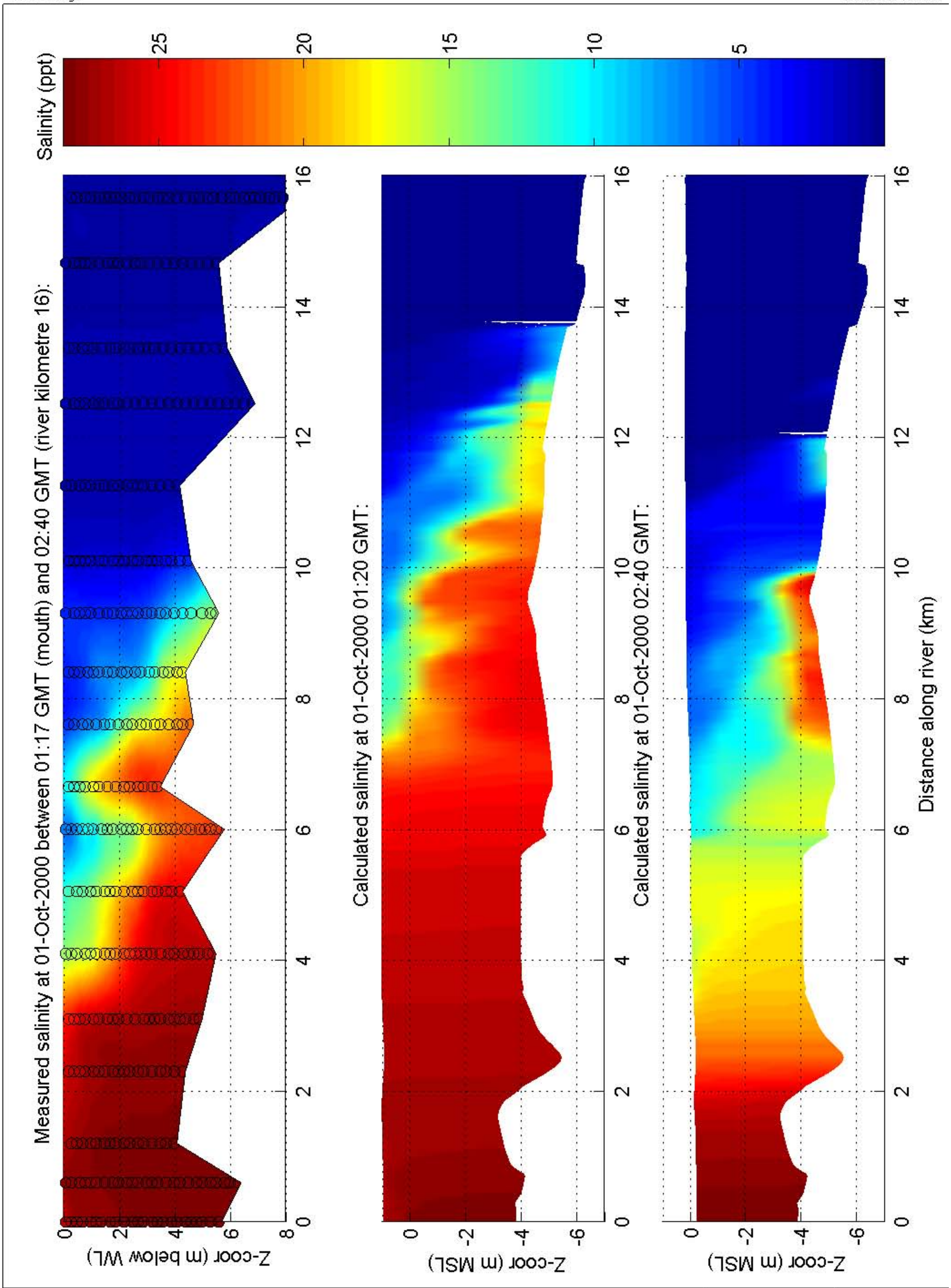
Calibration; Location: Kuala Selangor Bridge; 5.26 km upstream Conditions: Tidal range 2.6 m (average = 2.7 m); Discharge 16 m3/s (average = 60 m3/s)	Run ID:	SEM
	Run date: 28 june 2000	
Selangor Malaysia R1504	Alkyon	Fig.4.10a



