Hydrodynamic analysis of the Johor River estuary

Additional MSc. thesis

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Singapore, October 2010

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Preface

This additional Master of Science thesis is the result of a eight weeks during study in partial fulfilment of the requirements for the double degree of Master of Science in Hydraulic Engineering and Water Resources Management and Master of Science in Civil Engineering, Hydraulic Engineering track, of the National University of Singapore and Delft University of Technology. The study has been carried out as part of the Singapore-Delft Water Alliance (SDWA) research programme 'Large-scale Sediment Transport and Turbidity in Singapore's Coastal Waters'.

I would like to express my gratitude for the competent supervision of Prof. dr. H. F. Cheong, Dr. Jahid Hasan, Dr. Bas van Maren, Prof. dr. ir. G. S. Stelling and Dr. ir. Han Winterwerp. Without their guidance and valuable remarks it would not have been possible to write this additional thesis. A word of thanks I also owe to my fellow student Johannes Becker for the inspiring conversations during the time we spent on our additional theses at SDWA. I would like to thank the people in SDWA for spending their time and sharing their knowledge to help me during this study.

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Abstract

Singapore's coastal waters are characterised by relatively complex tidal behaviour due to it's location between two large oceans with different tidal regimes. This complex tidal behaviour results in poor understanding of the hydrodynamics and sediment dynamics. The hydrodynamics of the Johor River estuary, including part of the Singapore Strait and the Johor Strait, are investigated with a computational model in order to enhance the understanding of the sediment dynamics. The computational model used for this study is the Singapore Regional Model Refined and Aligned (SRMRA), which was developed applying the Delft3D modelling system. The domain of this validated model covers part of the Andaman Sea, South China Sea and Java Sea.

An intra-tidal analysis over a period of 25 hours reveals that the tide propagates throughout the entire study domain up to the northernmost part of the Johor River. During the ebb phase in the estuary, the flow in the Singapore Strait is in the eastern direction. In contrast to many other shallow estuaries, the water levels are observed to be ebb dominant the further upstream.

The transport patterns in the Johor River estuary on a larger timescale are described by means of the residual flow. The depth averaged residual flow is stronger and more multi-directional near the mouth of the Johor River estuary than in the upstream part. An ebb dominant and flood dominant channel can be observed. The residual flow in the surface layer is directed in the ebb direction and the residual flow in the third layer from the bed is directed in the flood direction. Moreover, the residual flow in the surface layer is stronger than the residual flow in the lower layer.

The model predicts roughly a larger bed shear stress in the southern part of the Johor River estuary than in the northern part. In the area around Pulau Tekong the bed shear stress consequently was found to exceed most of the time 0.1 N/m^2, which is considered a reasonable value for the critical bed shear stress for erosion of fine sediments. In the northernmost part of the Johor River the predicted bed shear stress is small enough for a sediment trap to be developed.

Analysis of the particle paths shows that during the period of flood tide, flow from the Johor Strait may travel into the Johor River. Once a particle flows out of the estuary into the Singapore Strait during ebb, it is not likely to flow back into the estuary during flooding.

These findings contribute to a larger understanding of the hydrodynamics and sediment dynamics of the Johor River estuary.

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1. Introduction

Sediment dynamics have a considerable impact on human activities and the marine environment. On the other hand human interferences and the marine environment are known to have a large influence on the sediment dynamics. The strategic location of Singapore has a stimulating effect on development of the interface of land and water. Due to land reclamation and dredging in Singapore's coastal waters and changes in land use in the catchment areas feeding the Johor River estuary, sediment transport and turbidity have increased over the last decades. Knowledge of sediment dynamics is therefore of significant interest. Understanding of the sediment characteristics and the hydrodynamics is important to determine the sediment dynamics.

Sediment transport and turbidity in Singapore's coastal waters have relatively complex behaviour. Partly due to the complicated hydrodynamics, the sediment dynamics are not very well understood. One of the main reasons for the complexity of the hydrodynamics is the location of Singapore's coastal water among the Andaman Sea, the South China Sea and the Java sea, as is shown in figure 1. The water levels and flows in these water bodies are mainly driven by the tides in the Pacific Ocean and the Indian Ocean. The tide in the South China Sea is diurnal, while the tide in the Andaman Sea is semi-diurnal. Singapore's coastal waters are located at the point of interaction of these tides, which explains the complexity of the hydrodynamics.

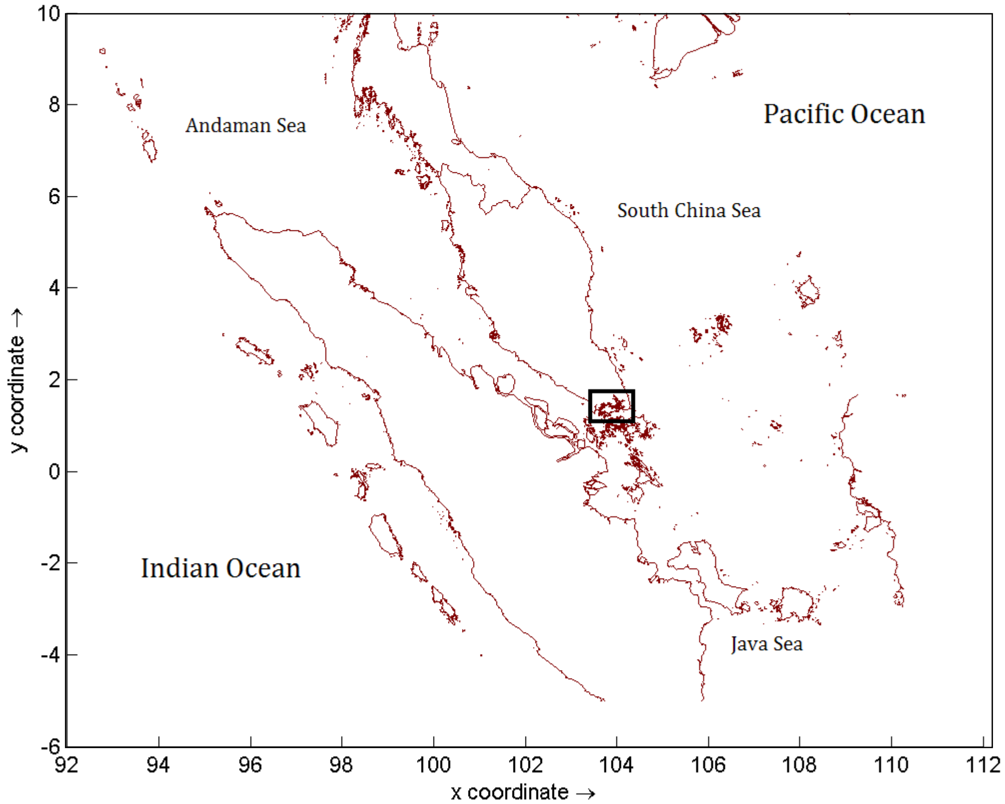

Figure 1. Overview of the geographic region (for enlargement of box see figure 2)

Important contribution to the hydrodynamics in Singapore's coastal waters is made by the Johor River in Malaysia, which mounds in the Singapore Strait. In the mouth of the Johor River, the flow is divided into two flows by the Pulau Tekong, as can be seen in the representation of the geographic area in figure 2.

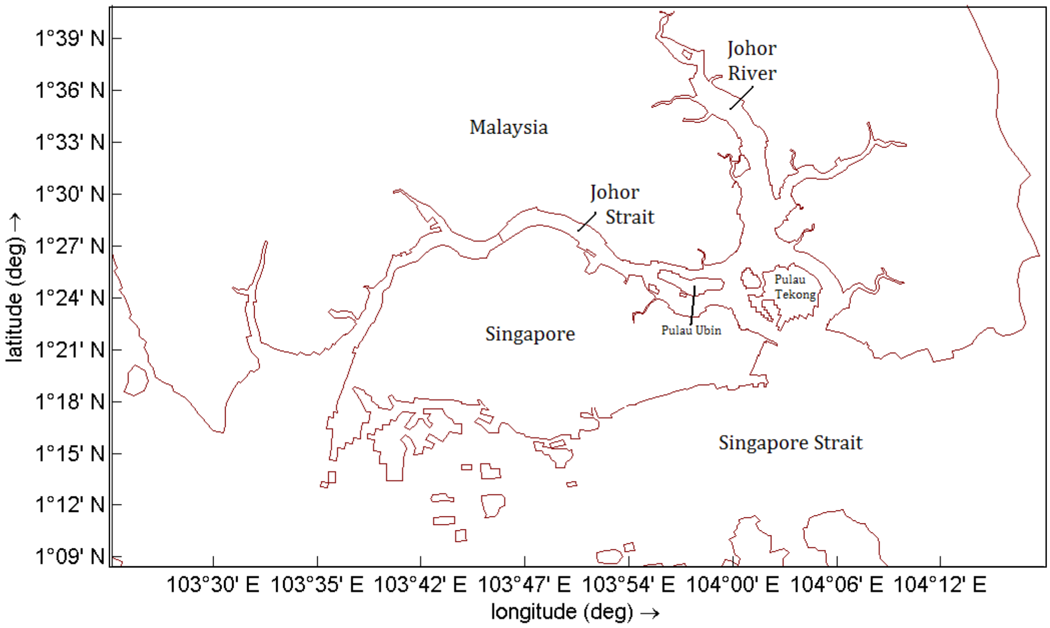

Figure 2. Overview of the geographic area

The objective of this thesis is to analyse the hydrodynamics in the Johor River estuary in order to understand the large scale sediment balance and sediment patterns in this area. A well calibrated computational model is used for this purpose. With this model hydrodynamic phenomena that are relevant for the sediment dynamics are investigated. An estimation is made of the tidal pumping, the residual flow, the flow asymmetry and the sediment reworking in the Johor River estuary.

2. Methodology

2.1. Model description

The computational model used for this study is the Singapore Regional Model (SRM), which was originally developed using the Delft3D flow modelling system (Zijl and Kernkamp, 2004). The domain covers part of the Andaman Sea, the South China Sea and the Java Sea which are all located around Singapore. A boundary fitted curvilinear orthogonal grid system is used for the hydrodynamic model simulation. Around Singapore is the inner part of this grid, especially the Johor River estuary, locally refined and better aligned, which gives the Singapore Regional Model Refined and Aligned (SRMRA). This grid is shown in figure 3 and figure 4.

