Morphodynamics Suriname River

Study of mud transport and impact due to lowering the fairway channel

M. Loose
September 2008
Contact information

Student:
Ing. Merijn Loose
Smitsteeg 6A
2611 BH Delft
tel.: 0615008963
c-mail: loose@telfort.nl
student number: 1271199

Graduation Committee:
Prof. dr. ir. H.J. De Vriend
Graduate Professor Hydraulics TU Delft
Dr. Ir. J.C. Winterwerp
Ass. Professor Env. Fluid Mechanics TU Delft
Dr. D.S. Van Maren
Postdoc River Eng.,Hydraulics TU Delft
Ir. J.K. De Groot
Hydronamic BV
Ir. A. Quist
Engineering consultancy Lievense BV
Ir. G. van Banning
Alkyon BV, hydraulic consultancy and research

Delft University of Technology
Faculty of Civil Engineering and Geosciences
Section Hydraulic Engineering
Stevinweg 1
2628 CN Delft

Hydronamic BV
P.O. box 43, 3350 AA Papendrecht,
Netherlands

Raadgevend ingenieursbureau Lievense BV
P.O. box 3199, 4800 DD Breda,
Netherlands

Alkyon BV, hydraulic consultancy and research
P.O. box 248, 8300 AE Emmeloord,
Netherlands

Cover picture by J.C. Knoope
Preface

This thesis report is the finishing part of my master study hydraulic engineering at Delft University of Technology.

Ir. Jorrit de Groot, an employee from Boskalis Westminster NV, asked me to study the morphologic development of the Suriname River fairway. The following report is the result of this question and his supervision.

Readers who are interested in the hydrodynamic and morphodynamic processes which are decisive for the morphologic development can find this in chapter 5.

I want to thank all the people that cooperated in this project or supported me during the graduation process.

First of all my graduation committee; De Vriend, Winterwerp, Van Maren, De Groot, Quist and Van Banning.

I want specially thank Winterwerp for the fact that his door always stood wide open and the way he helped me with the theoretical approach.

Many thanks, to Royal Boskalis Westminster NV for providing me a graduation project, the workplace to execute it and providing me a visit to Suriname, to Alkyon BV for using their computer model and for the accommodation to stay overnight at Zwolle and to the Maritime Authority Suriname (MAS) for enabling me to use the measurement data.

Also thanks to the Delft3D specialists Gijs van Banning for his supervision and Bart Grasmeijer, Luitze Perk and Jaap de Groot from Alkyon BV for helping me out with the 3D modelling part of the study.

Thanks to all other graduation student colleagues for having fun at the office days and for supporting each other and for having eye-opening discussions. From Boskalis: Thomas, Stephan and Gerben and from Alkyon: Claire and Maarten. Special thanks for Gerben de Jong as my roommate at the Boskalis office for supporting me and as pleasant company during the graduation period.

Merijn Loose
August 2008
Summary

The fairway through the Suriname River is the most important transport route for import and export of cargo as well as for inland transportation of goods. The artificial fairway channel provides entrance to the port of Paramaribo and Paranam. These two ports are significantly important for the Suriname economy. Especially the export of aluminium oxide is the backbone of the economy of Suriname. Therefore the fairway channel must keep its present navigability to ensure consistent national revenue.

The motivation for this thesis project is the intention of lowering the fairway channel to increase the navigable depth. Several stakeholders such as BHP Billiton and Suralco are recently considering investing in lowering of the fairway channel to create a cost-effective fairway for their bauxite and alumina transport activities.

To obtain the navigable depth, the fairway has to be dredged at the shallow locations in the fairway channel. It is to be expected that the fairway will accrete sediment where the capital dredging has removed the sediment, back to its initial level. After the capital-dredging phase, maintenance dredging is probably required to keep the fairway at the required navigable depth.

For the investing companies and the contracting companies it is important to know in advance what the amount of sedimentation rate will be in the lowered fairway after capital dredging. The sedimentation rate of the lowered fairway channel will define the feasibility of the whole dredging project on the long term.

This study focussed on the mud dynamics in the Suriname River and the effect of lowering the fairway to increase the navigability. The two main questions to be answered are:

1. Which hydrodynamic and morphodynamic processes created the present morphologic situation in the lower reach (km 42-87) of the Suriname?
2. Will the above mentioned hydrodynamic and morphodynamic processes change after lowering the fairway and how do these changes affect the sediment transport in the river estuary and the morphological development of the lowered fairway channel?

This study will focus only on a particular section of the Suriname River Estuary, namely between Nieuw Amsterdam (km 42) and Paranam (km 87).

The downstream section km 0-42 is excluded, because variations in the direction of currents and wave heights at open sea are significant causing trouble to distinguish the individual processes which impact the sediment transport. The measurement data show a large scatter, making it unable to recognize the individual hydrodynamic and morphodynamic processes.
The fairway as a transport route is only needed until Paranam (km 87) and therefore the upstream part of the river, above Paranam, is excluded as well.

To achieve the goal of this thesis project, the available measurement data is used to describe the physical elements of the Suriname River Estuary, which are considered important for the sediment transport. It appeared that the mud concentrations and mud transport in the waters of the Suriname River Estuary strongly influence the morphologic development. Mud is picked up by the flowing water and transported (mainly) in suspension in the direction of the current. To classify which processes influence the mud concentrations and which processes dominate the mud transport in a numerically way, first measurement data of the tidal movements, velocity measurements and salt concentrations are analysed. Analyzing the data resulted in recognizing several hydrodynamic processes, which are potentially dominant for the mud transport in the Suriname River Estuary. However, the measurement data alone, are not sufficient to quantify the hydrodynamic and morphodynamic processes in the study area and certainly not sufficient to estimate the morphological development of the river bed. The computer tool Delft3D is used for further analysis of the hydrodynamic and morphodynamic processes, plus the estimation of the morphological development of the present situation and the effect of lowering the fairway.

The tidal elevation analysis revealed the tidal wave in the Suriname River Estuary to be asymmetric (short duration of flood and higher flood currents). The tidal wave starts as a symmetric wave at the estuary mouth (km 32) and increases its asymmetry until Domburg (km 70) according to the measurements data. Based on the tidal asymmetry, it is to be expected that the tidal movement causes a high instantaneous mud transport landward during the relatively short flood period and a low instantaneous mud transport seaward during the relatively longer ebb periods.

Whether this also accounts for an asymmetric shape of the current velocity is unknown, since no long term current velocity data is present. Therefore, it is impossible to define the impact of the tidal asymmetry on the sediment transport in longitudinal direction of the Suriname River Estuary based on measurement data.

A strong longitudinal density gradient between the salty seawater and the fresh river water can result in a residual flow at the bed in landward direction and a residual flow at the surface. This residual flow of two separated directions is called gravitational circulation. If the average sediment concentration at the bed layer is higher than the sediment
concentration at the surface layer (thus the stratification of the water is strong), the residual flow transports more sediment landward at the bed than seaward at the surface. The stratification of the estuary causes salt gradients between the surface layer and the bed layer, especially between the Ocean (km 20) and Paramaribo (km 54). This results in fluid density differences between surface and bed. Therefore, the lower dense water remains on top of the higher dense water at the bed due to buoyancy. The stratification appears to be amplified by the high sediment concentrations in the water column according to the salinity and velocity measurement analysis.

According to the Delft3D model results it is clear that the effect of the sediment and salt density on the fluid mixture in the Suriname River Estuary is important for the cumulative sediment transport. The four most important processes that influence the cumulative sediment transport are:

- Tidal asymmetry (between km 32-83)
- Gravitational circulation (between km 32-54)
- Damped turbulence (entire area)
- Residual river discharge (entire area)

The simulation of the present situation includes the four most important sediment transport processes. The damped turbulence due to the density gradients within the fluid mixture causes extra stratification of the sediment concentrations. The longitudinal density gradient of the salt gradient causes deformation of the velocity depth profile. The combination of the stratified sediment concentrations and the deformed velocity depth profile results a tendency to import sediment into the study area. The tidal asymmetry also tends to import sediment during spring tides and tends to export sediment during neap tides, but only if enough sediments are present on the bed to be eroded by the current velocities. The residual river discharge tends to export the sediment seaward due to advection of the fluid mixture.

These processes are included in the simulation within the model, resulting in a balance in sediment transport during one spring-neap cycle of 15 days, but it was not succeeded to separate the impact of each individual process on the sediment transport.

Extreme conditions such as extraordinary high tidal amplitude (extreme spring condition), very low river discharges or extreme supply of muddy sediments from the Ocean side could be a reason for an occasional import of sediment in the study area.

Lowering the fairway channel hardly influences the balance of the sediment transport processes. The change of the cross section is too small to impact the sediment transport balance on the long term. The width of the fairway channel compared to the width of the entire river is negligible small.
Although the model shows a long term balance of sediment transport in the longitudinal direction of the system, the erosion and sedimentation pattern does not show a balance within the cross section of the study area between km 43 and 83.

The model shows erosion in the deeper sections, such as the artificial fairway, due to strong currents and thus high shear stresses at the bed. On the other hand, the shallow sections (at the river banks) in the same cross section tend to accumulate sediments due to low currents and thus low shear stresses at the bed.

According the calculated currents and shear stresses this erosion and sedimentation pattern seems plausible, and one would expect further erosion of the deeper parts and narrowing of the river. In reality there is a different erosion and sedimentation pattern, namely a river channel which is quite evenly shallow in the whole cross section and a very wide cross section compared to the depth.

The bed level measurements of the last decades do not show any tendency of erosion of the deeper sections and accumulations of the shallow section. Something is opposing the accumulation of the shallow section and erosion of the deeper section.

The consolidation of the settled sediments was not able to be simulated with the Delft3D-FLOW module. The settling and consolidation strongly influences the erodibility of the sediment bed. Implementing the consolidation process should significantly improve the erosion and sedimentation pattern of the muddy river estuary simulation.

Implementing the consolidation process should also include the presence of fluid mud at the bed of the river estuary. Possible density cross current of fluid mud could be an explanation for the dispersion of mud over the entire cross section in stead of deposits at the shallow sections at the river banks.

Past studies have proven the presence of fluid mud but did not prove the mobility of the fluid mud as a density current. One of the characteristics of fluid mud is that it gains strength and is therefore less erodible than loose sediments at the bed, which could explain why the mud is liable to the higher bed shear stresses when it flows to the deeper section within the cross section.

If an estimation or calculation of the sediment transport and morphology of the river estuary is needed again in the future, it would be very helpful if the quantity and quality of the measurement data is better than the present available measurement data.

For future morphology studies or for validation of the computer model it should also be investigated how the flocculation process behaves in the Suriname River and what fall velocity belongs to the sediment flocs and what composition of sediments those flocs contain.
# Table of contents

Contact information............................................................................................................. II

Preface ................................................................................................................................. III

Summary............................................................................................................................... IV

Table of contents................................................................................................................. VIII

List of Figures ...................................................................................................................... X

List of Tables ....................................................................................................................... XII

List of Appendices .............................................................................................................. XII

1 Introduction.....................................................................................................................1
   1.1 Problem analysis ........................................................................................................2
   1.2 Thesis objectives ......................................................................................................3
   1.3 Set up of the report ..................................................................................................4

2 Suriname River Estuary; a physical description ..............................................................6
   2.1 Background ..............................................................................................................6
   2.1.1 Suriname river estuary ......................................................................................6
   2.1.2 Suriname mud ....................................................................................................7
   2.1.3 Suriname coast ...................................................................................................8
   2.2 Topography and bathymetry ..................................................................................12
   2.3 Tide and water levels ............................................................................................16
   2.4 Currents ................................................................................................................18
   2.5 Wind and waves ....................................................................................................21
   2.6 Salinity ...................................................................................................................21
   2.7 Sediment ...............................................................................................................22
   2.7.1 Sediment composition ......................................................................................22
   2.7.2 Sediment displacement ....................................................................................26
   2.8 Navigation .............................................................................................................28
   2.9 Measurement data ................................................................................................29

3 Suriname River Estuary system analysis ......................................................................32
   3.1 Classification based on tidal characteristics .........................................................32
   3.1.1 Qualification of estuary classification ...............................................................33
   3.1.2 Quantification of estuary classification ............................................................35
   3.1.3 Conclusions tidal analysis ................................................................................37
   3.2 Classification on salinity and velocity distribution in depth profiles .....................38
   3.2.1 Partially mixed estuary .....................................................................................39
   3.2.2 Laterally well-mixed estuary ............................................................................40
   3.2.3 Qualifying classification .................................................................................41
   3.2.4 Quantifying classification ...............................................................................42
   3.2.5 Conclusions salinity and velocity structure .....................................................46
4 Suriname River Estuary Delft3D model .................................................................54
  4.1 The reason and the way of using the Delft3D model ........................................54
  4.2 Alkyon model ....................................................................................................56
    4.2.1 2-Dimensional model ...............................................................................56
    4.2.2 3-Dimensional model ...............................................................................56
  4.3 Approach of adjusting the existing model ........................................................57
  4.4 General layout of model ....................................................................................59
    4.4.1 Software ......................................................................................................60
    4.4.2 Processes ......................................................................................................60
    4.4.3 Grid and bathymetry ...................................................................................60
    4.4.4 Horizontal grid ............................................................................................60
    4.4.5 Vertical grid ..................................................................................................60
    4.4.6 Timeframe, boundary and initial conditions .............................................61
    4.4.7 Physical parameters .....................................................................................63
    4.4.8 Numerical parameters ................................................................................65
  4.5 Simulating the physical processes in Delft3D ...................................................65