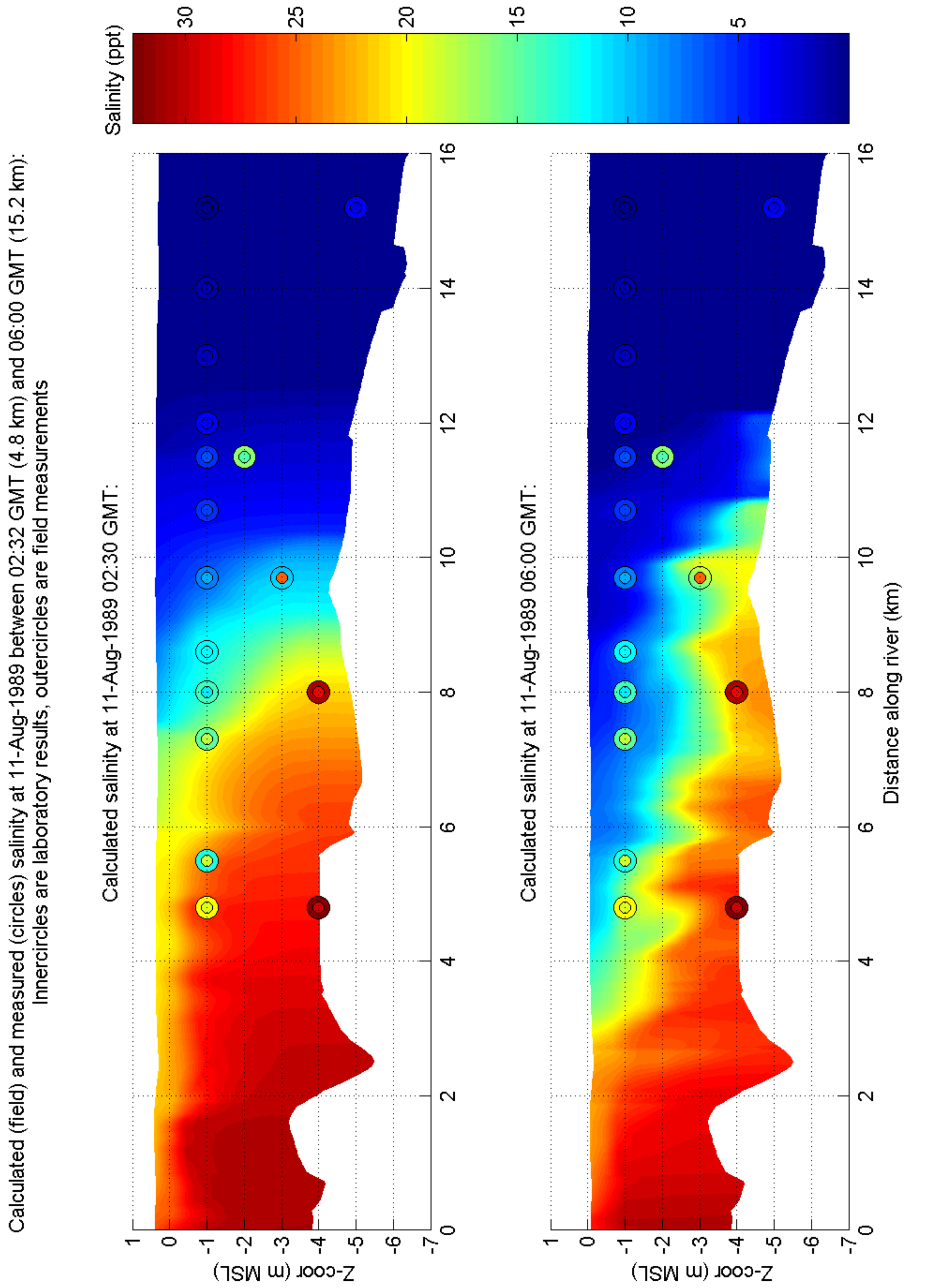
Calibration; Location: Kg Belimbing; 15.87 km upstream from mouth Conditions: Tidal range 3.9 m (average = 2.7 m); Discharge 45 m3/s (average = 60 m3/s)	Run ID:	NA
	Run date: 30 sept. 2000	
Selangor Malaysia R1504	Alkyon	Fig.4.10b