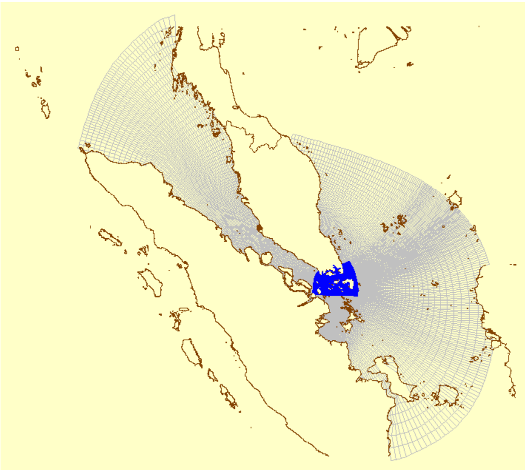

Figure 3. Domain of the SRMRA

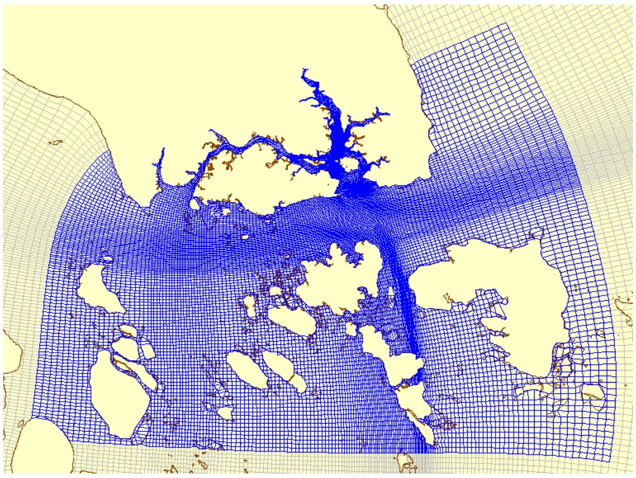

Figure 4. Inner part of the SRMRA model domain

At the offshore boundaries the model is forced by harmonic constituents and residual flows and at the landward boundaries by several river discharges. The incoming river discharges for the main stream of the Johor River are estimated using monthly rainfall records at different rain gauge stations surrounding the river. The bathymetry is determined by means of Admiralty charts (Hasan et all, 2010). The bathymetry in the Johor River estuary is in the model defined as shown in figure 5.

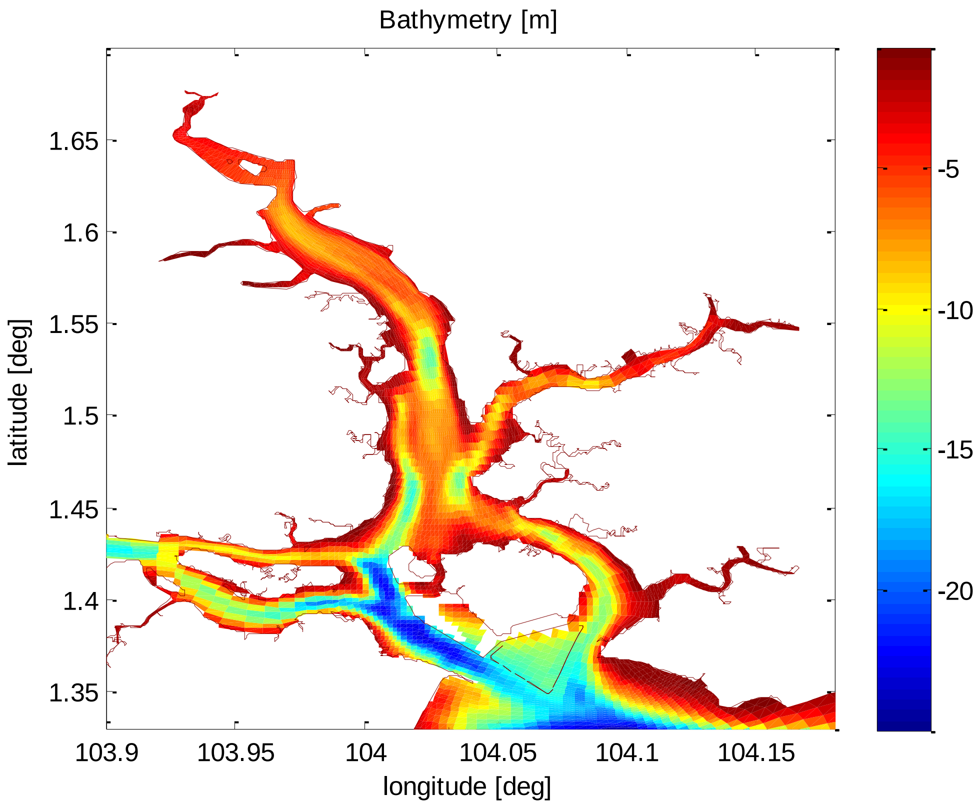

Figure 5. Bathymetry in the Johor River estuary

In the model several selected observation locations are included. Some of them are shown in figure 6.

For the purpose of this thesis two model runs have been made, one 2D simulation and one 3D simulation, both with hourly map file output information and history file output information every 20 minutes. For the 3D simulation, the water depth in the model is divided in 10 layers by means of a σ-grid. This implies that the number of layers is constant and that the layer thickness varies with depth. Although the simulated runs cover the entire year 2004, the time span covered by the simulations for this study is the spring neap cycle between 11 June 2004 and 26 June 2004.

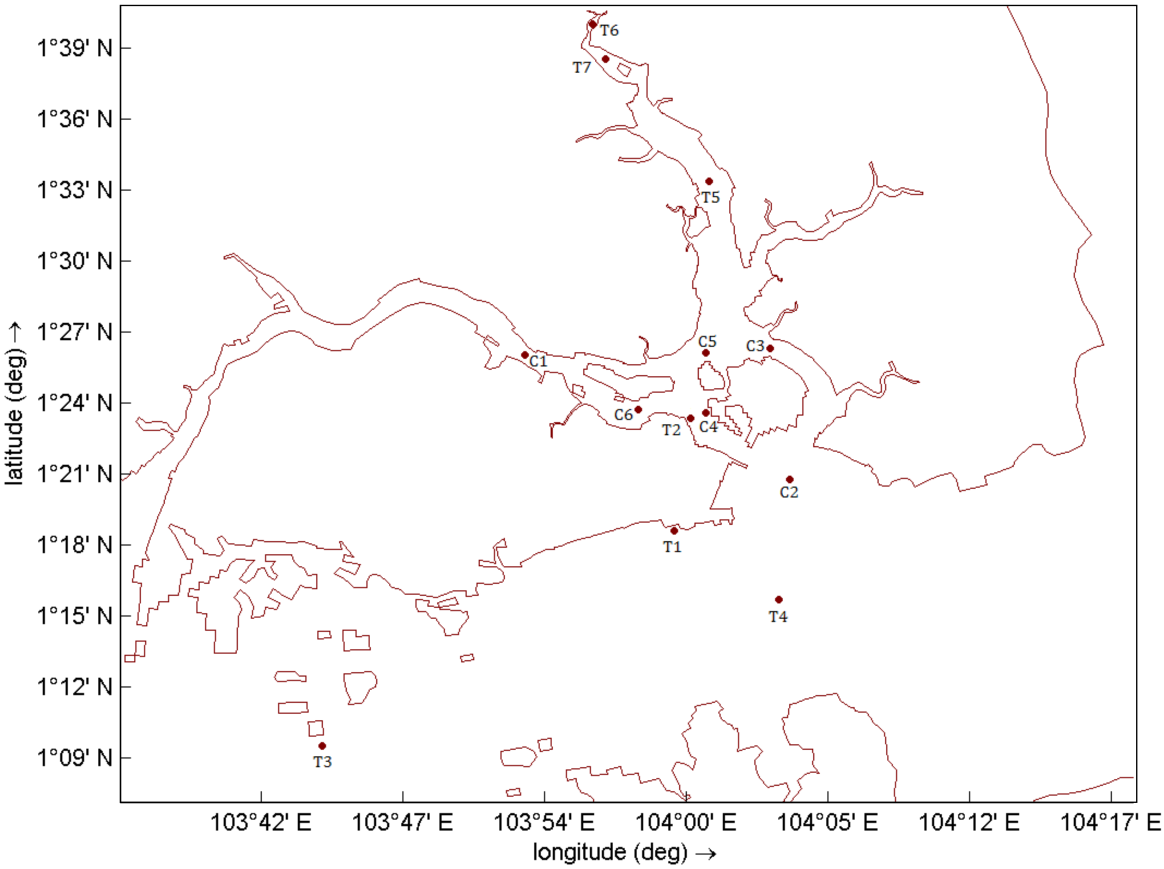

Figure 6. Locations of the observation points

The model was validated using field measurements of water level and currents at six locations in Singapore's coastal water obtained by the Maritime and Port Authority of Singapore. The locations of the water level measurements are T1, T2 and T3, and for the current C1, C2 and C3.
The results are shown in figure 7 and figure 8. [1] In general, the model predicts the water levels and the currents quite well. However, the currents are sometimes a bit overestimated and the water levels are sometimes slightly out of phase.

[1] Courtesy of Dr. G. M. J. Hasan

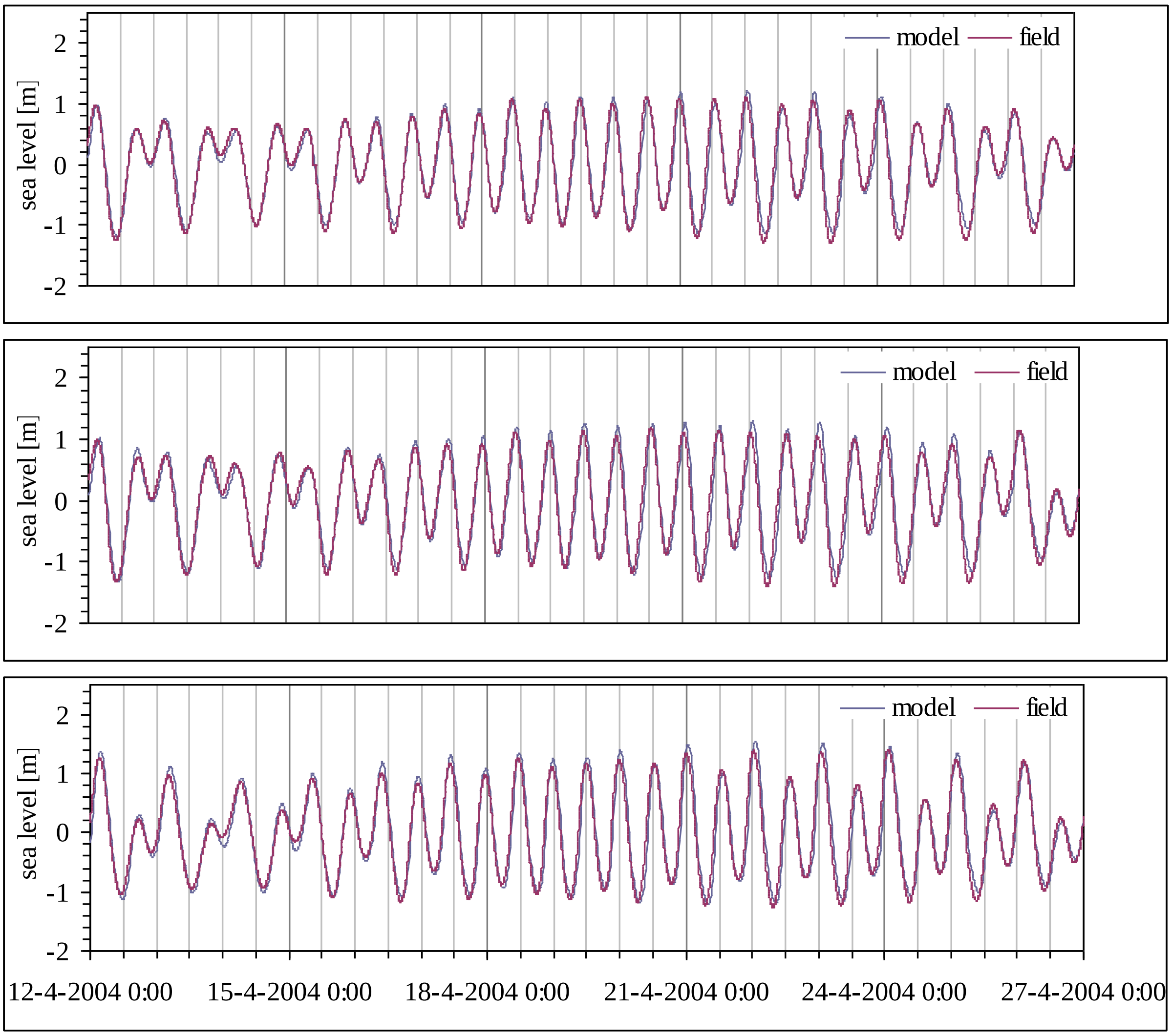

Figure 7. Comparison of model results and field measurements of water levels at stations T1, T2 and T3 respectively