5 Analyzing model results .........................................................................................70
  5.1 Compare model results with system analysis ....................................................70
    5.1.1 Tidal characteristics ....................................................................................70
    5.1.2 Velocity and salinity structure of the vertical water column .......................73
  5.2 Sediment transport capacity analysis .................................................................77
  5.3 Morphodynamic modeling of the study area .......................................................81
    5.3.1 Effect of critical bed shear stress on the cumulative transport ....................81
    5.3.2 Effect of sediment density in the fluid mixture on the cumulative transport .84
    5.3.3 Effect of salinity in the fluid mixture on the cumulative transport .............85
    5.3.4 Effect of Suriname River discharge on the cumulative transport ................86
    5.3.5 Effect of sediment supply from Ocean boundary on the cumulative transport .87
    5.3.6 Effect of initial conditions on the cumulative transport ..............................87
    5.3.7 The simulated cumulative transport compared to the transport capacity ....92
  5.4 Erosion and deposition of the present situation ................................................95
  5.5 Erosion and deposition due to lowering of the fairway ....................................97

6 Conclusions and recommendations .......................................................................101
  6.1 Conclusions .......................................................................................................101
  6.2 Recommendations .............................................................................................104

References .................................................................................................................106

Appendices ...............................................................................................................108
List of Figures

Figure 1.1: Location of Suriname in South-America 1
Figure 1.2: The course of the fairway through the Suriname River 1
Figure 2.1: Mud banks along the Guyana Coast 9
Figure 2.3: Sketch map of the coastal behaviour along Guyana Coast 11
Figure 2.4: Suriname River Estuary topography between boundaries 12
Figure 2.5: Width and depth of the lower reach of the Suriname River Estuary 13
Figure 2.8: Water depth of a wide and shallow cross section in the Suriname River near Jagdust 14
Figure 2.9: Water depth of a narrow and deep cross section in the Suriname River near Leonsberg 14
Figure 2.10: Cross section Suriname River near Leonsberg and Jagdust during HHW 15
Figure 2.11: Relations between the tidal ranges in the Suriname River 16
Figure 2.12a: Water discharge at Leonsberg in Suriname River at neap tide, May 12, 1966 17
Figure 2.12b: Water discharge at Leonsberg in Suriname River at spring tide, May 21, 1966 17
Figure 2.13: Sketch map of equatorial currents at the northern part of South America. 18
Figure 2.14a: Suriname River annual discharge 1966-1985 20
Figure 2.14b: Suriname River instantaneous discharge for the year 1983 20
Figure 2.16: Minimum and maximum salt concentrations along channel axis. 21
Figure 2.17: Folk’s classification system 23
Figure 2.18: Sediment composition of Suriname River water samples in longitudinal direction 25
Figure 2.19: Development of the density in the layer of fluid mud in the Suriname Fairway 25
Figure 2.20: Bed samples sediment composition in longitudinal direction 26
Figure 2.21: Average freight per ship (in- and export) navigating through the Suriname Estuary 28
Figure 3.1: Current phase and elevation phase of progressive wave and standing wave 33
Figure 3.2: A plot of the measurements at Leonsberg 23 July 1982 34
Figure 3.3: Tidal cycles in the Suriname River Estuary at the 4th of June and 31st of January 2004 35
Figure 3.4: Superposition of tidal constituents M2 and M4 for the Domburg station (km 70) 36
Figure 3.5: Salinity and velocity distribution in a partially mixed estuary 39
Figure 3.6: Salinity and velocity distribution in a well-mixed estuary 40
Figure 3.7: Salinity depth profiles of measurements at Leonsberg 1982 and tidally averaged salinity 41
Figure 3.8: Salinity depth profiles of measurements at BEM 2007 and tidally averaged salinity 41
Figure 3.9: Velocity depth profiles of measurements at Leonsberg 42
Figure 3.10: Stratification circulation diagram of Hanssen and Rattray (1966) 46
Figure 3.11: Bifurcation Suriname River and Commewijne River 47
Figure 3.12: Two measurement campaigns close to the bifurcation to estimate velocity phase 47
Figure 3.13: Schematisation of sediment transport due to tidal asymmetry 50
Figure 3.14: Schematisation of velocity depth profile due to residual river discharge and longitudinal density current 51
Figure 4.3: Tidal elevation according measurement data at MAS Paramaribo 2004 62
Figure 4.5: Computed water levels at Leonsberg (km 43) and Domburg (km 70) 71
Figure 5.2: Computed tidally averaged current velocity at Leonsberg and Domburg 71
Figure 5.3: Computed instantaneous cross section discharge at Leonsberg (km 43) during spring 72
Figure 5.4a: Computed (T524b) tidally averaged (over 15 days) velocity profile including salinity 74
Figure 5.4b: Computed (T527) tidally averaged (over 15 days) velocity profile without salinity 74
Figure 5.5a: Computed (T524b) tidally averaged (over 15 days) salinity profile including sediment density 75
Figure 5.5b: Computed (T526) tidally averaged (over 15 days) salinity profile without effect sediment density 75
Figure 5.6a: Computed (T525c) tidally averaged (15 days) discharge depth profile at Leonsberg (km 43) 78
Figure 5.6b: Computed (T525c) tidally averaged (15 days) sediment concentration depth profile 78
Figure 5.7: Top view of the study area, including indication of the cross sections used to analyse the sediment transport capacity 79
Figure 5.8: Theoretical estimation of cumulative sediment transport capacity at Leonsberg (km 43) 80
Figure 5.9: Theoretical estimation of cumulative sediment transport capacity at Leonsberg (km 43) 80
Figure 5.10a: Comparison between measured and computed (T524b) mean sediment concentration in longitudinal direction 81
Figure 5.11: Tidally averaged (15 days) computed bed shear stress [N/m2] 82
Figure 5.10b: Comparison between measured and computed (T533) mean sediment concentration in longitudinal direction 83
Figure 5.12 Cumulative sediment transport at Leonsberg (km 43); effect critical bed shear stress
84
Figure 5.13 Cumulative sediment transport at Leonsberg (km 43); difference in- and
85
excluding sediment density effect
Figure 5.14 Cumulative sediment transport at Leonsberg (km 43); difference in- and
86
excluding salinity effect
Figure 5.15 Cumulative sediment transport at Leonsberg (km 43); River discharge of
86
300 and 500 m3/s
Figure 5.16a and b Initial sediment layer thickness and the computed sediment layer
88
thickness after 15 days model computation (run T543b)
Figure 5.17a and b Initial sediment layer thickness and the computed sediment layer
89
thickness after 15 days model computation (run T525c)
Figure 5.18 Cumulative sediment transport at Leonsberg (km 43); effect initial layer thickness
90
Figure 5.19 Cumulative sediment transport at Leonsberg (km 43); effect wave-action at sea
91
Figure 5.20 Computed depth averaged sediment concentration at Leonsberg (km 43)
92
Figure 5.21 Theoretical depth averaged sediment concentration at Leonsberg (km 43)
93
Figure 5.22 Theoretical cumulative sediment transport capacity at Leonsberg (km 43)
93
Figure 5.23 Computed cumulative sediment transport at Leonsberg (km 43)
93
Figure 5.24 Sedimentation (positive) and erosion (negative) pattern of present situation
95
after 15 days computation
Figure 5.25 Difference in bathymetry between present and future situation (layout 1)
97
Figure 5.26 Computed Sedimentation and erosion of the bed of the fairway
98
channel (km 43-km83) after 15 days (T542); present situation
Figure 5.27 Computed Sedimentation and erosion of the bed of the fairway
98
channel (km 43-km83) after 15 days (T543); future situation (layout 1)
Figure 5.28 Computed sedimentation of the bed of the fairway
98
channel (km 43-km83) after 1 year (T543); future situation (layout 1)
Figure 5.29 Sedimentation (positive) and erosion (negative) pattern of future
99
situation after 15 days computation (run T543)
Figure 5.30 Sedimentation (positive) and erosion (negative) difference between
100
present situation and future situation

In appendices:
Figure 1: Schematisation of migration mud banks along Guyana Coast
Figure 2: Bathymetry of Suriname River Estuary after Nedeco 1968
Figure 3: Bathymetry of Suriname River Estuary after MAS 2002-2004
Figure 4: Wind roses from an offshore location near the Suriname Coast
Figure 5a, b, c and d: top view Delft3D model grid cells
Figure 6a, b, c and d: velocity differences between present situation and future
situation (lowered fairway), after Alkoyon, 2007
Figure 7a: Computed bed shear stress during current slack just after flood current
Figure 7b: Computed bed shear stress during slack just after low water
Figure 7c: Computed bed shear stress during slack just after high water
Figure A1: Tidal dominance Leonsberg km 43
Figure A2: Tidal dominance Jaglustbank km 47
Figure A3: Tidal dominance BEM Paramaribo km 58
Figure A4: Tidal dominance Domburg km 70
Figure B1: Velocity/salinity profile Leonsberg km 43
Figure B2: Velocity/salinity profile BEM Paramaribo km 58
Figure C1: Sediment transport capacity Leonsberg km 43
Figure C2: Sediment transport capacity MAS Paramaribo km 51
Figure C3: Sediment transport capacity BEM Paramaribo km 58
Figure C4: Sediment transport capacity Dijkveld bar km 62
Figure C5: Sediment transport capacity Domburg km 70
Figure D1: Salinity and sediment concentration along fairway axis km 0-90
Figure F1: Cumulative sediment transport all runs Leonsberg km 43
Figure F2: Cumulative sediment transport all runs MAS Paramaribo km 51
Figure F3: Cumulative sediment transport all runs BEM Paramaribo km 58
Figure F4: Cumulative sediment transport all runs Dijkveld bar km 62
Figure F5: Cumulative sediment transport all runs Domburg km 70
Figure H1: Sedimentation along axis fairway channel km 43-82 run T542 present situation
Figure H2: Sedimentation along axis fairway channel km 43-82 run T543 future situation
List of Tables

Table 2.1: Modified Wentworth sediment classification 22
Table 2.2: Sediment concentrations [kg/m³] around slack water at several cross sections 24
Table 2.3: Relationship between CD and NSP 30
Table 3.2: Tidal analysis results for the M₃ and M₄ components at the four observation stations 37
Table 3.3: Stratification-circulation parameters according Hansen and Rattray (1966) 45
Table 4.1: Distribution of grid layer thickness in vertical direction 61

In appendices:
Table 1: Tidal constituents of four measurement stations according to Delft3D-TIDE
Table 2: Delft3D simulation runs; parameter settings

List of Appendices

Appendix A; List of measurement data

Appendix B; plots of velocity and salinity measurements
   B.1 plots of current velocity measurements
   B.2 plots of tidally averaged current velocities at measurement locations
   B.3 plots of salinity distribution at measurement locations

Appendix C; Delft3D-FLOW manual content for sediment simulation
   C.1 Simulating transport of salt and sediment
   C.2 Fall velocity and settling
   C.3 Cohesive sediment erosion and deposition
   C.4 Density effect on fluid
   C.5 Transport boundary condition
1 Introduction

Suriname is situated at the northeast coast of South-America (Figure 1.1), north of the Amazon River delta. The neighbouring countries are (British) Guyana, French Guiana and Brazil. It has roughly 450,000 inhabitants of which at least half of them live in the capital Paramaribo.

The fairway (Figure 1.2) through the Suriname River is the most important transport route for import and export of cargo as well as for inland transportation of goods. The artificial fairway channel provides entrance to the port of Paramaribo (km 55) and Paranam (km 87). The port of Paramaribo possesses the largest general and container terminal of Suriname; while from the port of Paranam the main export (Alumina or aluminium oxide) of Suriname takes place. These two ports are significantly important for the Suriname economy. Especially the export of aluminium oxide is the backbone of the economy of Suriname. Therefore the fairway channel must keep its present navigability to ensure consistent national revenue.

The motivation for this thesis project is the intention of lowering the fairway channel to increase the navigable depth. Several stakeholders such as BHP Billiton and Suralco are recently considering investing in lowering of the fairway channel to create a cost-effective fairway for their bauxite and alumina transport activities.
1.1 Problem analysis

The current transport situation through the fairway channel is cost inefficient, and uncompetitive. To transport cargo over the Suriname River, the Alumina industry is using various types of ships, with sizes ranging from 5,000 till 40,000 Dead Weight Tons (DWT) (hydronamic, 2004). Especially the larger ships are loaded only for a limited part, and are topped up at other locations (i.e. Trinidad near Chaguaramas) before they sail to their destination.