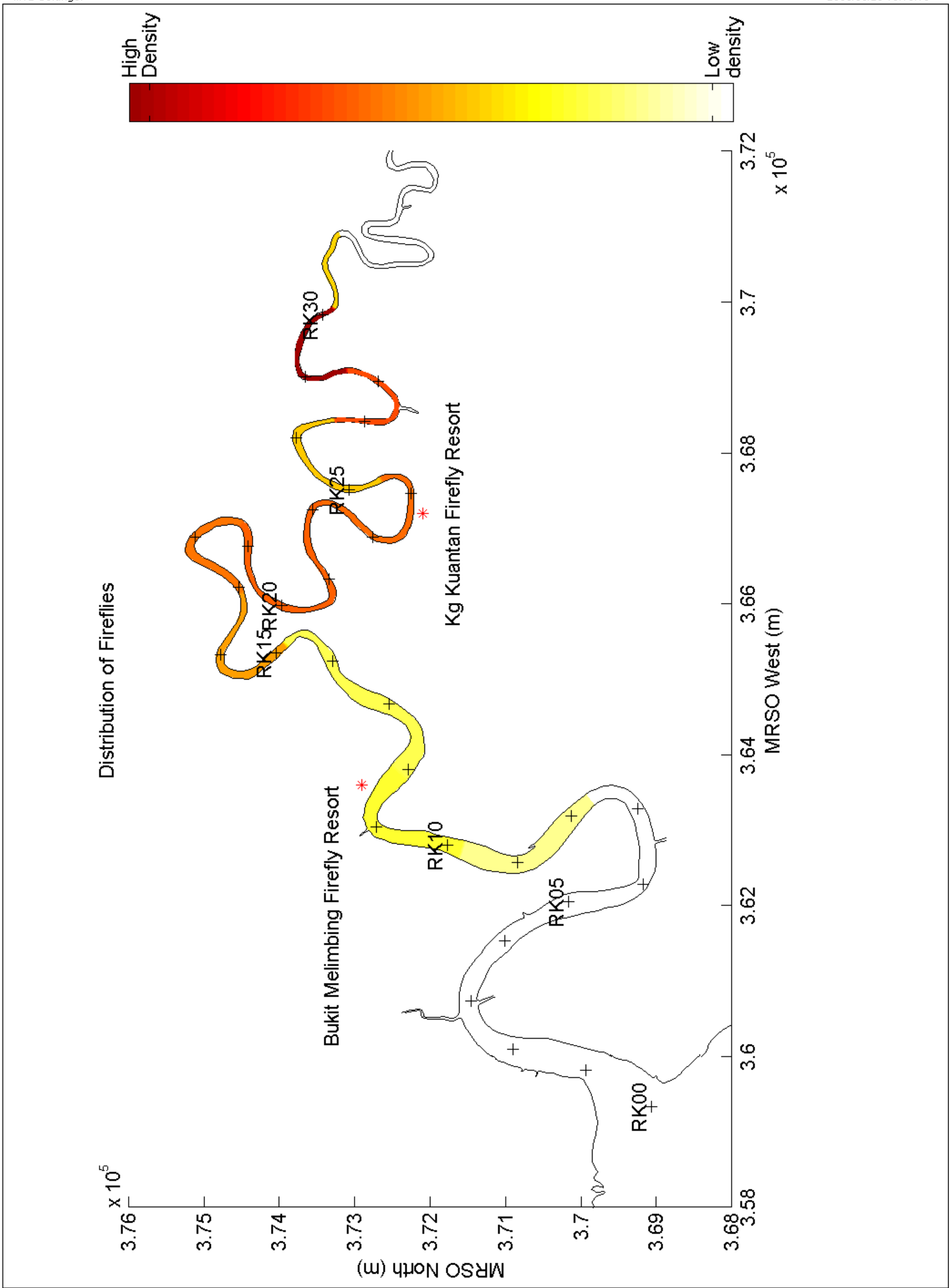
Calibration; Location: Kuala Selangor Bridge; 5.26 km upstream Conditions: Tidal range 3.2 m (average = 2.7 m); Discharge 193 m3/s (average = 60 m3/s)	Run ID:	SEM
	Run date: 2 october 2000	
Selangor Malaysia R1504	Alkyon	Fig.4.10c



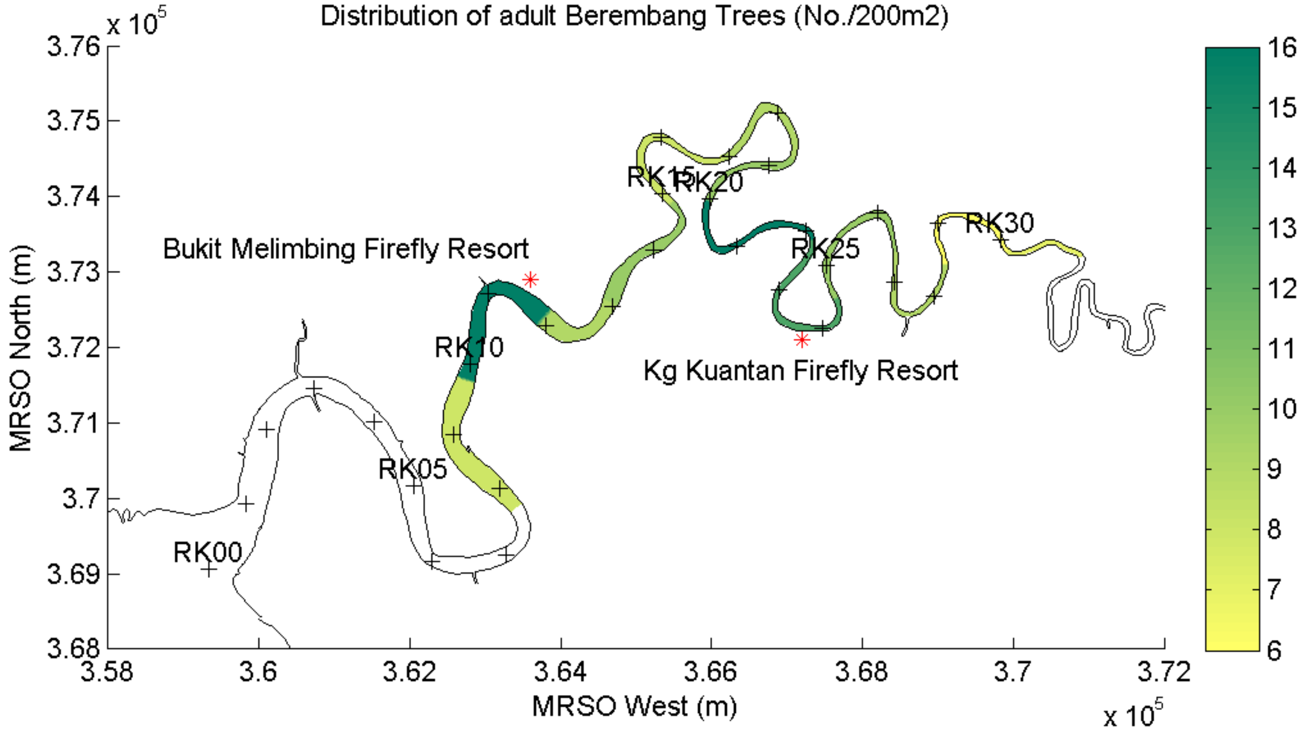
Validation based on salinity levels (data Dr. Kadir) Conditions: Tidal range 3.9 m (average = 2.7 m); Discharge 72 m3/s (average = 60 m3/s)	Run ID:	SEM
	Run date: 1 october 2000	
Selangor Malaysia R1504	Alkyon	Fig.4.11