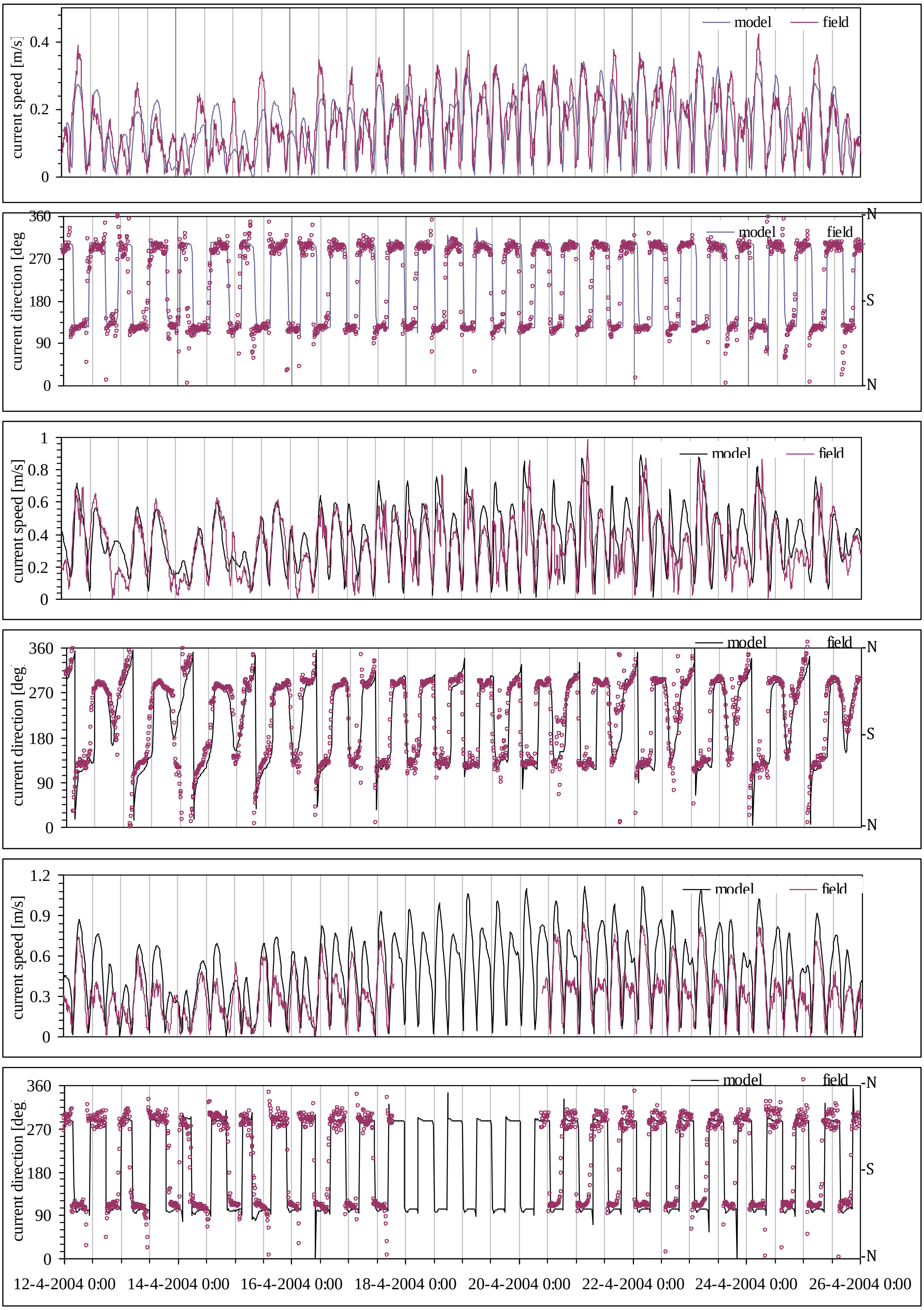

Figure 8. Comparisof model results and field measurements of the flow velocity and direction at stations C1, C2 and C3 respectively

As every model, this model has a few shortcomings. The shortcomings that are important for this thesis concern the upstream part of the Johor River.
In the model the Johor River has a closed end at approximately 1°40’ N, as is shown in figure 9. In reality, however, the river extends beyond Kota Tinggi, as shown in figure 10.

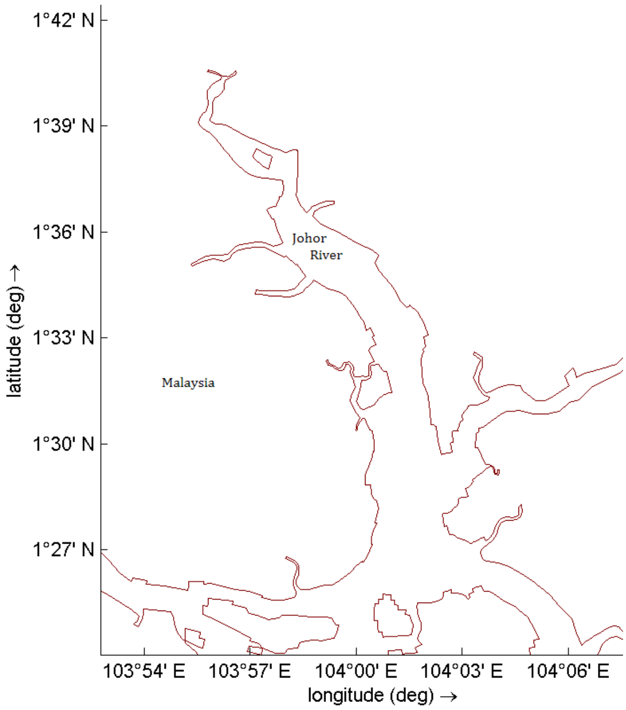

Figure 9. Land boundaries in the model

Figure 10. Land boundaries on the map

Another relevant difference between the model and reality is the shape of the island and the narrowing at 1°38’ N. The flow in the model is slightly wider than in reality. This changes the relative importance of river driven and tide driven flow. As stated before the bathymetry is determined by means of Admiralty Charts. These data are not very recent, as a result of which the present bathymetry can be different. The method of estimating the incoming discharge can be considered to be a shortcoming as well, as only information about the monthly variation in the rainfall is used for the estimation. In the model an estimation has been made with respect to the roughness of the bed and the banks in the estuary. For this estimation a single value is assumed at all locations and all time steps, which is a simplification of reality. Another simplification of reality is the fact that the effect of the inter tidal area is not taken into account. During high tide and during low tide the model has the same land boundaries. A last shortcoming concerns the shallow water equations that are solved in the Delft3D flow modelling system. The use of these equations implies amongst others that the changes in the slope of the bed level are small. This may not be the case, as several islands are situated in the area of study. These shortcomings do not seem to significantly influence the results of the model study.

2.2. Model analysis

With the computational model several hydrodynamic phenomena are analysed. These phenomena are relevant for the sediment dynamics. Each phenomenon has it's own significance in the analysis.
The intra tidal analysis in chapter 3 gives a general impression of how the water masses move in the water bodies and how the exchange between the offshore waters and the coastal waters takes place within one tidal cycle. This knowledge is of large importance, because the sediment is transported by these water masses and therefore the movement of the sediment is determined by the movement of the water masses. For this analysis the depth averaged velocity in the 2D model run is adopted.
In order to investigate these movements on a larger time scale, the residual flow over one spring neap cycle is defined, as is described in chapter 4. This gives an idea of the transport patterns of sediment in suspension. The depth averaged residual currents are taken into account, as well as the residual flow near the surface and near the bottom, for which the 3D model is adopted.
In chapter 5 the investigation of the flow asymmetry and sediment reworking is described. The flow asymmetry mainly defines in which direction the sediment particles in suspension are being taken. The reworking capacity of the flow determines where the sediment can be eroded, transported to and deposited. In this respect, the bed shear stress is important. The value of the bed shear stress determines whether the sediment particles are eroded, deposited or kept in suspension. The maximum bed shear stress at each location is calculated, as well as the percentage of the time that a critical bed shear stress of 0.1 N/m^2 is exceeded during the spring neap cycle.
This analyses would yield information which would provide a more apparent impression of the hydrodynamics in the Johor River estuary, which may contribute to the understanding of the sediment dynamics.

3. Tidal pumping

The movement of the water masses in the estuary defines to a large extent the transport of the sediments. In order to analyse the movement of the water masses in the estuary, the water level fluctuations and the magnitude and direction of the depth averaged velocity are investigated over the time span of one tidal cycle. For this intra tidal analysis the 2D model run is used. These results are displayed in figure 11 to figure 16. The direction mentioned is the direction to where the current is flowing. So, zero degrees means flow to the north and 270 degrees means flow to the west. Several conclusions can be made of this figures.

Firstly, it is noticeable in figure 16 that the tide propagates throughout the entire domain up to the upstream part of the Johor River. The tidal wave deforms during the propagation through the estuary, as the estuary becomes narrower and shallower further upstream. Due to reflection of the water, the amplitude of the tide increases. The tidal lag between T4 in the more open waters of the Singapore Strait and T6 in the upstream reaches of the Johor River is small, in the order of one or two hours. The tidal wave is almost a standing wave, since the direction of the velocity changes almost at the same time as the water level starts decreasing again after a rise of water level or increasing again after a decline of water level.

A very important conclusion can be drawn from figure 11. In this figure it can be seen that during the ebb phase the flow in the Singapore Strait is in the eastern direction. Most of the particles flowing out of the estuary are flowing into the direction of the South China Sea. The south east coast of Singapore, at the west side of the Johor River estuary, is not likely to receive any of the flow particles of the Johor River.

At the two considered stations in the Johor River estuary, C4 and C5, an asymmetry is noticed in the magnitude of the flow velocities. At both locations the ebb flow is stronger than the flood flow, which means that the asymmetry is ebb dominant. One should be careful however, before concluding that the asymmetry in this part of the estuary is ebb dominant, because only two locations are considered and these locations are situated at the intersection of flows. The velocities at these locations are strongly influenced by the local bathymetry as well.