By increasing the navigable depth of the fairway to Paranam and Paramaribo, the load factor of the ships can be increased. This will lead to lower transport costs, and will make the local industry more competitive in the international markets. Lower transport costs can also draw bauxite transports from other regions (e.g. Corantyn River) to produce alumina in the factory at Paramam.

Economic and technical analysis reveals that a minimum navigable depth of 6 m below CD (Chart Datum) is cost-efficient. Currently at parts of the fairway, the minimum nautical depth is less than 4 m below CD. At high tide, a navigable depth of 6 m is obtained.

Nowadays several parties, such as BHP Billiton and Suralco, are considering investing in deepening of the fairway. The last forty years, several parties have been discussing to dredge the Suriname River fairway to create a cost-effective fairway. However, previously no agreement was accomplished to invest in such a project, between the concerning parties.

Recent morphodynamic studies and the approval of an Environmental Impact Assessment report indicate that the lowering of the fairway channel will start within the year 2008.

To obtain the navigable depth the fairway has to be dredged at the shallow locations in the fairway channel. By dredging the fairway, the morphological system in the river will probably be affected. It is to be expected that the fairway will accrete sediment where the capital dredging has removed the sediment, back to its initial level. After the capital-dredging phase, maintenance dredging is probably required to keep the fairway at the required navigable depth.

To assess the maintenance dredging requirements, knowledge about the hydro- and morphodynamic system is required, before estimations can be made about the sediment transport rate (m$^3$/year) of the fairway and the adjacent river channel.

The amount of capital and maintenance dredging is defining the success of the financial investment in such a dredging project. The capital dredging is the amount of sediment to be dredged between the bed level of the present situation and the bed level of the future situation. It is therefore easy to estimate the volume of sediment to be dredged.
The amount of maintenance dredging is less straightforward. Hydrodynamic and morphodynamic processes influence the sediment transport in the complex and dynamic river estuary system.

For the investing companies it is important to know in advance what the amount of sedimentation rate will be in the lowered fairway after capital dredging. The sedimentation rate of the lowered fairway channel will define the feasibility of the whole dredging project. For the dredging companies it is also important to know the sedimentation rate because they need to know what equipment is needed for maintenance dredging and to make a competitive offer to the client.

1.2 Thesis objectives

The goal of this thesis study is to qualify and quantify the morphologic development of muddy bed in the Suriname River Estuary of the present situation whereby a prognosis can be made for the required maintenance dredging to keep the fairway on the new navigable depth.

The hydrodynamic and morphodynamic processes are a part of a very complex and dynamic system in the Suriname River Estuary. The challenge for this master thesis is to understand, to qualify and quantify the physical processes that are accountable for the current morphology in the Suriname River Estuary.

This study will focus on three main hydrodynamic processes in the estuary that dominate the sediment transport:

- the residual river discharge;
- the tidal exchange and tidal asymmetry;
- the estuarine gravitational circulation flows.

These processes will be analysed individually in order to quantify the share of sediment transport for each process along the alignment of the Suriname River estuary.

This thesis project will answer the following questions:

Which hydrodynamic and morphodynamic processes created the present morphologic situation in the lower reach (km 42-87) of the Suriname River and what is the present quantity of sediment transport in time and space of this lower reach in the Suriname River?

Will the above mentioned hydrodynamic and morphodynamic processes change after lowering the fairway and how do these changes affect the sediment transport in the river estuary and the morphological development of the lowered fairway channel?
Based on literature research and measurement data, the hydrodynamic and morphodynamic processes which are decisive for the morphologic system will be defined.

The Delft3D computer tool is used to simulate the hydrodynamic and morphodynamic processes and thereby the computer tool is used to estimate the effect of these processes on the morphologic development of the present situation and the future situation after lowering the fairway channel.

The quantification of the sediment transport rate for this study will focus only on a particular section of the Suriname River Estuary, namely between Nieuw Amsterdam (km 42) and Paranaam (km 87).

The downstream section km 0-42 is excluded, although the fairway channel in this section also needs to be lowered to increase the navigable depth. The downstream section includes the outer part of the river mouth including the bifurcation with the Commewijne River. Variations in the direction of currents and wave heights are significant causing trouble to distinguish the individual processes which impact the sediment transport. The measurement data show a large scatter, making it unable to recognize the individual hydrodynamic and morphodynamic processes.

The fairway as a transport route is only needed until Paranaam (km 87) and therefore the upstream part of the river, above Paranaam, is excluded as well.

1.3 Set up of the report

This section will describe the set up of this report and can be considered as a reading guide.

The report is divided in 5 chapters. Starting with a full physical description (chapter 2) from literature and measurement data of the whole Suriname River Estuary including important elements such as;

- mud (sediment) characteristics
- topography and bathymetry
- tidal characteristics
- salt intrusion

The following chapter (chapter 3) will describe the analysis of the water level elevation measurement data (section 3.1) and the velocity and salinity measurement data (section 3.2) of the Suriname River Estuary. With the results of the analysis an attempt is made to quantify the sediment transport and morphologic development (section 3.3) due to tidal asymmetry and due to gravitational circulation.
Since the measurement data analysis did not develop in a successful quantification of the morphologic development, Delft3D-FLOW is used to simulate the hydrodynamic and morphodynamic processes in the Suriname River Estuary.

Chapter 4 discusses the recently made Delft3D model from Alkyon (section 4.2) and the approach of adjusting this existing model for this thesis project (section 4.3). The general layout of the model is summarized in section 4.4 followed with a discussion about the simulation of the hydrodynamic and morphodynamic processes within the Delft3D computations.

Chapter 5 is the part of this report that will give answer to the questions from the thesis objectives using the Delft3D model results. First the measurement data analysis from chapter 3 is compared to the Delft3D model results (section 5.1). The following section (section 5.2) will discuss the transport capacity of the study area and will estimate the interrelation between the tidal asymmetry, gravitational circulation and the residual river discharge. Section 5.3 discusses the sensitivity of the model results on several model parameters. The final two sections will discuss the present morphologic development and the future morphologic development according to the model results.

Finally the report ends with the overall conclusions and recommendations of the thesis.

All Figures and Tables are numbered according to the chapter numbers. For example: Chapter 2 starts with Figure 2.1, 2.2, etcetera. Chapter 3 continues with 3.1, 3.2, etcetera. Some Figures have been added between the text of the report and some of them have been added at the end of the report just in front of the appendixes. The appendixes are added as the end part of the report.
2 Suriname River Estuary; a physical description

This chapter describes the physical elements of the Suriname River Estuary, which are considered important for the sediment transport and the following system analysis.

The physical description includes a literature background, shows the configuration of the river estuary, the elevation of the water between the river mouth and the Afobakka dam, the waves caused by swell and wind, the salt content of the water, the configuration of the fairway channel, the intensity of navigation and the characteristics of the sediments.

Other elements such as vegetation, ecology, water quality, inhabitants, etc., have been left out of account, for the simple fact that these elements are assumed not to affect the hydro- and morphodynamic system.

The physical description is divided in 8 parts, which will be discussed in the next corresponding sections, namely background, topography and bathymetry, tide and water levels, currents, wind and waves, salinity, sediment and navigation. The last paragraph describes which available measurement data will be used for further analysis.

2.1 Background

This background summarizes the content of a number of studies that have been executed in and around the Suriname River estuary. Because this thesis will focus on the sediment (mud) transport in the Suriname River estuary it is beneficial to know which studies already have been executed and what conclusions have been made from these former studies. The section is divided in three parts, namely the Suriname River Estuary, the characteristics of the Suriname mud in detail and the Suriname coast developments.

2.1.1 Suriname river estuary

The coast of British Guyana, Suriname and French Guiana is referred to as the Guyana coast. Many studies about the characteristics of the muddy Guyana coast and estuaries have been executed. One of them was carried out specifically about Suriname, including a detailed study of the Suriname River Estuary.

The government of Suriname invited the Netherlands Engineering Consultants “NEDECO”, to carry out a transportation study. This transportation study is divided in a transport study and a hydraulic investigation. The report is published in 1968, with the title: “Suriname transportation study, report on hydraulic investigation” (Nedeco, 1968).

The transport part studies the transportation system and future needs for transport services. The hydraulic investigation studies the hydraulic, geo-morphological and sedimentological characteristics of the Suriname seacoast and of the estuaries and lower reaches of the Suriname, Coppename, Corantijn and Nickerie River. The purpose of this investigation is obtaining information required for the transportation study, for
determining the navigability of the estuaries and lower reaches of the above rivers and for the feasibility of measures for improving navigability.

At the Suriname coast, the river mouth and in the Suriname River, field investigations were carried out, which were used to give a detailed description of the hydraulic and morphologic system. These descriptions of the hydraulic and morphologic system have been very helpful to achieve some of the objectives of this master thesis.

2.1.2 Suriname mud

Mud (definition in subsection 2.7.1) is present all over the world in various appearances and quantities. Many scientists have studied the characteristics of mud in the last decades. The behaviour of mud in general and the processes that take place in the water will not be described in detail.

In the years before 1983 a study of the mud specifically in the Suriname Estuary has been carried out. Ir. T.J. Heuvel graduated at Delft University of Technology in 1983 with his master thesis report: “Study of the behaviour of mud in and around the estuary of the Suriname River, in relation to the navigability of the fairway from the sea to Paramaribo”. The measurements executed for his thesis and the measurement data have been recorded in a project report. Bed densities, salinity concentrations and water velocities have been measured on several locations during particular periods. Data of navigation in the preceding years has been gathered and reported. This project report also contains data from bed heights measured between the years 1960 until 1983 on several locations.

Conclusions of Heuvel relevant to this project: (Heuvel, 1983)

- Between the years 1955 and 1980, the Vissersbank (a tidal flat at the coast on the east side of the estuary) has been increasing in size through accretion of mud originated from the coastal zone. It is expected that from the year 1982 Vissersbank will decrease its size.
- The density distribution in the top layer (0.5 meter) of the consolidated bed in “accretion areas”, like the fairway and the shoals, is different as the density distribution in “erosion areas”. Because a layer was present before erosion starts, an eroding bed is already consolidated in the past. Therefore, higher density gradients in “erosion areas” are present. When the bed is accreting, lower gradients are present because this layer is building up its height.
Below the top layer of 0.5 meter, the density distribution of the bed is fairly uniform.

- From observations of the density distribution it can be concluded that the fairway channel between buoy 4 (km 15) and Paramaribo (km 45) is mostly “filled” with a layer of fluid mud (1100-1200 kg/m³) and a static mud suspension in the water (1030-1100 kg/m³).
- An unknown part of the static suspension in the fairway channel is in motion under influence of the tidal current.
- The sea bed around the fairway channel at light ship buoy (km 4) has been eroding since 1967. In 1983, the surrounding depths have increased so much that the fairway channel has disappeared. It is expected that in the following years through erosion of the sea bed the fairway channel gradually will disappear. This means that the beginning of the channel will shift in the direction of the shore line.
- In the fairway channel between buoy 2a (km 10) and buoy R1 (km 25) the depth of the channel between the years 1970 en 1981 has been decreased with an average of 0.5 meter. The decrease of the fairway depth appears to be the cause of a decrease in navigation intensity of ore-ships in the same period.
- Agitation of the fairway channel because of navigation is being caused by the return current beneath a ship. Especially the ore-ships with a large draught, which are navigating to the sea through an opposing flood current, give significant additional turbulence, stirring up fine bottom sediments.

The Nedeco and Heuvel studies have both observed a small layer of 1-2 cm brown coloured soft mud on the bed above shoals. The occurrence of living organisms in the small layer (worms and crabs) could suggest that this top layer is been loosened through bioturbation and therefore liable to oxidation. This small layer could be the reason that erosion of the mud could occur below the value of the critical bed shear stress of the settled mud beneath this thin mud layer.

2.1.3 Suriname coast

The open, unprotected coast of north eastern South America, subject to moderate levels of wave energy from the outer continental shelf, is for several reasons an unusual environment with respect to process-response relationships. First, the nearly 1,600 km of shoreline between Amazon and Orinoco Rivers is an accreting muddy coast. Second, this coast is one of only a few in the world where present-day processes have formed mud into almost linear, (shore-attached) migrating banks (Figure...
2.1). Finally, accumulations of tenacious fluid mud front the coast periodically to form an inaccessible shoreline at low tide that serves as a buffer to wave attack and a storage facility for fine-grained sediments.

Fine suspended sediments from the Amazon River are transported along the coast in a zone 0–40 km wide as far as the mouth of the Orinoco River. As well as being transported in suspension (150 x 10^6 m^3/yr) this fine sediment is carried in mud banks (100 x 10^6 m^3/yr) which migrate from east to west (Nedeco, 1968).

The bed configuration in the coastal belt along the Guyana coast shows a regular pattern of giant shoals (mud banks) extending obliquely from the coast into the sea. The general shape and alignment of these mud banks are schematized in Figure 1 A and B. The average distance along the coast between two banks is about 45 kilometres, the variations being between 30 and 60 km (Nedeco, 1968). In some cases, a small bank of similar shape can be observed between two larger ones.