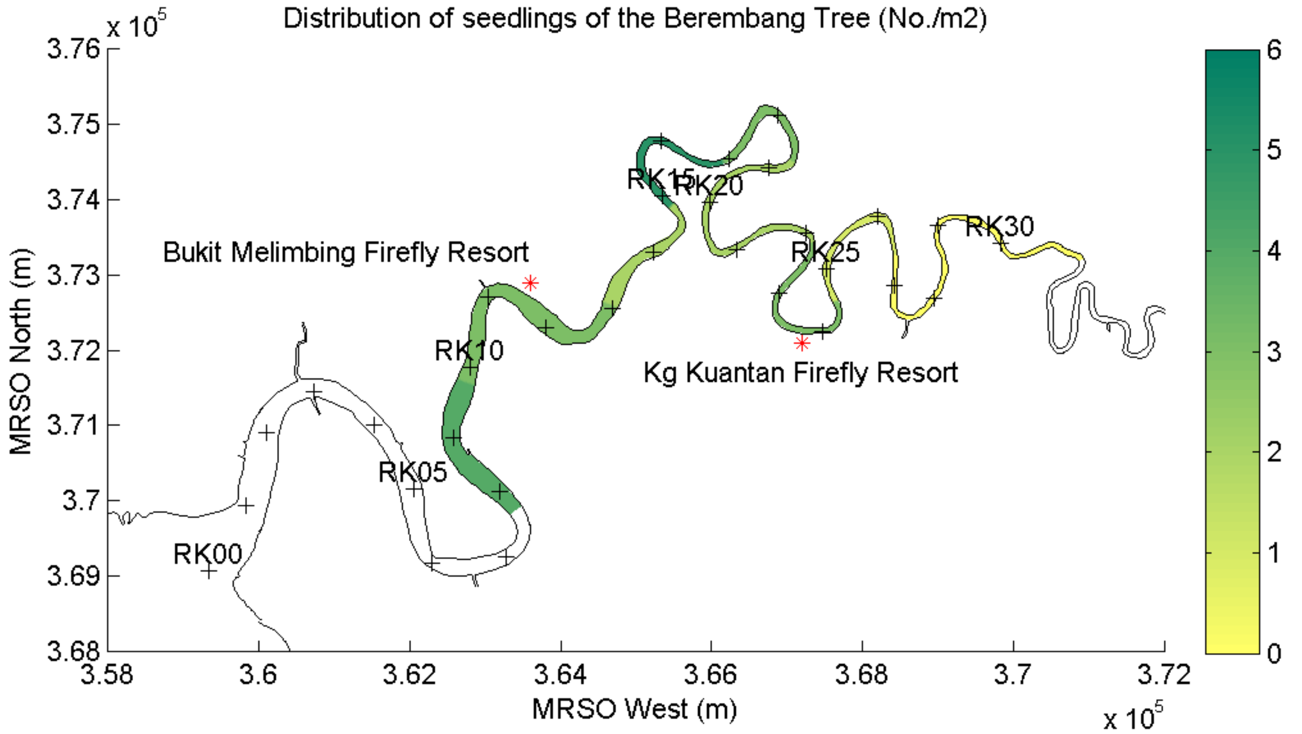


Validation based on salinity levels (data Bruce Nelson) Conditions: Tidal range 1.5 m (average = 2.7 m); Discharge 23 m3/s (average = 60 m3/s)	Run ID:	SEM
	Run date: 11 aug. 1989	
Selangor Malaysia R1504	Alkyon	Fig.4.12



Distribution of Fireflies in the Selangor Estuary Source: Malaysian Nature Society 2002		Run ID:	-
Selangor Malaysia	R1504	Alkyon	Fig.5.1