When the velocities at the stations T4 and C4 are compared with each other, one may find that the turn of the flow velocity kicks in at C4, which is in the Johor River estuary, slightly before it kicks in at T4, in the Singapore Strait. However, the turn of the water level fluctuation is slightly later at C4 than at T4. This might be explained by the fact that the more inland, the less the time span is between the turn of the water level fluctuations and the turn of the flow direction.

If one compares station C4 in the estuary and C6 in the Johor Strait, it is remarkable that the turn in flow direction is generally less abrupt at C4. The moment that the flow turns towards ebb direction is almost the same for both locations. Conversely, the moment that the flow turns into flood direction is earlier at C6 than at C4. This makes that the flood period at C4 is relatively short when compared to the flood period at C6. This might be due to the smaller flood flow velocities at C4.

The timings of the turn of the flow direction in T5 and T6, both in the Johor River, are fairly similar. The flow direction at C6 turns slightly before this moment. One should take into account the fact that the general orientation of the flow is different. The flow pattern at C5 does not fit well in this overall image. This may be attributed to the

complex flow situation at location C5, just north of Pulau Tekong Kechil and in the area where several flows merge.
An very uncommon phenomenon in estuaries can be observed at stations T4, T5 and T6. When the water flows from the Singapore Strait to the upstream part of the Johor River, the period of decreasing water level becomes shorter than the period of increasing water level. In contrast to many other shallow estuaries, the water levels become ebb dominant. Usually, the propagation velocity of the tide is higher during flood tide and lower during ebb tide. This is because during flood tide is the water level usually larger than during ebb tide, and the velocity depends on the water depth, as the tide in deeper water experiences relatively less resistance of the bottom friction. Continuity requires the amount of water that flows in to the domain to flow out again. By this fact a tidal distortion is caused that increases when the tide moves inland. The tidal distortion results in a shorter period of rising tide than the period of falling tide, which makes the water levels flood dominant. The reason for the opposing behaviour in the Johor River estuary is unknown at this stage and remains to be invetigated.