The mud content of the coastal waters is very high (hundreds to thousands mg/l). The suspended mud particles are in a flocculated state. When the mud concentration exceeds a threshold value, the flocs no longer settle solitarily but begin to agglomerate. A gel is formed and settles as a whole, while the water is expelled through the voids (Delft Hydraulics, 1962; Diephuis, 1966). This gel is referred to as fluid mud. An important property is that it damps wave motion. Fluid mud with densities between 1,100 and 1,250 kg/m^3 occasionally occur along the north western flanks of the mud banks when rapid sedimentation takes place (Nedeco, 1968).

The westward migration of the mud banks results from the deposition of fluid mud at the west side of the mud banks and the simultaneous erosion on the east side, where in the mean time the sediment lost most of its wave-attenuation property due to consolidation. East of the mud banks, the waves are therefore less attenuated and they may reach the shore and break. In this environment wave energy appears to be sufficiently high for the erosion of mud as well as for the erosion of sand and shell elastics (Wells, 1977; Wells and Coleman, 1978). The
obliqueness of the waves and the long shore current are probably the driving forces to transport the eroded mud to the west, where it can accrete at the west side of the bank. The erosion, depositions, waves and currents around the mud banks in general have been schematized in Figure 1 C, D and E.

The cause of migrating of the mud banks from east to west is still unclear for scientists. There are some theories, which can explain the process; however, there are no hard evidences that certify them.

Wells did research in this matter and he states that the accumulation of fluid mud at the nose of a mudflat causes attenuation of the incoming waves and changes their form from sinusoidal to solitary-like (Wells, 1977; Wells and Coleman, 1978). However, the waves also affect the fluid mud. Lhermite (Augustinus, 1980) demonstrated in laboratory tests that the orbital motion of the water waves, although reduced by the viscosity of the mud, continues into the pelite deposit. He also found that the residual movement in the fluidized mud followed the direction of wave propagation. This indicates that fluid mud may be transported in a fluidized state. Wells (1977) and Wells and Coleman (1978) consider radiation stress from solitary waves to be a dominant factor in the transport of fluid mud.

Wells and Coleman (1981) speak about transportations of mud. Interruptions in the long shore transport of mud may occur temporarily each time a mud bank migrates past a river mouth. Tidal currents sweep coastal muds into and out of local rivers with the flood-ebb cycle. However, severe siltation problems and high turbidities in the Suriname River entrance suggest that some muds derived from offshore remain in the rivers, especially during periods of mud banks passage.

Augustinus (1989): Five series of aerial photographs of coastlines have been compared with the aid of a geographical information system (the DELTA-MAP computer program). With this method, the net amount of coastal accretion and erosion per kilometre along the coastline was calculated over a period of 34 years. From a comparison of the series of aerial photographs, it appears that the mudflats along the Suriname coast have steadily grown in length between 1947 and 1981. Augustinus explains the differences in migration speed along the coast of Guyana, Suriname and French Guiana by the differences in orientation of the coast towards the main direction of wave propagation.

Eisma, Augustinus and Alexander (1991) have done research in recent change from erosion to deposition along the Suriname coast. They concluded that the measurements on series of air photographs taken between 1947 and 1984 demonstrate that before 1966 erosion prevailed along the Suriname coast, which turned to overall deposition after 1966. After comparison with data on wind direction and wind strength collected at Kourou (French Guiana) between 1963 and 1986, they claim that this change is related to a shift in the strength and direction of the trade winds during January until April. They also
concluded that mud deposition on the coast of the Guyana’s is related primarily to the strength and the direction of the trade winds and not to the intensity of supply from the Amazon River.

The coastline between two mud banks is liable to erosion. The same way as the mud banks migrate from east to west this erosion area also migrates from east to west between the two mud banks. In this erosion area, local accretion of sand occurs. Namely, small but long-stretched “dunes” of sand are deposited on the muddy shore. Price describes these depositions as ‘shallow based, perched sandy ridges, which rest on clay along a marshy or swampy, seaward facing tidal shore, with other beach ridges stranded in the marsh behind’ (Price, 1955). Nowadays these ridges are called cheniers. These cheniers generally consist of a medium-coarse grained fluviatile siliceous sand.

The Suriname Coast can be schematized as units presented in Figure 2.3. The smallest coastal unit consists of a mud bank and an adjacent erosive eastward part (Augustinus 2004).

This background describes the complexity and diversity of the Suriname River estuary. A fact is the presence of mud banks at the Suriname coastline and these mud banks shift across the Suriname River mouth as well. However, the next mud bank to reach the river mouth is to be expected in about 15 years minimum. The expected high mud concentrations and the presence of large quantities of fluid mud at the river mouth is therefore the next 15 years not a concern for the sediment transport rate in the Suriname River.

Figure 2.3 Sketch map of the coastal behaviour along the Guyana coast. after Augustinus 2004.

The flowing water including high mud concentrations is very important for the sediment transport of the Suriname River estuary.
22 Topography and bathymetry

Four large rivers flow into the Atlantic Ocean at the Suriname coast. The two larger ones, the Corantyn and the Marowijne, are located at the border of Guyana and French Guiana respectively. The smaller Coppenome and Suriname Rivers are situated between these border rivers. The last 6,000 years the coast of Suriname has extended seaward. A seaward accretion of about 40 km took place; meaning approximately 6.5 m per year (Nedeco, 1968). The accretion mainly consisted of Mara clay and Para clay.

The topography of the Suriname Estuary could be classified as a bar-built Estuary. Bar-built estuaries have a characteristic bar (Braamspunt km 31) across their mouths and are generally associated with depositional coasts, like the Suriname Coast.

A hydroelectric station is constructed in the Suriname River at Afobakka (km 194). The construction of the dam was completed in 1964, creating a reservoir lake (Brokopondo Lake) upstream of the dam. The Suriname River Estuary is bounded by this hydroelectric station (km 194) near Afobakka on one side and on the other side by the river mouth next to Braamspunt (km 31), where it debouches its water in the Ocean. Figure 2.4 visualizes the whole river estuary system between these two boundaries.

The Suriname River flows in northern direction, with large local meanders and sharp bends alternating with fairly long straight sections. Some creeks debouch into the Suriname River; however, these creeks are very small. The most important tributaries are the Para River (km 63), the Paulus Creek (km 64) and the Surnau Creek (km 75).

The Commewijne River also debouches into the Suriname River before the water reaches the Ocean. The confluence of the Commewijne and the Suriname Rivers lies at Nieuw Amsterdam (km 41).

The lower reach of the Suriname River Estuary, where the tidal influences are strong, shows a general widening in a seaward direction, although large variations in the width can be observed (Figure 2.5; thick blue line).
Where bends occur, the estuary is relatively narrow, while in the rather straight sections the estuary is comparatively wide.

In the same Figure 2.5, a longitudinal depth profile of the estuary is presented along an alignment, which follows the natural channel (the average level of the bed as the pink straight line). Downstream of Paranam the dotted green line is the alignment depth profile following the existing fairway.

As could be expected, there is a close relationship between the width and the depth. The wide sections, such as km 46-53 (Jaglust bank), km 58-65 (Dijkveld bank) and km 77-85, are comparatively shallow, while the places with considerable larger depth coincide with the narrow bends at Leonsberg (km 43) and Paramaribo (km 55).

![Figure 2.5 Width and Depth of the lower reach of the Suriname River Estuary after Nedeco 1968](image)

Between the years, 2002 and 2004 MAS surveyed the whole river estuary from the shoal area at the coast until Paranam (km87), presented in the colour chart in Figure 3. The depth contours are different compared to the Nedeco chart (Figure 2) from 1968.

Conclusions about the morphology changes based on these two charts between the year 1968 and 2004 have not been made, because Nedeco used another reference level (SLW) and it is unknown what criteria has been used to define the bed level.

The fairway channel has more or less the same depth and alignment. Because of fixed beacons in the fairway, the ships have always taken the same route and therefore created a fairway channel by eroding the sediment through return current and turbulence of the propeller activity.

The coastline near Braamspunt (km 31) has been extended westwards, indicating that the Bar at the river mouth has been increased between the years 1968 and 2004.

The depth of a narrow cross section at Leonsberg (km 43) and the depth of a wide cross section at Jaglust bank (km 47) have been surveyed at four different moments of time in the last 50 years. The first moment is the year 1958, before the construction of the Afobakka dam and the following years 1970, 1981 and 2004. Therefore, the depths can be compared to each other to see how the riverbed is changing its height during these years as is presented in Figure 2.8 and 2.9.
The bed level before the construction of the Afobakka dam, is compared to the following years substantial higher, except for the inside bend at Leonsberg. The bed level increase, until 50 years after construction of the dam, can be caused by the regulation of the river discharge. The peak river discharges during a wet season do no longer occur. The high peak discharges in downstream direction, formerly the bed shaping conditions, are no longer flushing the sediments out of the estuary into the sea as before the construction of the dam.

According to the depths of the years 1981 and 2002, it seems that the depth is no longer increasing its height due to the construction of the dam.
The depth of the Suriname River is relatively small compared to the width of the river and the width of the fairway channel is relatively small compared to the width of the river. In Figure 2.10, two cross sections during high water near Voorberg (Leonsberg km 43) and Jagtlust (km 47) are visualized. The water flowing through the River is like a thin layer of water flowing over a smooth bed.

The survey data of the different years that have been compared with each other has been measured with different instruments and different techniques. For this reason, it could be possible that the data reference from one year is not corresponding with another year. The instruments from 1956 might have a different accuracy as the instruments from 2004. Another point of attention is the fact that the survey measurements are widely spread, sometimes with a distance of more than 100 meters. Small deviations in the bed height are not visible in the graphs. Especially, considering the relative small width of the fairway, (width is approximately 80 m.) it is unwise to estimate solid conclusions from these data. The definition of the river bed level is assumed to be the same for all the measurements. Knowledge about these definitions is not conclusive. Normally the bed is defined as the level, where the sediment density reaches over 1250 kg/m³, corresponding with a defined acoustic frequency. The graphs can be used for defining rough trends and not for detailed riverbed morphology.

Figure 2.10 Cross section Suriname River near Leonsburg (km 43) and Jagtlust (km 47) during HHW; height and length have the same scale.
2.3 Tide and water levels

The information about the tide along the whole Guiana coast shows that along the Suriname Coast the tide has a semi-diurnal character. The average tidal range is about 1.8 m, with an average of 2.8 m for the range at spring tide and an average neap tide range of 1.0 m (Nedeco, 1968). Such a tidal range classifies the Suriname Estuary as a mesotidal estuary according to Davies (1964) after Dyer (1997).

The Suriname Estuary can be classified as a synchronous estuary, because friction and convergence have equal and opposite effects on the tide and therefore the tidal amplitude is quite constant along the estuary until the riverine section (km 120) is reached as is presented in Figure 2.11.

The shoaling and narrowing of the estuary slows the progress of the tidal wave, increasing its amplitude, but at the same time the friction attenuates the wave energy decreasing its amplitude.

![Tidal range during Neap, Spring and Average tide](image)

Figure 2.11 Relations between the tidal ranges in the Suriname River

The change of the amplitude of the tidal wave when propagating up-river is shown in Figure 2.11 in which the observed tidal wave amplitudes at several measurement stations have been plotted in longitudinal direction of the Suriname River Estuary.

These stations are at the guiding light (km 25), at Nieuw Amsterdam (km 41), at Paramaribo (km 54), at Paranam (km 87), at Joden Savanne (km 120), at Phedra (km 133), and at Berg and Dal (km 164).
During neap tidal conditions, the tidal wave amplitude until Phedra appears to be larger than at open sea. Upstream of Phedra the tidal amplitude attenuates to zero.

During average tidal conditions, the tidal wave amplitude until Paranam increases its height in the order of 10%. Upstream of Paranam the tidal amplitude attenuates to almost zero at Berg and Dal.

During spring tidal conditions, the tidal wave amplitude remains more or less the same until Paranam. Upstream of Paranam the tidal amplitude attenuates with the same gradient as for average tidal conditions and therefore it is expected that the tidal wave will be totally attenuated before it can be reflected at the Afbakka dam (km 194).

On May 12 and May 21, 1966, the ebb and flood volumes of the Suriname River Estuary were measured in a cross section near Leonsberg (km 43) (Nedeco 1968). During these days, the discharge of water through the Afbakka dam was 200 m³/s. Because of local rainfall north of the dam, the fresh water discharge in the river mouth has been somewhat higher, possibly 250 m³/s. The results of the measurements are presented in Figures 2.12a and 2.12b.

On May 12, the residual outward flow was 38 * 10⁶ m³ and on May 21, it was 22 * 10⁶ m³. The volume of the river discharge during the measuring periods was about 11 * 10⁶ m³, which means that part of the outflow is caused by the asymmetry of the vertical tide. The asymmetry will be analysed in the following chapter.