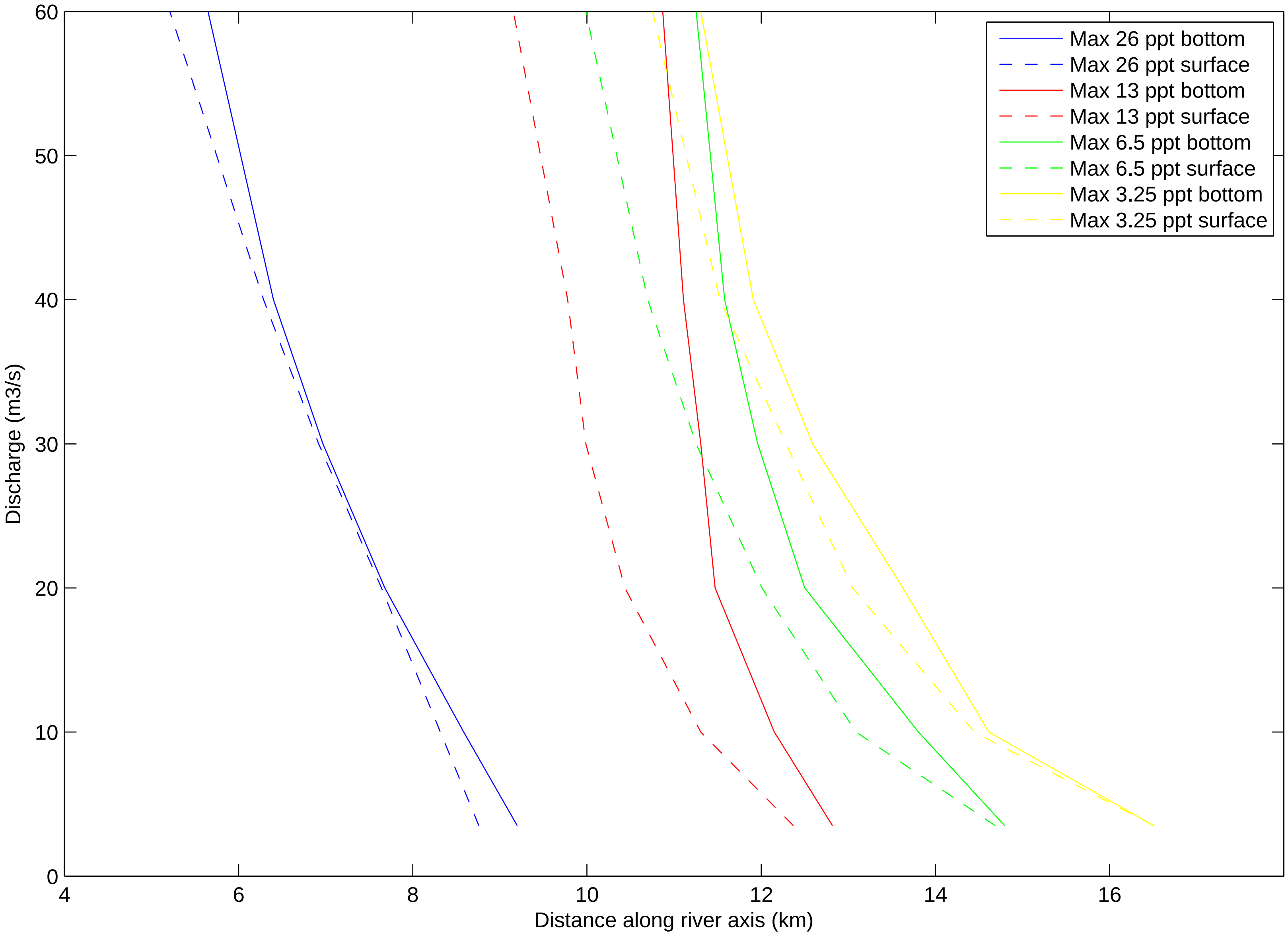




Distribution of Berembang Trees in the Selangor Estuary Source: Malaysian Nature Society 2002	Run ID:	-
Selangor Malaysia R1504	Alkyon	Fig.5.2

Relation between maximum salinity intrusion and discharge

For an average tidal cycle (tidal range 2.7 m)