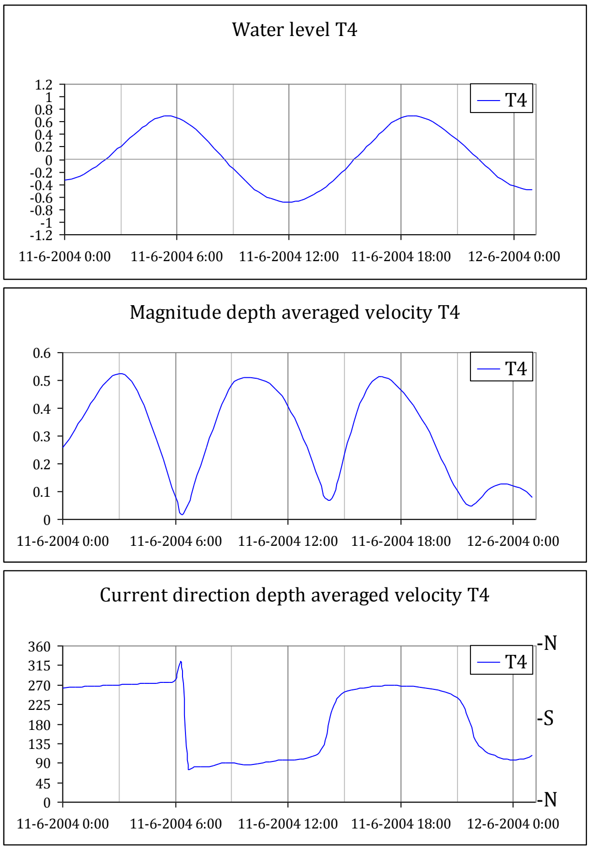

Figure 11. Water level and velocity at T4

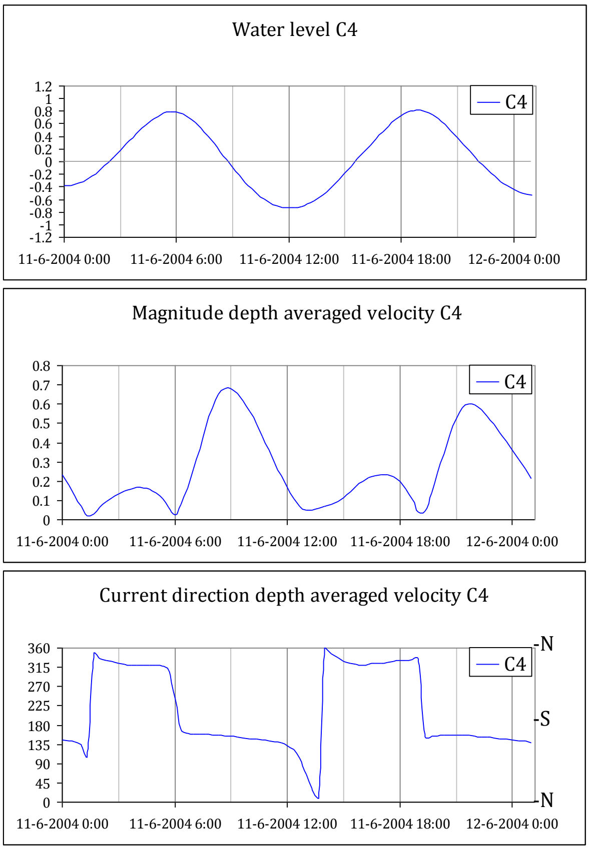

Figure 12. Water level and velocity at C4

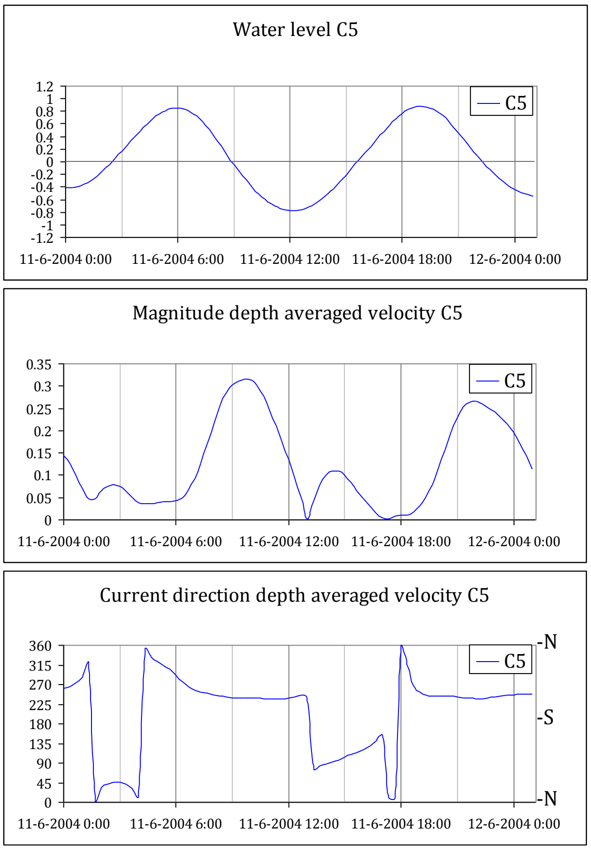

Figure 13. Water level and velocity at C5

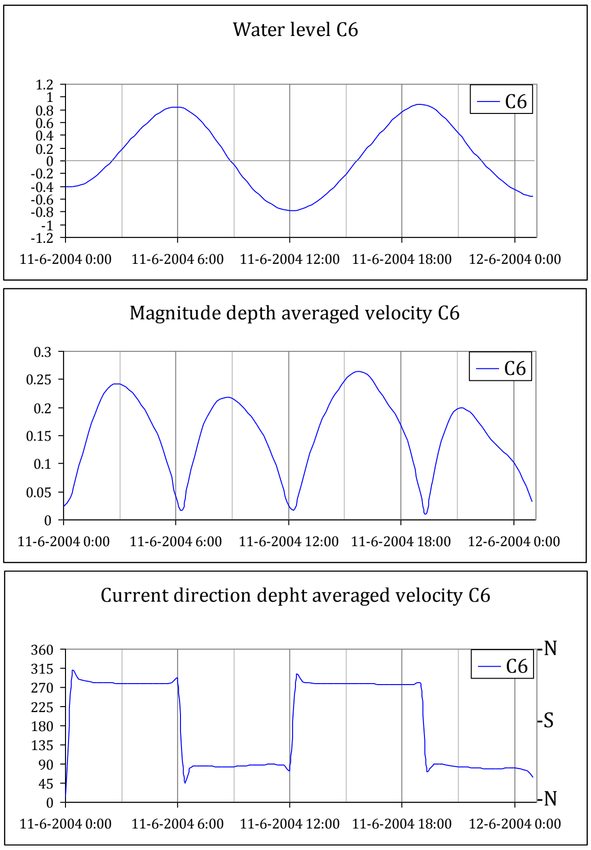

Figure 14. Water level and velocity at C6

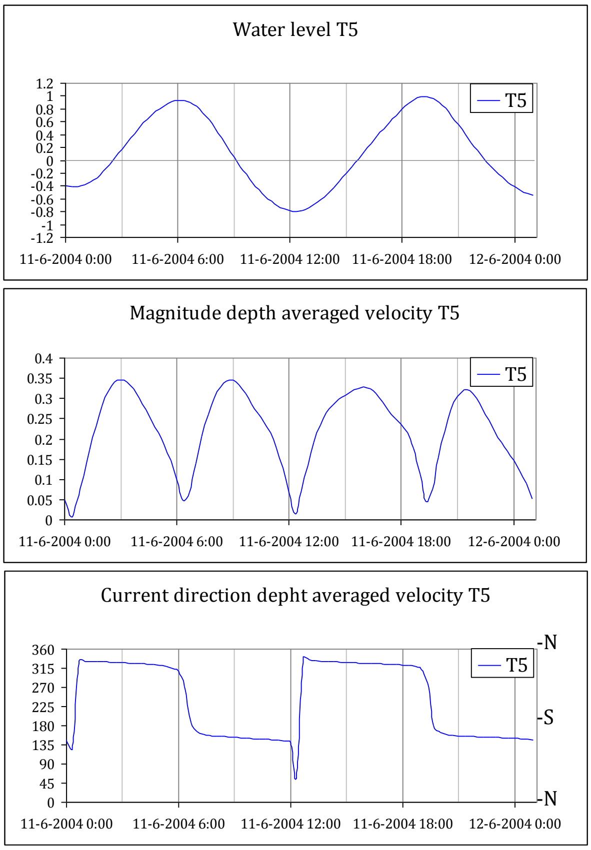

Figure 15. Water level and velocity at T5

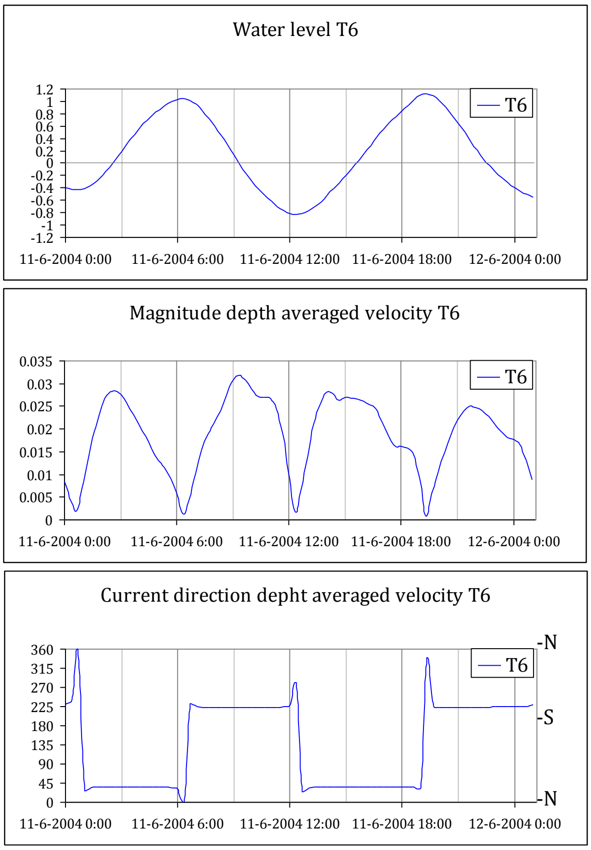

Figure 16. Water level and velocity at T6

4. Residual flow

4.1. Depth averaged residual flow

In order to investigate the transport patterns in the Johor River estuary on a larger timescale, the residual flow is estimated using the results of the SRMRA. The residual flow is calculated by averaging the flow velocities over one closed spring neap cycle. Firstly, the depth averaged residual flow is modelled with the 2D model run. To prevent numerical artefacts, no residual flow is calculated if the maximum flow velocity is less than 0.2 m/s. The results are shown in figure 17. The residual current is generally in the order of 0.1 m/s and less. In the middle of the estuary is a channel with residual flow in flood direction and another channel with residual flow in ebb direction visible. West of Pulau Tekong, the residual flow pattern is quite complicated, showing both directional and magnitude variations. Due to the river outflow into the Johor River, the total depth averaged residual flow should be in downstream direction. The residual flow in the Singapore Straits is predominantly to the west.

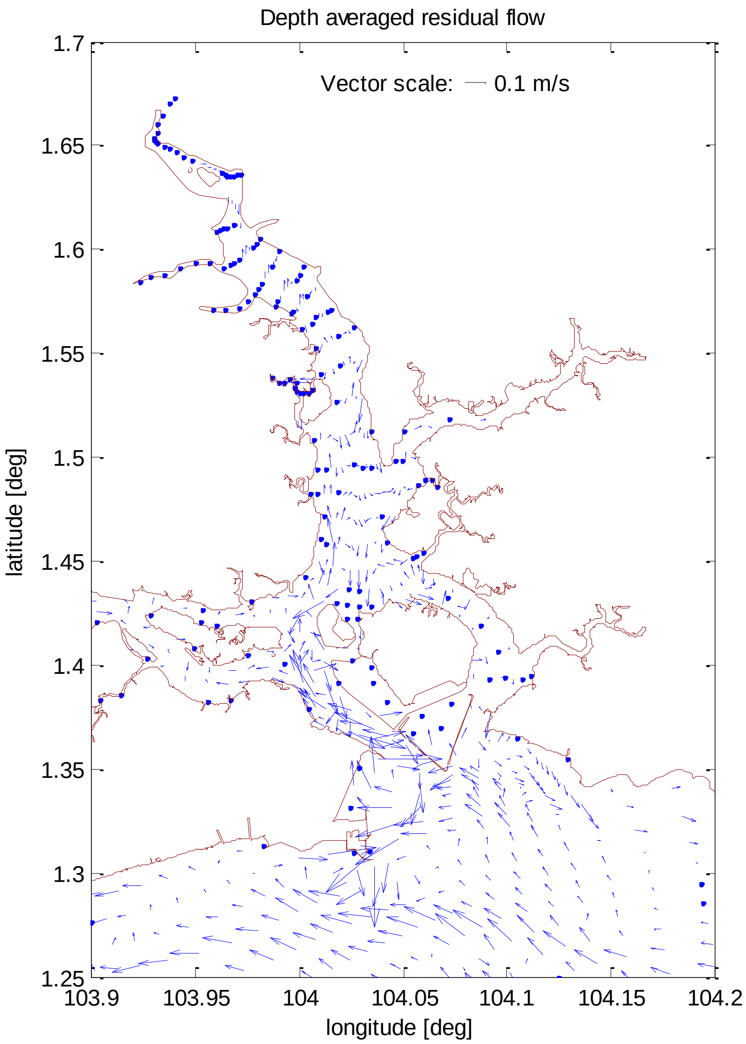

Figure 17. Depth averaged residual flow

4.2. Residual flow the in surface layer and in the third layer from the bed

To investigate the residual flow in more detail, the residual flow in the surface layer and the third layer from the bed is computed. Two apparent observations can be derived from figure 18 and figure 19. Firstly, the residual flow in the surface layer is predominantly directed in the ebb direction and the residual flow in the lower layer is predominantly directed in the flood direction. Secondly, the residual flow in the surface layer is stronger than the residual flow in the lower layer. Both observations are according expectation.

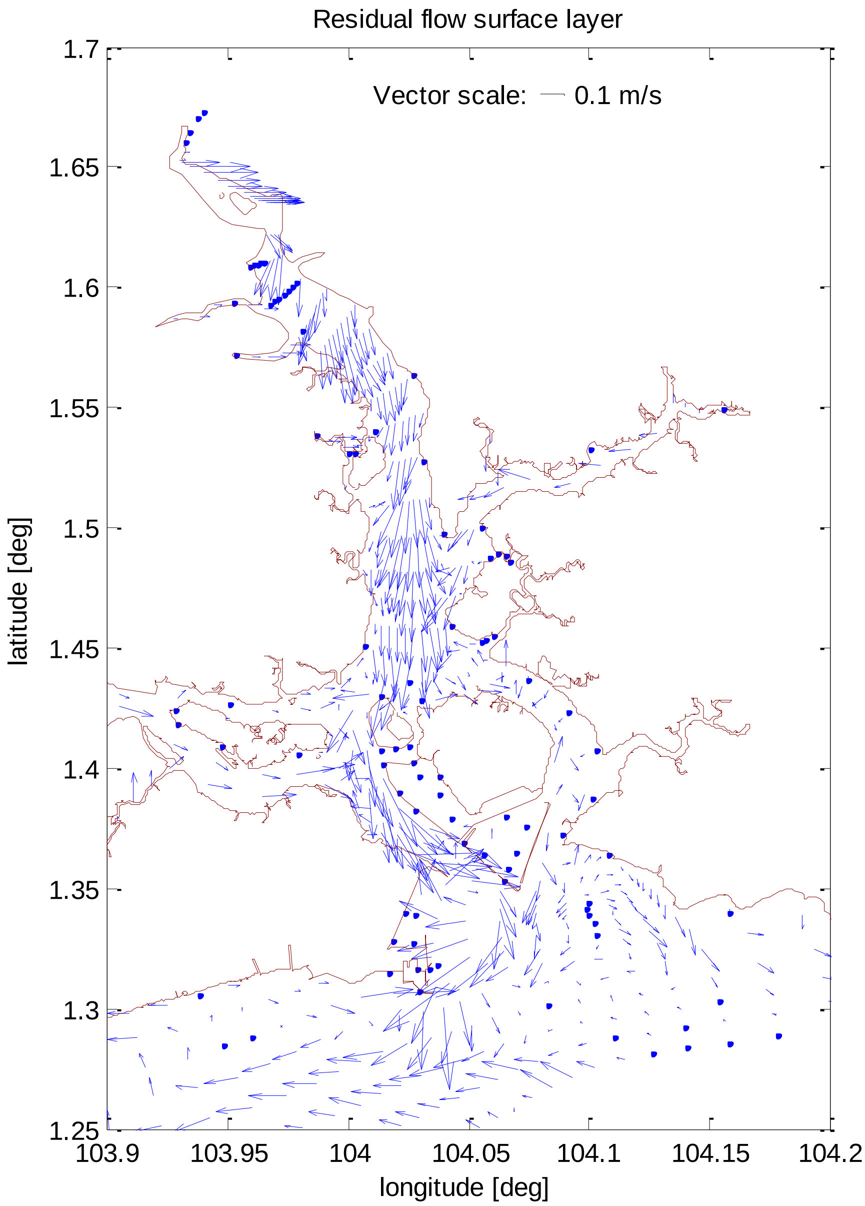

Figure 18. Residual flow in the surface layer

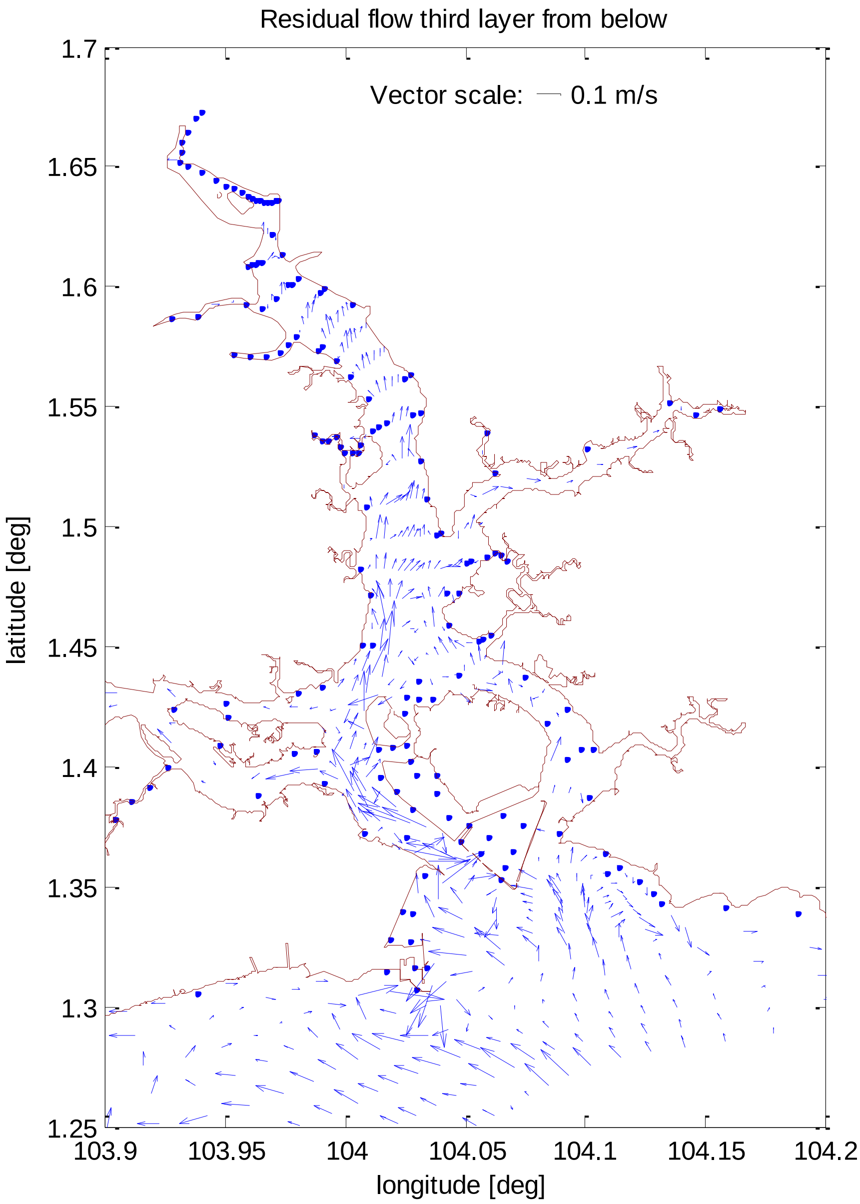

Figure 19. Residual flow in the third layer from the bed

During the start of the flood tide, the flow in the surface layer is in opposite direction as the flow in the bottom layer, but during other tidal conditions the directions of flow in both layers are the same in the different layers, as can be seen from the snapshots of the flow velocity along a length axis of a part of the Johor River in figure 20 and figure 21. The fact that continuity requires the velocities to be stronger in deeper parts of the estuary and weaker in the shallow parts of the estuary can be observed in the figures.