According to the Nedeco study, the tidal prism is 120 * 10⁶ m³ during an average tidal range of 1.85 m. In other words on average 120 * 10⁶ m³ of water flows in and the same amount flows out again during one tidal period through the cross section at Leonsberg (km 43).

![Figure 2.12a Water discharge at Leonsberg in the Suriname River at neap tide, May 12, 1966, after Nedeco](image1)

![Figure 2.12b Water discharge at Leonsberg in the Suriname River at spring tide, May 21, 1966, after Nedeco 1968](image2)
2.4 Currents

In the shelf area, the dominant component of the flow is the Guiana current. The main flow crosses the continental shelf from southeast to northwest, visualized in Figure 2.13. The velocity of the current at the Ocean between the Marowijne and Suriname Rivers varies between 0.5 m/s during a greater part of the year and a peak of 0.9 m/s in April. Near the coast, this flow is parallel to the coast and due to bed friction the flow velocity decreases as the water depth decreases. Strong winds can increase the strength of the current in the shallow area.

![Figure 2.13 Sketchmap of the equatorial currents at the northern part of South America. The most important currents are indicated by arrows, after Augustinus 1980](image)

For the Nedeco-study, measurements of currents in the Suriname River Estuary shoal area have been taken with floats in 11 stations. The scatter in the results appears to be large. The variations in the strength and the direction of the ocean current and the wind-induced currents in the shallow shoal area seem to be at random. Due to local and offshore alternating weather conditions, the currents in the Suriname River Estuary shoal area are indistinctive. This is a reason to focus this thesis on the more up-river section of the Suriname River Estuary as is mentioned before.

The focus of this thesis is the river section between Nieuw-Amsterdam and Paranam (km 41-87). The currents in this section are more distinctive. The tide-driven currents are clearly dominant over the wind/wave-driven, density-driven currents and the river current. Beside, the dominant currents are in the same direction as the alignment of the river channel. This fact makes it possible to predict and validate the currents in the river section in time at certain water levels.

In general, it is clear that during falling water the current velocity has an opposite direction as during upcoming water. The turning point between an upstream current and a
downstream current is not in phase with high water, which is the turning point between falling water and rising water. During the first moments of rising water, just after low water, the current velocity is still in downstream direction but decreasing. The opposite is true for the first moments of falling water, just after high water.

The maximum ebb and flood currents decrease in longitudinal direction. At Leonsberg (km 43) the maximum velocity is 1.8 m/s, at Paramaribo (km 58) and Zoelen (Commewijne km 4) it is 1.3/1.5 m/s, and at Overbridge (km 101) it is 0.8 m/s.

The measurement results are not conclusive about the difference between ebb and flood current. Some measurements comply with the literature that the flood currents are 10-20% higher than the ebb currents; however, that does not account for all the measurement campaigns. That can be due to daily inequality of the tidal elevation and also depend on the location where the measurements have been taken.

The measurement campaigns have one thing in common and that is the longer period of ebb current and therefore a shorter period for flood currents during a tidal cycle. This is partly due to the river discharge coming from upstream and partly due the asymmetry of the tide propagating through the Suriname River Estuary.

The share of the river discharge in the currents in the Suriname and Commewijne River is small compared to the maxima and minima of these tidal currents. However, the river discharge is constant in time compared to the fluctuating tidal discharge.

Before the construction of the dam the highest peak discharge measured between the years 1952 and 1966 at Pokigron was 800 m³/s. Pokigron is situated ca. 100 km upstream of Afobakka. The catchment area between Pokigron and Afobakka in those years was a third of the total area, therefore it can be expected that the highest peak discharge would have been of the order of 1200 m³/s at Afobakka.

The Suriname River discharge at present is mainly dominated by the discharge of the Afobakka dam. The Suriname discharge just downstream of the dam is between 200 and 450 m³/s as is visualized in Figure 2.14 a and b. The additional discharge due to small creeks is between 0-50 m³/s according Nedeco, 1968. Normally rivers have a large difference between minimum and maximum discharge due to periods of high runoff due to rainfall and low runoff due to dry periods. Therefore the river discharge is quite a constant situation all due to the regulation of the water flowing through the dam.

The discharge through the Commewijne River is not regulated like the Suriname River and data about the discharge is not present as well. Nedeco has made an estimation of the mean discharge of 120 m³/s based on a ratio between catchment area and discharge of
other rivers in Suriname. According to the discharge data from Pokigron the highest peak discharges are two times as high as the average discharge. Therefore, a peak discharge for the Commewijne River would be of the order of 240 m³/s.

![Discharge Suriname River at Alobakka](image1.png)

*Figure 2.14a Suriname River annual discharge 1966-1985 after Augustinus 1980*

![Discharge Suriname River at Alobakka](image2.png)

*Figure 2.14b Suriname River instantaneous discharge for the year 1983 after WLA 1983*
2.5 Wind and waves

The wind in the area of the Suriname Estuary blows mainly from directions between northeast and east with a very small variation during the year. In Figure 4 wind roses are shown from an offshore location approximately 220 km off the Suriname Coast. The most wind speeds appear between 5-10 kn/s, during winter period wind speeds between 10-15 kn/s also occur.

The waves at this offshore location have a direction of North-north-east to East-North-east. During summer and autumn, the wave height is about 1-2 m and during winter and spring, the appearance of wave heights between 2-3 m is dominant.

All the waves at the river mouth have a North-north-east direction with hardly any variance and the waves are 1 m lower as the offshore waves. In the winter and spring period the wave height is between 1-2 m and in the summer and autumn period they are smaller than 1 m.

The waves do not tend to break on the shoreline, but attenuate part of their energy on the muddy sea bed before they reach the shore. Braamspunt is protecting the Suriname River Estuary from direct wave penetration. The waves cannot reach the river section directly. Therefore, a lot of wave energy is lost, due to which the waves on the river section are generated through local wind and through navigation activity.

2.6 Salinity

The salt content in the river estuary varies mainly because of the tide driven currents with salt water flowing in and out of the estuary and fresh water flowing from the Suriname and Commewijne River. Nedeco in the year 1968 and WLA in the year 1983 have executed measurements to estimate the salt content of the water. From the results, it appears that the salty waterfront during upcoming water travels until Domburg (km 70) and during falling water, the minimum salt concentrations fall back to Paramaribo (km 50), presented in Figure 2.16.

![Figure 2.16 Minimum and maximum salt concentrations along channel axis.](image)

Especially in the range between Leonsberg (km 43) and Paramaribo (km 52) large differences, occur in the salt content at the surface and the salt content at the bed (Heuvel,
1983). These differences between surface and bed are evidence of the presence of reasonable salt stratification between Leonsberg and Paramaribo.

2.7 Sediment

Sediment can consist of boulder, cobble, pebble, gravel, sand, silt or clay particles, which are distributed in size of the particles. According to the modified Wentworth sediment classification (Wentworth, 1922) particle sizes are distributed as is presented in Table 2.1.

The Suriname River Estuary till Paranam (km 87) only consists of sand, silt and clay particles. The interaction and combination of these particles define the composition and transport of the sediment. Many compositions of the sediment are present in the Suriname River Estuary and therefore will be discussed in the following subsection.

<table>
<thead>
<tr>
<th>Class</th>
<th>Particle Size Range (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>&lt; 0.0039</td>
</tr>
<tr>
<td>Silt</td>
<td>0.0039 -- 0.0625</td>
</tr>
<tr>
<td>Very fine sand</td>
<td>0.0625 -- 0.125</td>
</tr>
<tr>
<td>Fine sand</td>
<td>0.125 -- 0.25</td>
</tr>
<tr>
<td>Medium sand</td>
<td>0.25 -- 0.5</td>
</tr>
<tr>
<td>Coarse sand</td>
<td>0.5 -- 1</td>
</tr>
<tr>
<td>Very coarse sand</td>
<td>1 -- 8</td>
</tr>
<tr>
<td>Gravel</td>
<td>8 -- 32</td>
</tr>
<tr>
<td>Pebble</td>
<td>32 -- 64</td>
</tr>
<tr>
<td>Cobble (rubble)</td>
<td>64 -- 256</td>
</tr>
<tr>
<td>Boulder</td>
<td>&gt; 256</td>
</tr>
</tbody>
</table>

Table 2.1 Modified Wentworth sediment classification

2.7.1 Sediment composition

The Suriname River Estuary is mainly dominated by the presence of mud. Mud is a cohesive sedimentary material consisting of very fine particles intermediate in size between clay and fine sand. The particle size distribution of the sediment defines the composition. Sediment is defined as mud when 90% of the sediment does not contain sand particles according to the Folk classification system (Poppe, 2003) presented in the left triangle of Figure 2.17. The sediment is defined as sandy mud when 50% of the sediment does not contain sand particles.

The ratio between percentage of clay particles and percentage of silt particles must be between 0.5 and 2 to define the sediment as mud according to the right-side triangle of Figure 2.17.

The last thousands of years, mud has been accreted on the coast of Suriname, in spite of the open and middle-rough northeast coastline of South America. Beside mud, also sand and shell debris is present locally. This coarser sediment has gathered in the so-called cheniers (Figure 2.3), which lie parallel to the shoreline on the coast. Due to extension of
the coastline in seaward direction, these cheniers are also found more land inward. Then they are often used as foundation for cultivation, such as Paramaribo.

The mud appears in the water as suspended flocs or particles. The bed of the Suriname River estuary consists of mud that has been settled throughout centuries. Between the suspended mud in the water and the settled mud bed there is often a layer of fluid mud present. These three mud appearances will be discussed below.

![Figure 2.17 Folk's classification system after Poppe, 2000](image)

**Suspended flocs and particles**

The lower reach of the Suriname River Estuary flows through the mud depositions (approximately between the coastline and Domburg (km 69)). The water at the coastline, the river mouth and the lower reach of the Suriname River is visibly brown coloured, due to the sediment that is in suspension. The currents in the water keep the mud particles, which are “glued” together as flocs, in the vertical water column. Due to strong and turbulent currents the upward forces are bigger as the drop capacity due to gravity of the flocs. These mud particles travel through the river in down- and upstream direction following the current direction of the water.

The mud concentration in the water can be uniform in the entire water column; however, the concentration can vary through the vertical water column as well. In that case, the mud concentration at the surface is often lower as the mud concentration close to the bed. The amount of mud content in the water is strongly dependent on the currents, generated by tide, river discharge, waves, turbulence or density differences.

The results from the water sample measurements of Nedeco in the year 1968, between the sea until Paranam, show mud concentrations between 0,03 and 3,0 kg/m³. Locally, very high mud concentrations occur (in the order of 100 kg/m³), especially in the deeper areas and where the vessels have scoured the fairway channel (Nedeco, 1968).
Also in this estuary, Nedeco has observed two turbidity maxima. There is a region between Resolutie and Jaglust (km38-50) with high mud concentrations near Jaglust bar during slack of the vertical tide at high water (HW) and with high mud concentrations near Resolutie bar during slack of the vertical tide at low water (LW). The second region with a turbidity maximum is between Dijkveld Bar and Accaribo bar (km 58-86), also with high mud concentrations travelling up- and downstream following the tidal current.

In the year 1983 WLA executed measurements of sediment concentrations in the water during slacks of the vertical tide. The maxima, minima and mean sediment concentrations in the study area have been summarized in Table 2.2.

<table>
<thead>
<tr>
<th>Km</th>
<th>max HW [kg/m³]</th>
<th>min HW [kg/m³]</th>
<th>mean HW [kg/m³]</th>
<th>mean LW [kg/m³]</th>
<th>mean HW/LW [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>40.00</td>
<td>3.89</td>
<td>0.47</td>
<td>1.53</td>
<td>0.89</td>
<td>1.21</td>
</tr>
<tr>
<td>43.80</td>
<td>13.10</td>
<td>0.33</td>
<td>2.48</td>
<td>1.49</td>
<td>1.99</td>
</tr>
<tr>
<td>45.90</td>
<td>6.62</td>
<td>0.18</td>
<td>2.22</td>
<td>2.10</td>
<td>2.16</td>
</tr>
<tr>
<td>48.00</td>
<td>8.20</td>
<td>0.14</td>
<td>2.05</td>
<td>1.48</td>
<td>1.76</td>
</tr>
<tr>
<td>50.60</td>
<td>11.00</td>
<td>0.09</td>
<td>2.41</td>
<td>0.86</td>
<td>1.64</td>
</tr>
<tr>
<td>55.00</td>
<td>6.23</td>
<td>0.46</td>
<td>2.36</td>
<td>0.82</td>
<td>1.59</td>
</tr>
<tr>
<td>60.70</td>
<td>0.91</td>
<td>0.45</td>
<td>0.59</td>
<td>1.28</td>
<td>0.94</td>
</tr>
<tr>
<td>65.20</td>
<td>1.12</td>
<td>0.34</td>
<td>0.71</td>
<td>0.34</td>
<td>0.52</td>
</tr>
<tr>
<td>68.00</td>
<td>2.56</td>
<td>0.14</td>
<td>0.74</td>
<td>0.11</td>
<td>0.42</td>
</tr>
<tr>
<td>76.20</td>
<td>4.10</td>
<td>0.09</td>
<td>0.63</td>
<td>0.08</td>
<td>0.36</td>
</tr>
<tr>
<td>79.60</td>
<td>5.63</td>
<td>0.05</td>
<td>0.59</td>
<td>0.06</td>
<td>0.32</td>
</tr>
<tr>
<td>83.00</td>
<td>2.85</td>
<td>0.04</td>
<td>0.32</td>
<td>0.04</td>
<td>0.18</td>
</tr>
<tr>
<td>88.50</td>
<td>0.14</td>
<td>0.02</td>
<td>0.05</td>
<td>0.03</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Table 2.2 Sediment concentrations [kg/m³] around slack of the vertical tide at several cross sections in the study area, WLA 1983

The mean sediment concentration at the beginning of the study area can be up to 2.16 kg/m³ at km 46, more upstream the mean sediment concentrations decrease to almost zero at upstream end of the study area. The maximum sediment concentration can reach 13.1 kg/m³ during a slack of the vertical tide at high water (HW), even at km 80 very high maximum sediment concentration of 5.6 kg/m³ can occur.