Selangor Malaysia

R1504

Alkyon

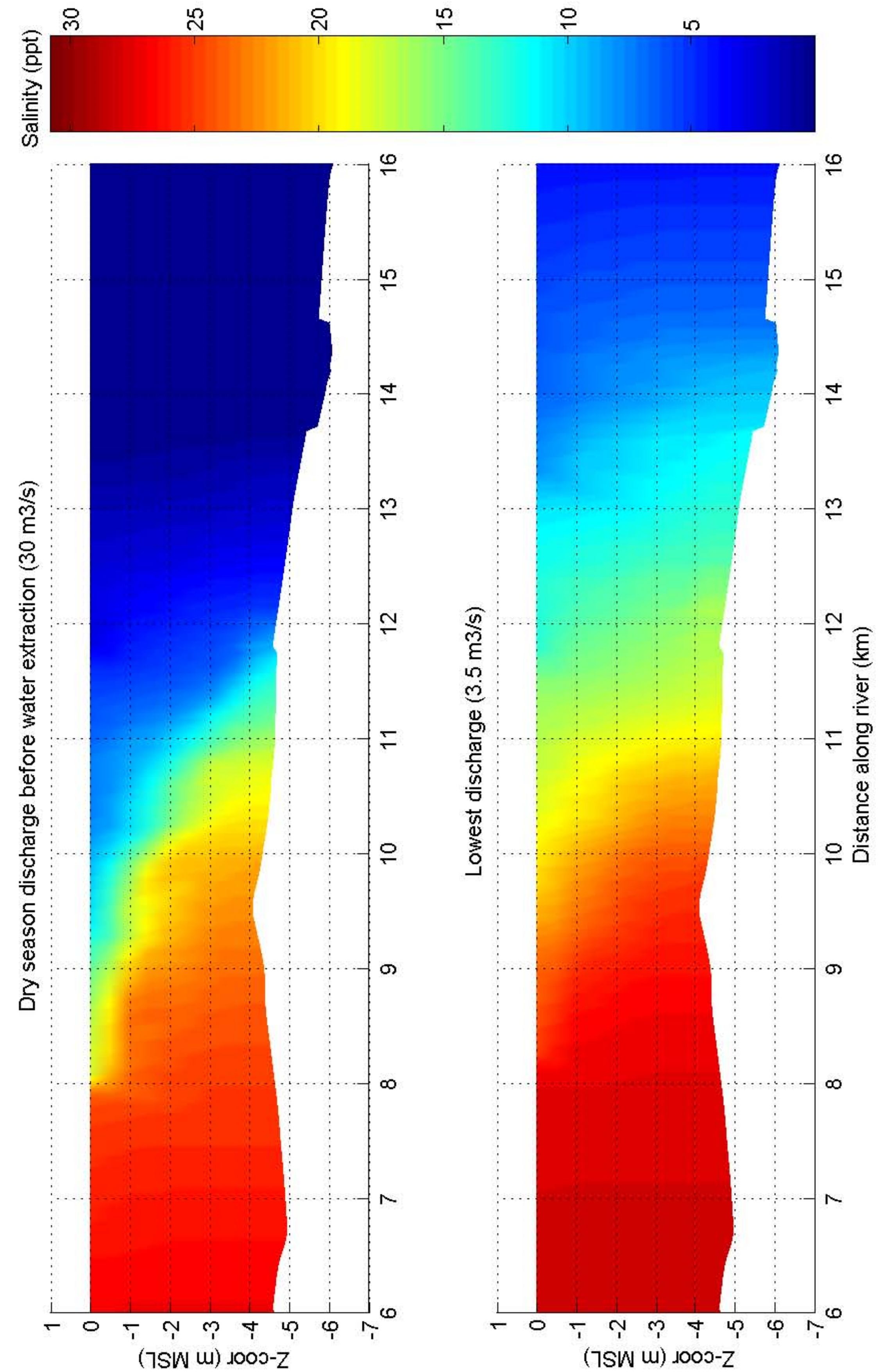
Fig.5.4

Run ID:

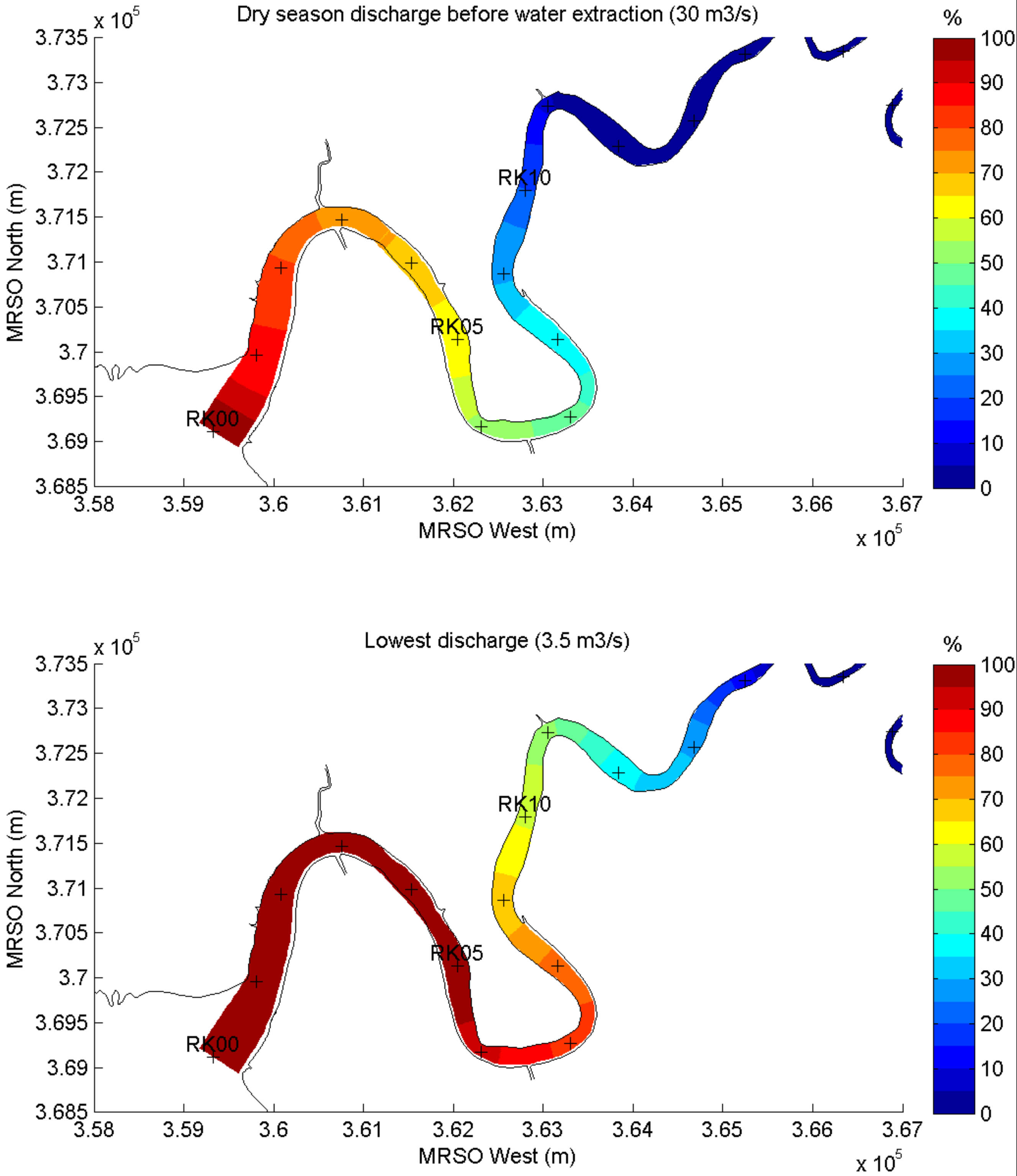
SEM

MvB Selangor

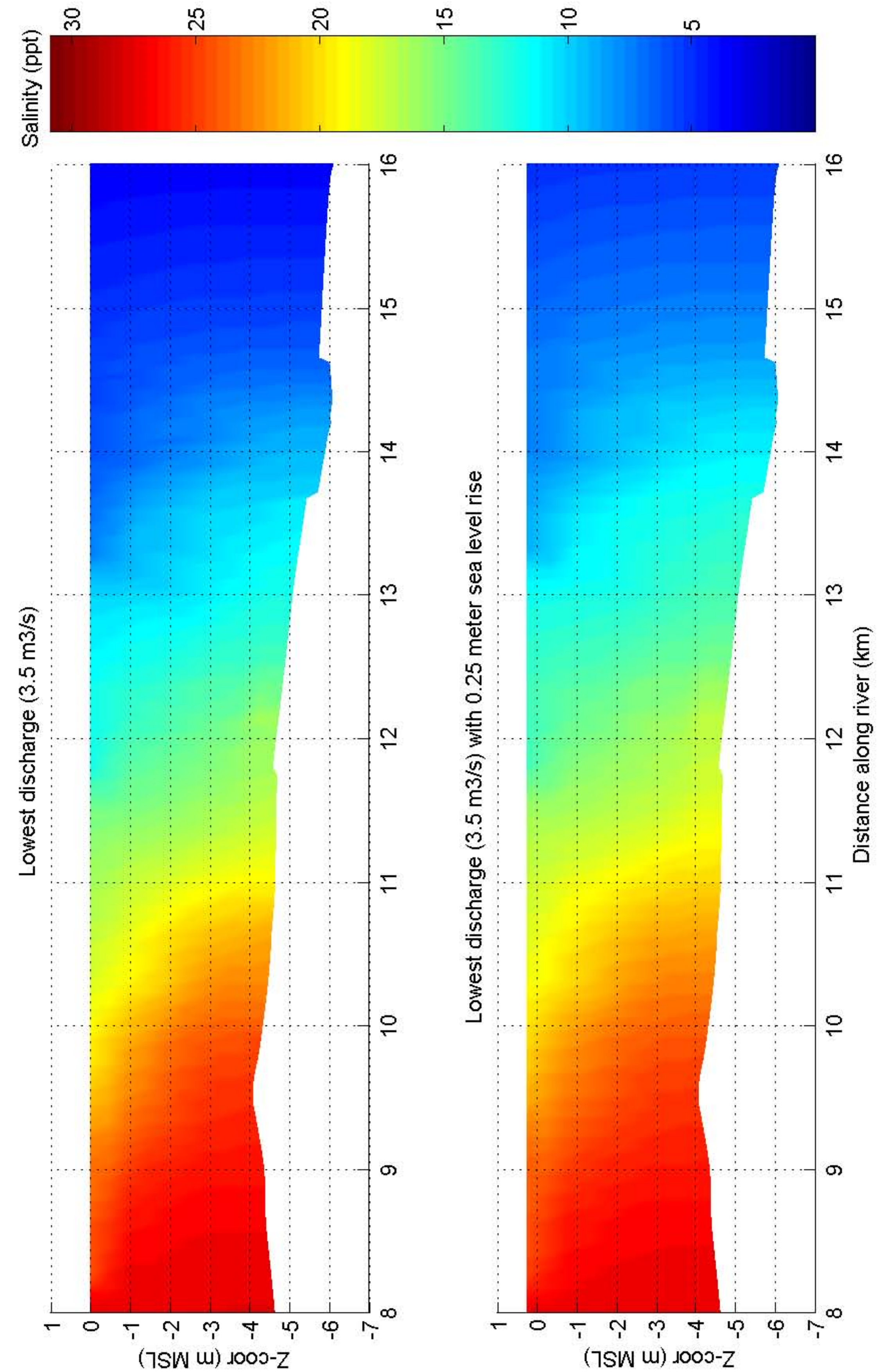
2008/06/23 13:21:17



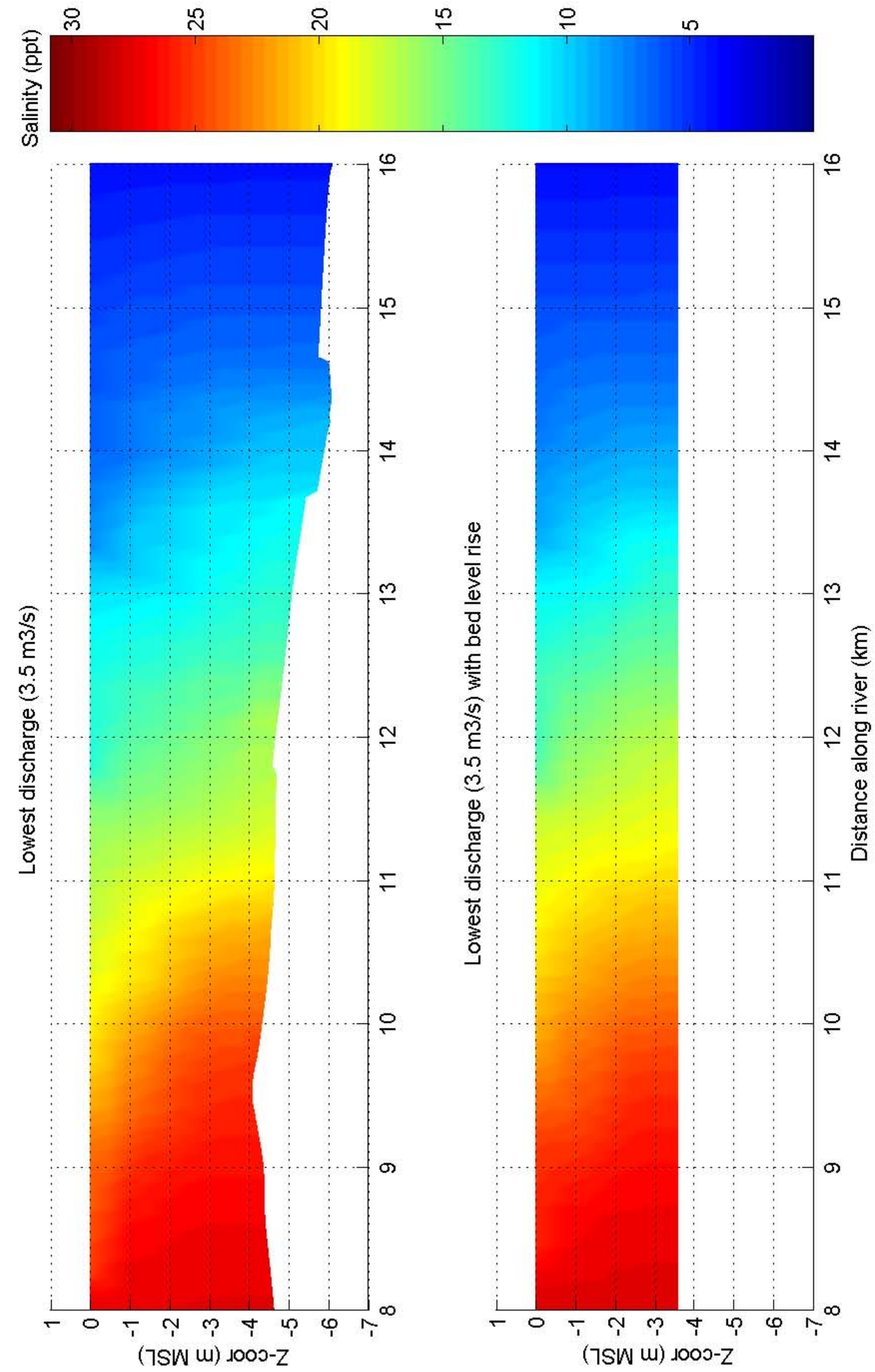
Advance of maximum salt intrusion	Run ID:	SEM
For an average tidal cycle (tidal range 2.7 m)		
Selangor Malaysia R1504	Alkyon	Fig.5.5



Percentage of time that salinity exceeds a harmful value of 6.5 ppt		Run ID:	SEM
For an average tidal cycle (tidal range 2.7 m)			
Selangor Malaysia	R1504	Alkyon	Fig.5.6



Maximum salt intrusion for the lowest discharge for current mean sea level compared to a rise of 0.25 metres For an average tidal cycle (tidal range 2.7 m)	Run ID:	SEM
Selangor Malaysia R1504	Alkyon	Fig.5.7



Maximum salt intrusion for the lowest discharge for current mean sea level compared to a simulated bed level rise For an average tidal cycle (tidal range 2.7 m)	Run ID:	SEM
Selangor Malaysia R1504	Alkyon	Fig.5.8