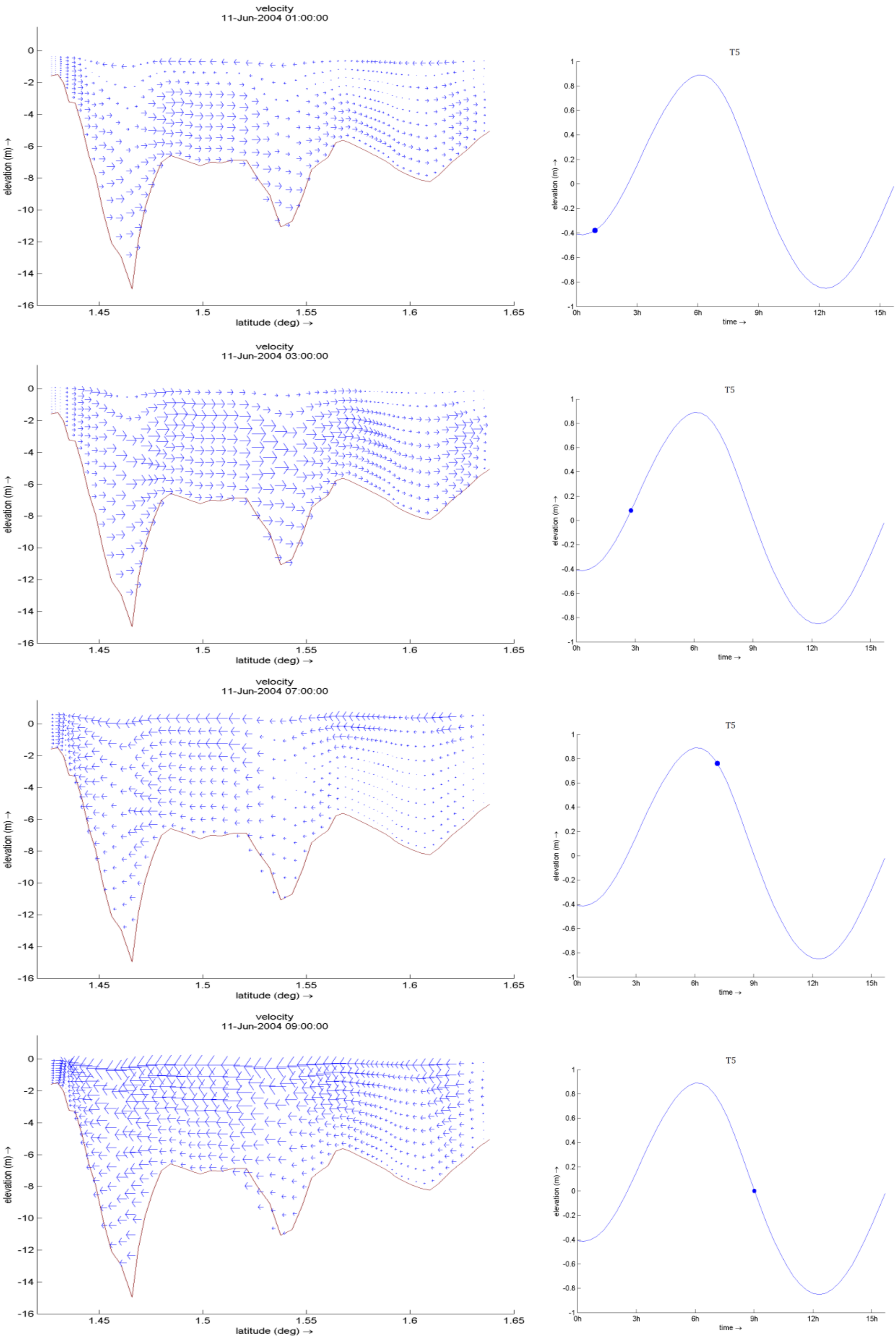

Figure 20. Snapshots of velocities along a length axis in a part of the Johor River during different tidal conditions

5. Flow asymmetry and sediment reworking

5.1. Flow asymmetry

In nearly all estuaries, the ebb and the flood flows are not equal to each other and the Johor River estuary is no exception. This can have a significant influence on the sediment transport. In figure 21 and figure 22 the maximum flow velocities during ebb tide and flood tide are displayed. For this computation the 2D model run is used. The flood tide and the ebb tide are determined by the water level in this calculation. When the water level is increasing, the tide is considered to be flood tide and when the water level is decreasing, it is considered to be ebb tide.

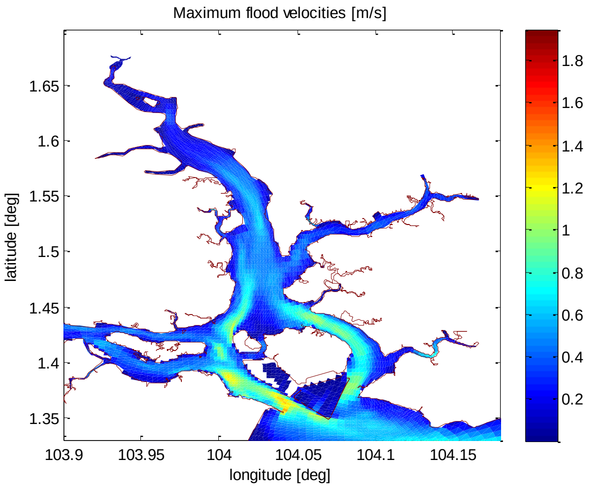

Figure 21. Maximum flood velocities

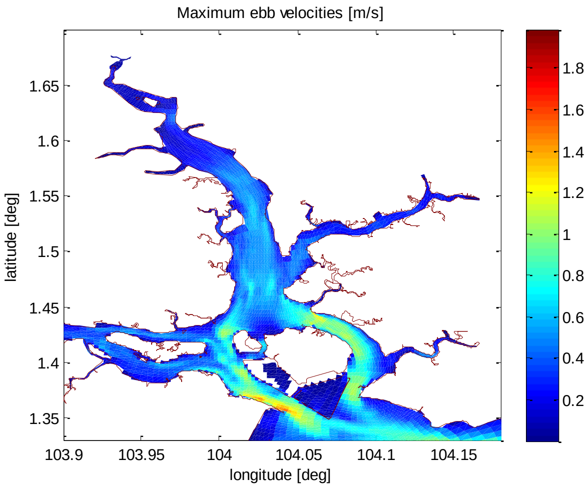

Figure 22. Maximum ebb velocities

Some insight in the tidal asymmetry is obtained by computing the ratio of the maximum ebb velocity and the maximum flood velocity at every location in the Johor River estuary. The representation of this ratio is shown in figure 23.

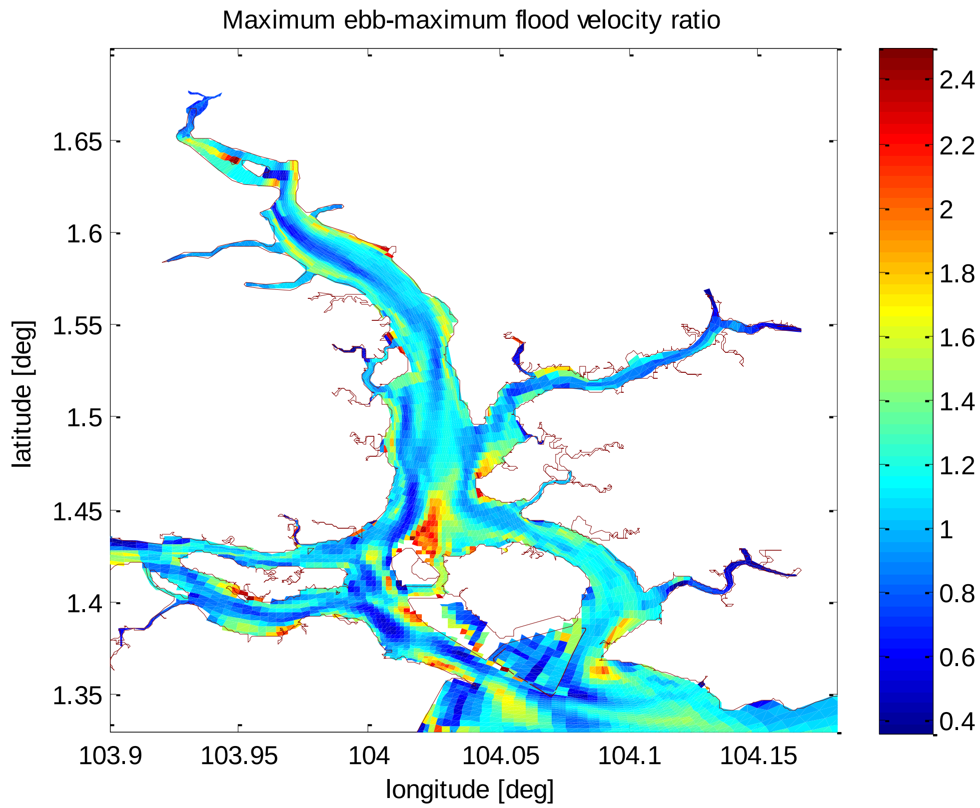

Figure 23. Ratio of the maximum ebb velocity and maximum flood velocity

Several channels are visible where the maximum ebb velocity is lower than the maximum flood velocity. The flow in these channels is flood dominant. In most of the shallow areas the flow is ebb dominant. In the shelter of some small islands and protrusions is, according to expectation, the ratio fairly higher or lower than one. In the branch on the west of Pulau Tekong the maximum flood velocity exceeds the maximum ebb velocity, while in the east branch the maximum ebb velocity exceeds the maximum flood velocity.

5.2. Sediment reworking

Erosion characteristics are of large importance for understanding the sediment dynamics. A significant parameter in this respect is the bed shear stress. The model results as depicted in figure 24 show that in the upstream part of the Johor river, the bed shear stresses predicted by the model are rather small and that the bed shear stress roughly increases in the downstream direction. The model predicts the largest bed shear stress in the Johor River estuary to be around Pulau Tekong, which can be explained by the strong flow velocity in that part of the estuary. One important remark is that the computed bed shear stress is based on the total drag, which consists of skin friction drag and form drag. For exchange between water and bed only the skin friction is relevant. This means that the actual value of the bed shear stress is lower than computed by the model.