Striking are the great differences in the mud concentrations at the ocean (km 0) in March and October, which must be ascribed to the differences in the wave-action, the wind-speeds and thus the wave-heights being greatest in March (Nedeco, 1968).

The sediments of several water samples taken by MOS, 2006 have been analysed to determine the sediment particle sizes. The percentage of the particle size smaller than 63 μm determine the composition of the sediment according the folk’s classification.

The composition of the sediments in longitudinal direction of the estuary is presented in Figure 2.18. Most of the water samples contain sediments that can be classified as sandy mud close to the line of a mud classification. The last section of the study area the
sediments rapidly change to a sand composition, however still some mud is present in some of the water samples.

**Fluid mud**

A mud-water mixture in which the individual flocs are no longer recognizable is called fluid mud. The density of such a layer according to Heuvel, 1983 is between 1100-1250 kg/m³ (sediment concentration: 165-385 kg/m³). Above approximately 1280 kg/m³ (450 kg/m³) the sediment suspension has no longer its fluid character and will therefore be the boundary between river bed and the fluid mud layer (Heuvel, T, 1983).

During measurements (30-07-1982) in the seaway close to Resolutie (km 38), a layer of mud has been observed. The density increase of this layer was not evenly distributed in depth. In Figure 2.19, the results are presented. Between 1100-1120 kg/m³ there is a sudden jump in the graph. In the surface layer of the fluid mud, a gradient of 270 kg/m³/m was found whilst in the lower layer until a density of 1250 kg/m³ a gradient of 320 kg/m³/m was found (Heuvel, 1983).
River bed

Borings of the bed top layer (0-2 m) have been taken by MOS 2006 to analyze the sediment composition in the laboratory. The percentage of the particle sizes smaller than 63 μm determines the composition of the sediment according the folk’s classification. The composition of the sediments in longitudinal direction of the estuary is presented in Figure 2.20.

The first part of the study area until km 68 near Domburg is dominated by the presence of mud and sandy mud in the top layer (2 m) of the river bed. Upstream of km 68 only three borings have been executed and therefore it is difficult to define the composition of the river bed in this upstream section of the study area. Beyond Paranam (km 87) the top layer of the bed consists mainly of sand, which is locally very course and sometimes mixed with some gravel (Nedeco, 1968).

Therefore it can be concluded that the section between Domburg (km 70) and Paranam (km 87) is a transition area where mud dominance transfers into sand dominated sediment composition in the top layer of the river bed.

![Figure 2.20 Bed samples sediment composition in longitudinal direction](image)

2.7.2 Sediment displacement

The scarce upstream supply of sediments in the lower reach of the Suriname River is estimated at 0.25 x 10⁶ tons per year and by the Commewijne River is estimated at 0.06 x 10⁶ tons per year (Nedeco, 1968). The greater part of this volume consists of finer sediments that are transported as suspended load. It means that the majority of the fine sediments found in the Suriname River are originating from the sea and transported into the estuary.

In the lower reach of the Suriname River, large quantities of mud are displacing under influence of the currents. ‘An accurate computation of the mud transports from the observed current velocities and mud concentrations of the water appears to be impossible’
(Nedeco, 1968), firstly, because of a strong gradient in the mud concentrations in a vertical direction, and secondly, because of the presence of a fluid mud layer on the bed.

Relatively small movements of the fluid mud contribute substantially to the total mud transport, but these movements are very difficult to measure.

According to Nedeco leaving out of consideration possible fluid mud displacements during neap tide conditions a flood period at Leonsberg transports 10,000 tons (ca. 3,800 m³) and an ebb period transports 15,000 tons (ca. 5,700 m³) in the year 1966 (after the construction of the Afobakka dam). During spring tide conditions Nedeco estimated a sediment transport exceeding 100,000 tons (38,000 m³) during flood period and exceeding 100,000 tons during the ebb period.

In the past, it appeared that a mud bank shifting in front of the river-mouth would cause an increase of sediment in the estuary. The fluid mud on the west side of the mud banks will not settle down because of attenuation of the waves, but instead they will be transported into the river-mouth. The actual distance from the west flank of the mud bank along the coast of Commewijne and Braamspunt is about 25 km. With an average migration velocity of 1.5 km/yr it will take 17 years (from November 2006) before the bank will have reached the Suriname Estuary. This mud bank is a very large one; it extends approximately 70 km along coast of District Commewijne (Sunecon, 2006).
2.8 Navigation

The fairway through the Suriname River is the most important transport route for export and import of goods as well as for inland transportation of goods. The fairway is the main entrance to the harbours of Paramaribo and Paramaribo. The harbour of Paramaribo is located approximately 56 km from the beginning of the fairway at sea and possesses the largest general and container terminal of Suriname, while from the harbour of Paramaribo (about 87 km from the beginning of the fairway at sea) the main exports of Alumina from Paramaribo takes place.

In Figure 2.21 the annual average freight per ship is presented for ships involved in international shipping dispatched by Paramaribo and Paramaribo, the two most important harbours of Suriname. Between 1981 and 2000 the greater part of the ships passing through the harbour of Paramaribo have an average freight of 11,000 tons. In the same period, the ships passing the harbour of Paramaribo have freight between 1,500 to 2,000 tons.

![Average Freight per Ship](image)

*Figure 2.21 Average freight per ship (in- and export) navigating through the Suriname Estuary, after statisticsen 1995-2000*

The ships navigating from and to Paramaribo are ore ships with capacities between 12,000 to 50,000 DWT (Dead Weight Ton). These ships with a draught of more than 4 m are obliged to take a pilot on board for assisting on navigating through the fairway. These ships have a large draught and often navigate with minimal keel clearance. When the ships navigate in the same direction as the tidal current and the draught of the ships are small because of no cargo weight, they are able to sail from the Ocean to Paramaribo without stopping. When these ships leave Paramaribo, it is impossible to reach the sea in one time, because the navigating speed is reduced through a high load of the ship. Therefore, these large ships lie at anchor at the deep section near Leonsberg (km 43) and can continue their way to the sea.
during the next high water. Approximately 200 ships per year call on the harbour of Paramaribo.

In the past, many ships followed the same route to enter and leave the Suriname River. Especially after the implementation of intensive beaconing (floating aids to navigation) to force the ships to follow the same narrow path, the turbulence of the water caused by the moving vessels and the physical contact between the vessels and the bed and also the propeller wash have produced a scouring of the bed. The channel bed (between km 0 and 65) lies up to 2 m below the level of the surrounding river bed, except for the deep sections.

The ships sailing from and to Paramaribo are tankers, container and bulk ships for import and export of goods like oil, timber and rice. Some of these ships are obliged to take a pilot on board for assisting on sailing through the fairway. These ships have a smaller draught than the ore ships. The ships can be fully loaded and can reach the sea in one time because the distance is smaller. However, these ships are less bound to the high water level, and therefore it is possible that also these ships will navigate with minimum keel clearance. Approximately 1000 ships per year call on the harbour of Paramaribo.

2.9 Measurement data

The physical description as above is based on the collected measurement data from in and around the Suriname River estuary. The data from these measurements are needed to study the sediment transport in the Suriname River Estuary system. The focus of this study is on the hydrodynamic processes such as tidal asymmetry, gravitational circulation and river discharge in relation to the sediment transport in the Suriname River estuary. Therefore, data of current velocities, tidal elevations, salt concentrations and sediment concentrations are analysed for further study.

The data that has been collected is summarized in appendix A.

A significant amount of data is given with respect to the reference level Chart Datum (CD). The relationship between CD and NSP (Normalised Suriname reference level) changes for different trajectories of the Suriname River and is given in the Table 2.3 (Lievense 2007b).
The bed level has recently (2002-2004) been surveyed, therefore the depths and alignment of the study area is almost up to date.

The tide and water levels have been monitored during recent years 2001-2006, therefore it was possible to describe the Suriname tidal character. However further analysis will give more insight in the asymmetry of the tide and how it can affect the sediment transport. The following chapter will classify the Suriname River Estuary on tidal characteristics and the impact on the sediment transport.

Only a few velocity measurement campaigns have been executed in the Suriname River Estuary. Of course such measurement campaigns are costly and comprehensive to execute. However for sediment transport studies it would be convenient to analyse measurements of long periods in time and at more locations in the Suriname River Estuary.

The velocity measurements that have been executed will be analysed to study the behaviour of the current during the tidal cycle and to classify the estuary on salinity and velocity structure.

The salinity of the water in the Suriname River Estuary has been monitored over the years. Therefore, knowledge about the intrusion of the salt in longitudinal direction of the estuary is present. During the velocity measurements, the salt concentrations have been monitored as well, giving more insight in stratification during a tidal cycle and local conditions. These salt measurements will also be analysed to study the stratification behaviour during the tidal cycle and to classify the estuary on salinity and velocity structure.

Monitoring of the quantity and load of ships navigating through the Suriname River Estuary is rather straight forward; however the impact of scouring, mixing and liquefaction of the mud on the bed of the river because of ship movement has not been monitored.

<table>
<thead>
<tr>
<th>Station</th>
<th>Chainage [km]</th>
<th>Proposed relationship between NSP and CD</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>0</td>
<td>CD = NSP -1.38 m</td>
</tr>
<tr>
<td>Geelidelicht (GL)</td>
<td>25</td>
<td>CD = NSP -1.38 m</td>
</tr>
<tr>
<td>Braamspunt (BR)</td>
<td>31</td>
<td>CD = NSP -1.36 m</td>
</tr>
<tr>
<td>Nieuw Amsterdam (NA)</td>
<td>40</td>
<td>CD = NSP -1.32 m</td>
</tr>
<tr>
<td>Paramaribo (PAO)</td>
<td>52</td>
<td>CD = NSP -1.26 m</td>
</tr>
<tr>
<td>Domburg (DB)</td>
<td>68</td>
<td>CD = NSP -1.25 m</td>
</tr>
<tr>
<td>Paramam (PAM)</td>
<td>88</td>
<td>CD = NSP -1.23 m</td>
</tr>
</tbody>
</table>

Table 2.3 Relationship between CD and NSP according to Levense, 2007b
Sediment characteristics can be measured through particle sizes and concentrations in the water, fluid mud or bed. These characteristics have been described in this chapter.

The goal of this study is to gain knowledge about the transport of sediments. It is possible to measure sediment transport, however only very locally on the bed for instance. The transport of muddy sediments takes place through the whole cross-section of the flowing water with a difference in surface layer transport and bed layer transport.

This 3-dimensional sediment transport fluctuating in time is difficult to measure. That is why we need to determine all the hydrodynamic and morphodynamic processes and characteristics to predict the quality and quantity of the sediment transport in the study area. The following chapter will analyse the tidal elevation measurements and the velocity and salinity measurements.
3 Suriname River Estuary system analysis

The mud concentrations and mud transport in the waters of the Suriname River Estuary strongly influence the morphologic development.

Mud is picked up by the flowing water and transported (mainly) in suspension in the direction of the current / flow. During ebb, the tidal flow is seaward and during flood the tidal flow is landward. In the river section influenced by the tide (roughly between the estuary mouth km 32 and Berg and Dal km 160), the magnitude of the residual river discharge is negligible small compared to the maximum and minimum of the tidal discharge. The instantaneous tidal discharge is flowing in and out of the system with a closed water balance averaged over multiple tidal cycles. On the other hand the residual river discharge is not a closed water balance and is flowing in downstream direction.

The density gradients of the fluid depend on salt concentrations, mud concentrations and temperature of the water. They all contribute to the transport of mud.

To classify which processes influence the mud concentrations and which processes dominate the mud transport in a numerically way, first measurement data of the tidal movements and the salt concentrations are analysed.

Section 3.1 discusses a classification based on tidal characteristics and section 3.2 describes several classifications based on the salinity and velocity distributions. Section 3.3 refers the possibility of phase shifts between the flow velocities in the Commewijne and the Suriname River, near their bifurcation. Section 3.4 defines the characteristics of the classification of the estuary and the resulting hydrodynamic processes on the mud transport.

3.1 Classification based on tidal characteristics

The shape of the tidal curve depends on the balance between the shape of the estuary and the effect of the bed friction. The variation along the estuary of the amplitude and phase of the tide will affect the current velocities and therefore affects the mud transport.

The propagation of the tidal wave is equal to the square root of the gravity acceleration multiplied with the water depth. So, due to the tidal variation of the water depth the wave crest of the long tidal wave (deeper water) will propagate more quickly than the trough (shallow water). The crest of the tide partially overtakes the trough, resulting in a shorter flood and longer ebb, and the highest velocities thereby occur during the flood tide.
In subsection 3.1.1, a qualification of the estuary is obtained based on visualization of the water level movement and velocity measurements. Subsection 3.1.2 will discuss the quantification of the estuary, based on the study of Speer and Aubrey (1985) after Dyer (1997) using tidal constituents to describe the tidal elevation.

### 3.1.1 Qualification of estuary classification

The Suriname River Estuary can be classified as a synchronous tide estuary, because friction and convergence have equal and opposite effects on the tide as is already discussed in section 2.3.

The tidal wave in the Suriname River Estuary is a progressive wave combined with standing wave properties (because of partial reflections due to bathymetry convergence in depth and width). This means that there is a progression in times of high water and low water and the turn of the current along the estuary.

A complete progressive wave propagates through the river channel with a certain phase velocity. The current velocity of a complete progressive wave is in phase with the elevation phase, resulting in maximum velocities during maximum and minimum water levels (Figure 3.1).

A standing wave does not propagate up river and therefore the current velocity is zero at the moment of slack of the vertical tide at high water and at low water, resulting in a phase difference between elevation phase and current velocity phase of exactly a quarter (\(\frac{1}{4}\pi\)) of the tidal period (\(2\pi\)) (Figure 3.1).

The phase difference between water level and current velocity is visualized in Figure 3.2; a plot of a measurement campaign at Leonsberg (km 43).
From the moment of decreasing water level after slack of the vertical tide, the current continues flooding (horizontal tide) for 60 minutes. The horizontal tide is providing the water for the rising water level further upstream. The other way around there is also a phase difference between horizontal tide and vertical tide. The ebb current also continues flowing seaward (for 90 min) despite the rising water level.

These phase differences between current velocity and tidal elevation indicate a dual character of a standing wave and a progressive wave as previously mentioned.

Figure 3.2 A plot of the measurements at Leonsberg 23 July 1982.

The Maritieme Autoriteit Suriname (MAS) keeps records of tidal information at several locations along the Suriname River. For this study, data from the years 2002 until 2005 is used. The tide measuring locations are:

- Braamspunt (km 31),
- Nieuw Amsterdam (km 41),
- MAS pier (km 52),
- Domburg (km 69).

The water level variations caused by the tidal elevation in the Suriname River Estuary are visualised in Figure 3.3 for the random dates:

- 4th of June 2004 during spring tidal conditions,
- 31st of January 2004 during neap tidal conditions.

The tidal wave enters the estuary and propagates with a certain velocity up-river. During spring the wave propagates up-river and the sinusoidal shape of the tidal wave is changed into an asymmetric wave during spring tidal conditions. During the neap tidal conditions the shape of the tidal wave is hardly affected, between Braamspunt (km 32) and Domburg (km 70). Mathematically this change in wave shape can be described by the development of higher harmonics as will be described in the following subsection 3.1.2.
3.1.2 Quantification of estuary classification

Shallow water tides are a convenient way of describing the shape of the tidal wave through a combination of harmonic waves. Physically, the tidal wave still experiences the same basic period but appears deformed, with a shorter rise and a longer fall of the water level.

Such a distortion of the tidal curve can be considered in terms of tidal harmonic analysis, and the generation from the $M_2$ tide\(^1\) of the $M_4$ shallow water tide\(^2\). The major part of the asymmetry of the tidal curve is represented by superposition of $M_2$ and $M_4$ constituents in terms of water level, visualized in Figure 3.4.

Speer and Aubrey (1985) have considered the implications of tidal constituent ratios and show that for an elevation phase $(2M_2 - M_4)$ between $0^\circ$ and $180^\circ$, the system will be flood dominant. For a phase of $180^\circ - 360^\circ$ it will be ebb dominant. In either case, the larger the $(M_4 / M_2)$ ratio, the more distorted and the more strongly flood or ebb dominated the system becomes. Therefore the tidal elevations of 4 measurement stations, as mentioned in section 3.1.1 are analyzed using Delft3D-TIDE (a harmonic tidal analysis module within Delft3D).

---

\(^1\) The $M_2$ constituent has speed 28.984 degrees/hour, corresponding to the rotation of the moon around the earth. The $M_2$ constituent is the dominant component of the tidal regime.

\(^2\) The $M_4$ constituent has speed 57.968 degrees/hour. The $M_4$ constituent is generated as a nonlinear interaction of the $M_2$ constituent with itself.
The mathematical representation of the tidal curve by superposition of $M_2$ and $M_4$, both in terms of water level and velocity is as follows:

\[ A = a_{M_2} \cos (\omega \cdot t - \theta_{M_2}) + a_{M_4} \cos (\omega \cdot t - \theta_{M_4}) \]  

\[ U = u_{M_2} \cos (\omega \cdot t - \varphi_{M_2}) + u_{M_4} \cos (\omega \cdot t - \varphi_{M_4}) \]  

\begin{align*}
A & \quad \text{shape of vertical tide} & U & \quad \text{shape of the vertical tide} \\
\alpha & \quad \text{amplitude of vertical tide} & \theta & \quad \text{phase of vertical tide} \\
u & \quad \text{amplitude of horizontal tide} & \varphi & \quad \text{phase of horizontal tide} \\
\omega & \quad \text{frequency of tidal constituent} & t & \quad \text{time}
\end{align*}

The elevation phase of $M_4$ relative to $M_2$ is $(2M_2 - M_4) = (2\theta_{M_2} - \theta_{M_4})$. The elevation amplitude ratio is $(M_4 / M_2) = (a_{M_4} / a_{M_2})$.

Time series of water levels for several years are available of the four observation stations. These stations have been monitored by the MAS, during the years between 2001 and 2005. The registration time interval is 10 minutes. Only a few datasets of one full year without any gaps were present. Datasets including a few gaps are also useful to analyse the tide. The following datasets were selected for analyse:

- Braamspunt 2004,
- Nieuw Amsterdam 2002,
- MAS Paramaribo 2004,
- Domburg 2004.
The tidal datasets of every 10 minutes are reduced to tidal datasets of every 30 minutes, because the software cannot process large time series.

The analysis can be used to determine $a_i$ (the local tidal amplitude of a constituent) and $\theta_i$ (local phase lag). With these datasets long period constituents and various small period constituents are determined explicitly and independently. For a proper representation of the tide, the 38 most important harmonic constituents are selected for the analysis of the tidal observations. Every constituent has its own characteristic frequency. The results from this tidal analysis are presented in Table 1

For the determination of the flood or ebb dominance of the Suriname River Estuary only the $M_2$ and the $M_4$ will be of importance. In Table 3.2 the resulting tidal components of $M_2$ and $M_4$ from the tidal analysis are presented for the four observation stations.

<table>
<thead>
<tr>
<th>Braamspunt km 32</th>
<th>Nieuw Amsterdam km 42</th>
<th>MAS Paramaribo km 52</th>
<th>Domburg km 96</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMPONENT</td>
<td>FREQUENCY</td>
<td>AMPLITUDE</td>
<td>PHASE</td>
</tr>
<tr>
<td>M2</td>
<td>4.88</td>
<td>0.02</td>
<td>93.8</td>
</tr>
<tr>
<td>M4</td>
<td>9.76</td>
<td>0.06</td>
<td>19.4</td>
</tr>
</tbody>
</table>

ELEVATION PHASE (θ) DIFFERENCE

| M2     | Braamspunt | 10.6 | 113.6 | 93.8 | 0.99 |
| M4     | Braamspunt | 5.42 | 113.6 | 19.4 | 0.33 |

ELEVATION AMPLITUDE (A) RATIO

| M2     | 0.024      | 0.087    | 0.072   | 0.108 |
| M4     | 0.052      | 0.076    | 0.034   | 0.020 |

DISTANCE BETWEEN OBSERVATION STATIONS

| dx     | 10         | 0.0032    | 0.0018   | 0.0020 |

Table 3.2 Tidal analysis results for the $M_2$ and $M_4$ components at the four observation stations.

### 3.1.3 Conclusions tidal analysis

It can be concluded from the tidal elevation analysis that the Suriname River Estuary is flood dominant (short duration of flood and higher flood currents).

Especially between Braamspunt and Nieuw Amsterdam the phase difference between $M_2$ and $M_4$ is increasing, due to a strong contraction in the width of the Estuary width. This results in a deformed asymmetric tidal curve as visualized in Figure 3.4. The same phase difference holds between Nieuw Amsterdam and Paramaribo, however relatively less. Between Paramaribo and Domburg the phase difference hardly decreases and therefore the tidal curve retains its asymmetry.

The amplitude ratio between $M_2$ and $M_4$ is increasing in upstream direction in the estuary. The increasing ratio indicates that the $M_4$ amplitude is constantly gaining height along the channel of the Suriname River Estuary. The larger the $M_4/M_2$ amplitude ratio, the more distorted and the more strongly flood dominated the system becomes.

The tidal elevation analysis does not include the analysis of the current velocity during the long periods of tidal elevation data, due to the simple fact that long term current velocity data is not available.

Date: September 2008
For the study of sediment transport it would be more effective to have long term data of current velocity, which can be analyzed to determine the flood dominance based on the current velocity constituents. These current velocity constituents can be more conclusive for the sediment transport due to the fact that the sediment transport is directly related to the current velocity and not to the water level elevation.

The influence of the tidal dominance on the sediment transport will be discussed in section 3.4.

### 3.2 Classification on salinity and velocity distribution in depth profiles

There is a great deal of variety in estuaries caused by the differences in the tides, the river discharge and the way these factors interact with the topography. Each estuary reacts differently in the way the processes of circulation currents, density stratification and mixing develop. An estuary can be classified based on the salinity distribution and flow characteristics within the estuary. Such a classification will lead to a better understanding of how the circulation of water in the Suriname River Estuary is maintained, and quantification which should assist predicting.

According to Dyer (1997), estuaries have been classified by Pritchard (1955) and Cameron and Pritchard (1963) by their stratification and the characteristics of their salinity distributions. They define four main estuarine types:

- a) highly stratified or salt wedge,
- b) fjords,
- c) partially mixed and
- d) homogeneous, or well mixed.

The Suriname River Estuary is not classified as one of the first two estuarine types (a and b). The estuary is classified as either type c or b, therefore the focus of this section is based on partially mixed (c) and well-mixed estuaries (d).

First, both estuary types will be described below, before a qualitative classification of the estuary is obtained and before several quantifications of the classification of the estuary are obtained. This section compares the classifications to determine one final classification for the Suriname River Estuary.
3.2.1 Partially mixed estuary

The energy involved in the tidal current movements is large and it is mainly dissipated in the estuary by working against the frictional forces on the bed. The friction causes eddies which lose their kinetic energy, because of density gradients and by viscous dissipation, creating heat. The turbulence eddies can mix both salt water upwards and fresh water downwards. Because of the mixing, the salinity of the surface layer is considerably increased, however the increase is not large enough to dissolve the buoyancy of the lower dense surface layer. Consequently, a distinct two-layer flow system is developed in the mean flows.

There is a layer in the water column where the tidally averaged flow is zero, which is called the level of no motion. This layer coincides with the level of the maximum vertical salinity gradient. Where the level of no motion reaches the estuary bed at the head of the salt intrusion there is a null point. The level of no motion and the null point are indicated in Figure 3.5.

The process by which gravity creates a flow with dense water flowing beneath less dense water is called gravitational circulation. The mixing between the horizontal layers tends to affect the longitudinal density gradients and therefore effects the gravitational circulation as well. It is very difficult to measure the gravitational currents, because they are small compared to the oscillatory tidal flow. Some sort of averaging process is necessary to determine them. A distinction needs to be drawn between the tidally averaged processes which reveal the residual flows and those occurring during the tide.

Typical salinity and velocity profiles in a partially mixed estuary are shown in Figure 3.5. The shape of the vertical salinity profile does not change much along the estuary. There is normally a zone of high salinity gradients at about mid-depth and the surface and bed layers are almost homogeneous (Dyer, 1997).

In partially mixed estuaries the tidal range can change significantly between spring and neap tides. The spring tides increase the turbulent exchanges of salt and fresh water, and as a consequence the vertical gravitational circulation and the stratification will reduce. High river discharge can cause the estuary to become more stratified, but the intensity of the mean gravitational circulation should diminish. However, the river discharge in the
Suriname Estuary is relatively constant and variation in stratification and gravitational circulation through river discharge is not expected to large.