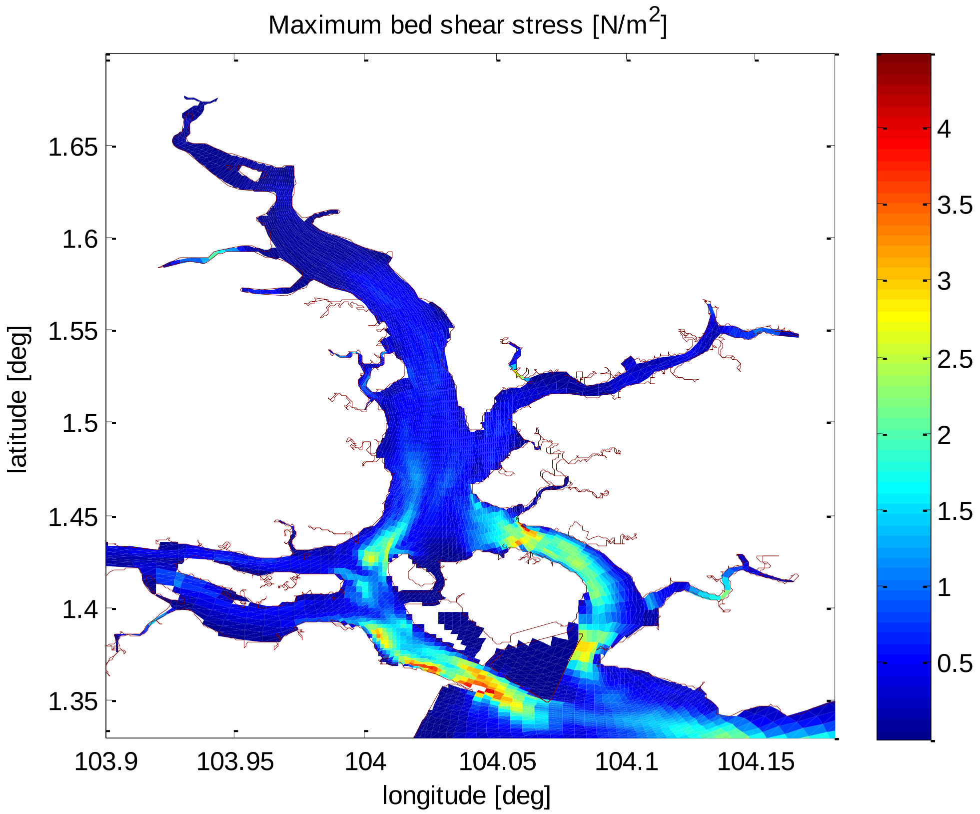

Figure 24. Maximum bed shear stress in the Johor River estuary

Sediment can be eroded when the bed shear stress is larger than the critical bed shear stress for erosion. The critical bed shear stress for erosion depends on the sediment characteristics and several other parameters. In general the bed shear stress needed to erode sediment is larger than the bed shear stress needed for keeping the sediment in suspension. The value of the critical bed shear stress for erosion of freshly deposited mud may vary between 0.1 N/m^2 and 0.5 N/m^2 (Winterwerp, 1989).
With a value of 0.1 N/m^2 for the critical shear stress it is probable that in several parts of the estuary no erosion will take place, as shown in figure 25. If there is any sediment in suspension available for settling, deposition will take place at these locations.

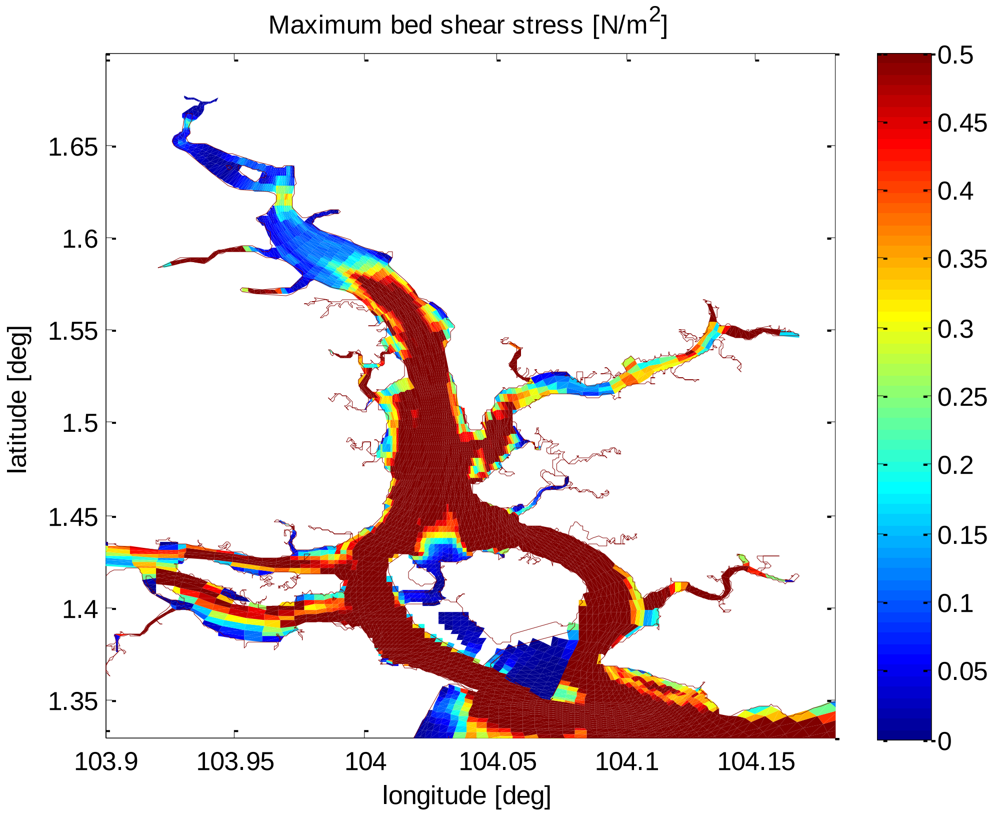

Figure 25. Maximum bed shear stress up to 0.5 N/m²

A stretch of circa 3 kilometre with bed shear stresses lower than the critical value of 0.1 N/m² is situated in the most upstream part of the Johor River. The magnitude of the depth averaged velocity at observation location T7, which is located in this part is shown in figure 26. The averaged velocity is approximately 0.04 m/s.

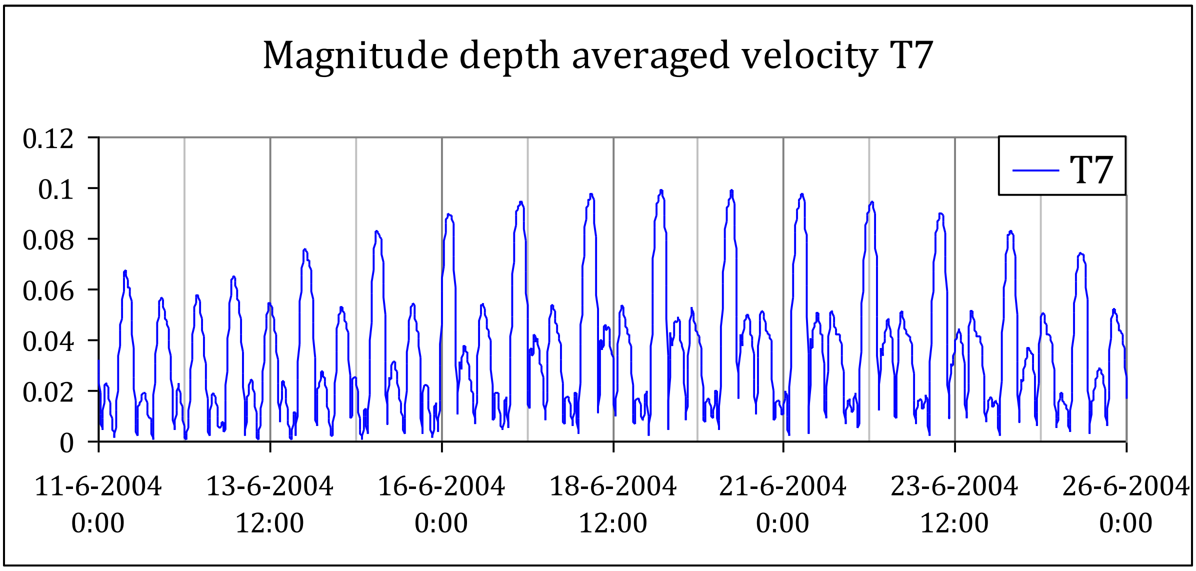

Figure 26. Magnitude of the depth averaged velocity at T7

With a depth of 5 meter and an assumed settling velocity for coarse sediment of 1 mm/s, it takes about 80 minutes for a sediment particle from the surface to deposit on the bed. In that time, with a depth averaged velocity of 0.04 m/s, the particle travels over roughly

200 meters. For the medium-sized sediments a settling velocity of 0.1 mm/s and a maximum ebb flow duration of six hours is assumed. This makes a maximum travel distance of circa 850 meter. Particles coming from upstream with a settling velocity of 0.1 mm/s or higher, will therefore permanently be trapped in the low shear stress zone of 3 kilometre. For the fine materials a settling velocity of 0.01 mm/s is assumed, the travel distances can be determined to be 8.5 kilometre. This means that only fine sediments can travel over the sediment trap. This calculation gives a rough indication. Due to several forms of turbulence the situation is more complex than described here. Nevertheless, it can be expected that the coarser particles consolidate in this part of the Johor River. This causes the bulk density to increase, and therefore the critical bed shear stress for erosion increases. The deposited sediment becomes more stable and less likely to be remobilized again.

If the critical bed shear stress for erosion of fine sediments is assumed to be 0.1 N/m^2, the percentage of the time that the bed shear stress exceeds the critical bed shear stress is shown in figure 27. This gives an indication about the probability that the sediment erodes.

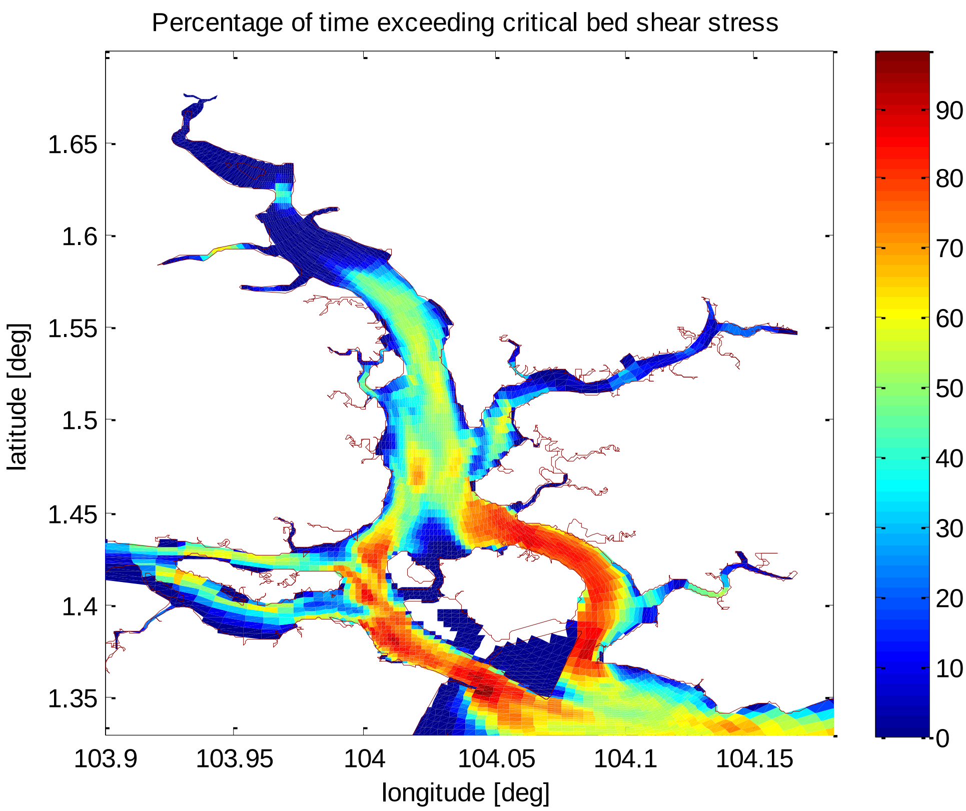

Figure 27. Percentage of the time that the bed shear stress exceeds 0.1 N/m^2

The tidal excursion is the distance over which a particle travels during the time that the water level rises from low tide to high tide or from high tide to low tide. If the average flow velocity is 0.25 m/s and a tidal cycle lasts 12 hours, the distance that a very fine particle travels in half a tidal cycle, is approximately 5.4 kilometres. This makes that a particle travels roughly 21 kilometres a day in total, in ebb and flood direction.
It is possible for a particle to travel from the Johor Strait to the Johor River estuary during ebb tide and then to flow into the Johor River the during flood tide. The particles

that travel out of the southern part of the estuary during the ebb phase, are likely to arrive in the Singapore Strait and not to return back into the estuary. Possible travel paths are illustrated in figure 28.

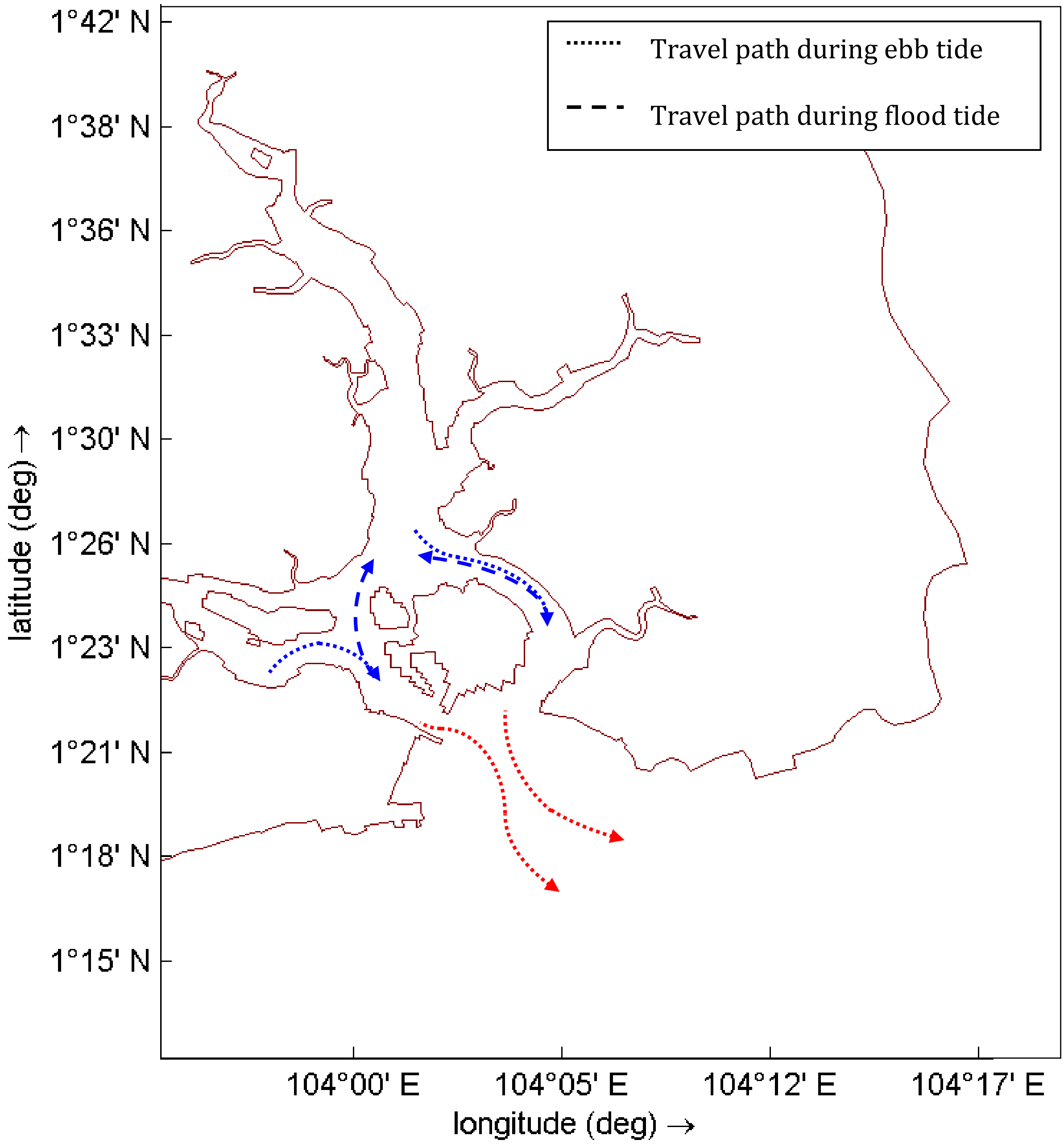

Figure 28. Possible travel paths of particles

6. Discussion

The hydrodynamic analysis in this thesis has been carried out for the period of one spring neap cycle in June of the year 2004. During this time span no extreme flood events occurred. In addition, the seasons in Singapore and surroundings are characterized by two monsoons. The north east monsoon occurs in December till March and the south west monsoon occurs in June to September. In the periods between the monsoons rainfall is likely to be less than during monsoons. The flow circulation in the Johor River estuary depends on the river discharge, which is subjected to the rainfall. For these reasons the analysis may return a different set of results for another period of the year.

Johannes Becker has done research about the properties of cohesive sediment in Singapore's coastal waters. His findings, combined with the obtained information about the hydrodynamics, can be a valuable contribution to a better understanding of the sediment dynamics in the Johor River estuary. One of the findings on the sediment properties is: 'TK samples have a higher undrained shear strength compared to JB and JC samples.'

The hydrodynamics at the locations of the TK samples have different characteristics than the hydrodynamics of the JB and JC sample locations. Due to the higher flow velocities and the higher bed shear stresses, it is not very likely that sediments settle down in the area of the TK samples. It is well possible that the sediments in the bed are present at that location for a long time, without being mobilized. This can cause the sediments to consolidate and the bed to become more and more stable. In relation to this, the higher undrained shear strength of the TK samples compared to JB and JC samples can be explained.

7. Conclusions and recommendations

7.1. Conclusions

In this thesis an analysis of the hydrodynamics in the Johor River estuary has been presented. This analysis reveals some interesting conclusions. During the ebb tide, when the water flows in the southern direction out of the river, the water in the Singapore Strait flows eastwards. Once particles flow out of the estuary into the Singapore Strait, they are not likely to flow back into the estuary.

In many shallow estuaries, the water levels become flood dominant land inward. In the Johor River estuary this is not the case, the water levels become ebb dominant. The reason for this fact is unknown at this stage.

The depth averaged residual flow is larger and more mixed in the southern part of the Johor River estuary than in the northern part. An ebb dominant and flood dominant channel can be observed. The residual flow in the surface layer is directed in ebb direction and significantly larger than the residual flow in the third layer from the bed, which is directed in flood direction.

The model results show that the bed shear stress roughly increases in the southern direction. In the area around Pulau Tekong the bed shear stress consequently exceeds most of the time 0.1 N/m^2, which can be considered to be a reasonable value for the critical bed shear stress for erosion of fine sediments. A sediment trap is located in the most northern part of the Johor River.

Concluding can be stated that the lack of clarity of the hydrodynamics in the Johor River estuary is decreased and that the sediment dynamics have lost some of their incomprehensibility.

7.2. Recommendations

The analysis carried out for this study is far from complete. Several issues have been addressed, but many are still open for more research. One of the recommendations with this respect is an investigation of the extent in the estuary and distribution over depth of the salinity. For small sediment particles, when the mass of the particles is negligible, the dynamics of these behave like the dynamics of the salinity. Locations where salinity is trapped are most likely to be places where sediment is trapped. Salinity is, unlike sediment dynamics, relatively easy to measure, which makes field measurements a very useful tool in the investigation. Research on this topic would therefore make an interesting contribution to a better understanding of the sediment dynamics in the Johor River estuary.

Another recommendation is the investigation of the analysis over another or longer time span. As explained before, due to the climate in Singapore and surroundings, the tide can vary throughout the year. Therefore an analysis over another or a longer time span might give a more complete picture of the hydrodynamics in the Johor River estuary.

8. References

- Dyer, K. R., “Estuarine sediment transport and deposition”, Chapter 6 of Sediment transport and depositional processes, Blackwell Scientific Publications, Oxford (1994)
- Hasan, G. M. J., H. F. Cheong and D. S. van Maren, “Preliminary study on response of suspended sediment concentration to tidal dynamics of a large estuary”, 19th KKNN Sympo (2010)
- Hasan, G. M. J., D. S. van Maren, and H. F. Cheong, “Improvement in hydrodynamic modeling by grid alignment and refinement of an estuary in a mixed tidal regime”, Proceedings of the 15th Physics of Estuaries and Coastal Seas (PECS) Conference (2010)
- Hoitink, A. J. F., P. Hoekstra and D. S. van Maren, “Flow asymmetry associated with astronomical tides: Implications for the residual transport of sediment”, J. Geophys. Res., 108(C10), 3315, doi:10.1029/2002JC001539 (2003)
- Li, M., L. Zhong, and W. C. Boicourt, “Simulations of Chesapeake Bay estuary: Sensitivity to turbulence mixing parameterizations and comparison with observations”, J. Geophys. Res., 110, C12004, doi:10.1029/2004JC002585 (2005)
- Maren, D. S. van, P. Hoekstra and A. J. F. Hoitink, “Tidal asymmetry in the diurnal regime: bed-load transport and morphologic changes around the Red River” (2004)
- Winterwerp, J. C. “The transport of fine sediment in the Wadden Sea, setup of the study” (2010)
- Winterwerp, J. C. “Flow induced erosion of cohesive beds; a literature study”, Rijkswaterstaat-Delft Hydraulics Report No 25 (1989)
- Zijl, F and H. W. J. Kernkamp, “Further Hydraulic model Studies for Pulau Ubin and Pulau Tekong Reclamation Scheme”, Delft Hydraulics Report Z3437 for Housing and Development Board (HDB) (2004)