Within partially mixed estuaries there can be considerable variation of structure in longitudinal direction of the estuary.

### 3.2.2 Laterally well-mixed estuary

When the tidal range is large, relative to the water depth, the turbulence produced by the velocity shear on the bed may be large enough to mix the water column completely and make the estuary vertically well-mixed. The well-mixed characteristics have been visualized in Figure 3.6.

It is difficult to be sure, however, that the concept of well-mixed really exists, as small variations may be lost in the averaging processes. Although, there is a gravitational circulation produced by the denser water trying to flow landwards beneath the fresher water, it does not overcome the vertical mixing of the tidal currents and amplifies the stratification.

In these estuaries the tidal flow will be much larger than the river discharge, as is the case in the Suriname River Estuary. Salinity increases evenly towards the mouth and the mean flow is seawards throughout the cross-sections. This invokes a tendency to drive the salt out of the estuary. The balance is made by an upstream turbulent exchange of salt, which is associated with the effect on the tidal flow of topographic irregularities and friction at the bed.

This estuarine type may show variations from section to section of the estuary. Near the head of the estuary where the tidal amplitude is reduced, river discharge dominates and a highly stratified structure results. In the Suriname River Estuary the tidal amplitude is not reduced until km 120 and salt intrusion does not reach this far. Therefore a highly stratified structure is not expected near the head of the estuary. Further downstream the tidal velocities increase and turbulent mixing can become more active, as a result a partially mixed structure can occur. Near the mouth the tidal currents may even be strong enough to produce well-mixed conditions.
3.2.3 Qualifying classification

To qualify the classification of the estuary, measurements of salinity and water velocities, taken during a campaign at Leonsberg and a campaign at BEM Paramaribo, are compared to the tidally averaged salinity and velocity depth profiles from Figure 3.5 and 3.6. The salinity depth profiles as presented in the Figures 3.7 and 3.8, both show stratified profiles as well as well-mixed profiles in time. During high water and two hours after high water the salinity at the bed is significantly higher than at the surface (stratified). During the rest of the tidal period, the salinity profile is not stratified.

![Figure 3.7 Salinity depth profiles at Leonsberg 1982 (km 43) and estimated tidally averaged salinity](image1)

![Figure 3.8 Salinity depth profiles of measurements at BEM 2007 (km 58) and estimated tidally averaged salinity](image2)

The tidally averaged salinity profile of the measurement data as presented in the right-hand side of Figure 3.7 and 3.8, resemble a partially mixed salinity profile (Figure 3.5) for Leonsberg (km 43) and a well-mixed salinity profile (Figure 3.6) for BEM Paramaribo (km 58).

It would be useful to compare the velocity profiles from Dyer (Dyer 1997) with the measured velocity depth profiles, but the measurement data is not very useful for a good comparison. The collected data do not include the direction of the velocity. Therefore, it is impossible to separate ebb currents from flood currents. However, if only the measurements during slack of the horizontal tide (turning of current direction) are neglected, we can assume that the measured velocities are respectively flood currents and ebb currents. This is done for the measurements from Leonsberg presented in Figure 3.9.
to show velocity depth profiles. The velocity depth profiles do not resemble a velocity depth profile from a stratified, or a well-mixed (Figure 3.5 and 3.6) estuary. To classify the estuary based on velocity structure the measurements need to include flow direction and a shorter measure time interval as executed at Leonsberg and BEM Paramaribo.

![velocity measurements during a flood and a ebb at Leonsberg 23 July 1982](image)

Figure 3.9 Velocity depth profiles of measurements at Leonsberg 1982

### 3.2.4 Quantifying classification

The limits of each estuary type cannot be clearly defined. Each type is more like a stage in a continuous sequence. This sequence will be dominated to a large extent by the river flow (fresh water), which causes buoyancy that tends to maintain stratification, and secondly by the tidal flow, which due to friction causes mixing.

Quantified classifications have been developed to characterise the ratio of these two factors, as well as the magnitude of the resulting salinity stratification. The major difficulty in this is that the gravitational circulation created by the density field modifies both the mixing and the stratification (Dyer, 1997). Additionally, the tidal variation of water depth, or cross-sectional area, and the advection along the estuary need to be included.

There are many different schemes that have been developed, mainly from dimensionless numbers, or parameters, used with tidally averaged variables. For this study four classification numbers will be calculated according to Dyer (1997):

1) flood number (Simmons),
2) estuary number (Pritchard),
3) stratification number (Prandle 1985),
4) scheme of Hansen and Rattray, using a stratification-circulation diagram.

The results are compared and a conclusion on the classification of the Suriname River Estuary will follow in the next subsection (3.2.5).
Flood number:
Simmons defined a flood number, which uses a flow ratio of river flow per tidal cycle to the tidal prism. A tidal prism has been defined by Nedco, 1968 by interpolating between a neap tide and a spring tide measurement at Leonsberg (km 43). Nedco defined an average tidal prism of $120 \times 10^6$ m$^3$ (section 2.3). The average river flow is 300 m$^3$/s as is described in section 2.4, so the river flow during 1 tidal cycle is $13.4 \times 10^6$ m$^3$.

The flow ratio is therefore $0.11$. When the flow ratio is about 0.25 the estuary is partially mixed and when it is less than 0.1 it is well mixed. So according to the flood number of Simmons this estuary should be classified as a partially mixed estuary but very close to a well-mixed estuary.

Estuary number:
The estuary number of Pritchard can be defined as:

\[ E_o = \frac{P_i}{Q_p \cdot T} \cdot \frac{(u_{\text{max}})^2}{g \cdot h \cdot (\Delta \rho/\rho)} \]  

(3)

- $P_i$: tidal prism
- $Q_p$: river discharge
- $T$: tidal period
- $u_{\text{max}}$: maximum amplitude of the tidal current
- $g$: acceleration of gravity
- $h$: mean water depth
- $\rho$: fluid mixture density

When $E_o > 10$ the estuary is well-mixed and when $E_o < 0.25$ it is stratified, in between it is partially mixed. This ratio is almost the same as the flow ratio of Simmons, but taking the depth and width as a significant variable as well.

According to this calculation for Leonsberg the estuary number is 15, which means that the estuary is well-mixed and not very close to the partially mixed boundary parameter. The estuary number calculated at BEM Paramaribo is even lower as at Leonsberg, namely 10. So the estuary classification should be well-mixed, but the upstream location BEM Paramaribo is more stratified as at Leonsberg.

Stratification number

The stratification number is a measure of the amount of energy lost by the tidal wave within the estuary relative to energy losses of mixing the water column. The stratification number is defined as:

\[ S_e = \frac{0.85 \cdot k \cdot U_0 \cdot L}{(\Delta \rho/\rho) \cdot g \cdot h^2 \cdot u_f} \]  

(4)

- $k$: friction coefficient (=0.001 for mud)
- $L$: estuary length
- $h$: mean water depth
- $U_0$: maximum amplitude of the tidal current
- $u_f$: tidally depth averaged current
- $\rho$: fluid mixture density
The estuary length \( L_e \) is between Braamspunt (km 31) and Afobakka dam (km 194); and \( u_r \) is the tidally depth averaged current or the residual river current.

Values of \( S_r < 100 \) indicate stratified conditions, \( 100 < S_r < 400 \) partially mixed, and \( S_r > 400 \) well-mixed conditions.

The stratification number at Leonsberg is 250 and at BEM Paramaribo it is 600. So at Leonsberg the stratification of the estuary can be classified as partially mixed and at BEM Paramaribo it is well-mixed.

Prandle (1985) also shows by comparison with data that \( \frac{\Delta s}{\langle s \rangle} = 4 \cdot S_r^{-0.55} \), where the angled brackets indicate a tidally depth averaged value, and \( \Delta s \) is the tidally averaged surface to bed salinity difference. For Leonsberg \( \Delta s/\langle s \rangle \) should be 0.19 and for BEM Paramaribo it should be 0.12 according to some estuarine measurement data and flume tests.

**Hansen and Rattray diagram**

Hansen and Rattray have used two dimensionless parameters to characterize estuaries: a stratification parameter \( \Delta s/\langle s \rangle \) and a circulation parameter \( u_r/u_0 \). The main difference with classifications described as above is the need for measurement data in the vertical water column for the Hansen and Rattray classification. The other (flood number, estuary number and the stratification number) mainly use the tidally averaged currents, depth and width to estimate the classification.

The stratification parameter is defined as the ratio of the tidally averaged surface to bed difference in salinity \( \Delta s \) divided by the tidally averaged vertical or cross-sectional salinity \( \langle s \rangle \). The circulation parameter is the ratio of the net surface current during one tidal cycle \( u_r \) to the tidally averaged cross sectional velocity \( u_0 \), which is the same as the residual river current.

The Hansen and Rattray classification diagram is shown in Figure 3.10. Type 1a estuaries have slight stratification and coincide with the laterally homogeneous well-mixed estuary. In type 1b estuaries there is appreciable stratification, but no residual landward bed flow. In type 2 estuaries the flow reverses at depth and corresponds to the partially mixed estuary, the difference between a and b is the same as for type 1. In type 2 both advection and diffusion contribute to the upstream salt flux. In type 3 estuaries the lower layer is so deep that circulation does not extend to the bed, e.g. fjords. Type 4 estuaries have more intense stratification: the salt wedge type.
The data from these measurements have been used to determine the classification of the Suriname River Estuary, however the data had to be slightly adjusted to calculate the average salinities and velocities during 1 complete tidal cycle. The velocity data does not include the direction of the current and therefore it was impossible to know whether a measured velocity was ebb or flood current, which is quite important to calculate the tidally averaged surface velocity and the tidally average bed velocity. The missing data is replaced with a zero velocity, interpolated or extrapolated using the other measured data, also taken into account that the tidal cycle has to be 12 hours and 25 minutes between two slacks of the vertical tide at high water and at low water.

The measurement data and calculated averaged salinities (Figure 3.7 and 3.8) and velocities are visualized in plots which are included as appendix B.

The calculated stratification parameter and the circulation parameter are shown in Table 3.3.

<table>
<thead>
<tr>
<th>stratification parameter</th>
<th>leonsberg km 43</th>
<th>Paramaribo km 58</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;Δs&gt; [%]</td>
<td>0.303</td>
<td>0.019</td>
</tr>
<tr>
<td>&lt;S&gt; [%]</td>
<td>0.5</td>
<td>0.102</td>
</tr>
<tr>
<td>&lt;Δs&gt;/&lt;S&gt; []</td>
<td>0.606</td>
<td>0.19</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>circulation parameter</th>
<th>leonsberg km 43</th>
<th>Paramaribo km 58</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;Δu&gt; [m/s]</td>
<td>0.207</td>
<td>0.07</td>
</tr>
<tr>
<td>&lt;U&gt; [m/s]</td>
<td>0.083</td>
<td>0.042</td>
</tr>
<tr>
<td>&lt;Δu&gt;/&lt;U&gt; []</td>
<td>2.5</td>
<td>1.68</td>
</tr>
</tbody>
</table>

Table 3.3 Stratification-circulation parameters of Hansen and Rattray (1966), calculated with data from measurement campaigns at Leonsberg (1982) and Paramaribo (2007).

The calculated parameters have been plotted in the stratification-circulation diagram as is shown in Figure 3.10. From these two locations it can be concluded that the estuary is appreciable stratified at both locations (type b). The parameters of Leonsberg classify the estuary as a partially mixed estuary (type 2) and the parameters of Paramaribo classify the estuary at the dividing line of a partially mixed/well-mixed estuary (type 1/2).

The stratification-circulation diagram shows a direction of change (Δx) for positions towards the mouth of the estuary. The direction from the Leonsberg parameters to the Paramaribo parameters is not in line with the expected direction according to the diagram.
3.2.5 Conclusions salinity and velocity structure

All four the classifications give different results. The flow classifications (flood number and estuary number) do not take into account the friction of the bed. A sandy estuary has a bed friction coefficient between ten and hundred times higher than a muddy estuary. So the classification, based solely on the flow parameters in the estuary, could be effective if the bed roughnesses of the estuaries are all of the same order of magnitude.

The stratification number does take the bed friction coefficient into account and therefore results in a classification that resembles the qualified classification and the Hansen and Rattray classification as well.

However, the Hansen and Rattray classification results in a higher stratification compared to the stratification number. This could be due to the fact that the Hansen and Rattray classification is based on measurement data. Apparently the stratification (Hansen and Rattray) is higher as is predicted with the stratification number. This could be due to the fact that the high sediment concentrations in the water amplify the salinity stratification.

According to the stratification number this estuary is partially mixed at Leonsberg. At BEM Paramaribo it is well-mixed. This is more or less in line with the qualified classification after Dyer and with the quantified classification from Hansen and Rattray.

According to the Hansen and Rattray diagram the parameters of Leonsberg classifies the estuary as a partially mixed estuary (type 2). The parameters of Paramaribo classifies the estuary at the dividing line of a partially mixed/well-mixed estuary (type 1/2).
The influence of the salinity and velocity distribution on the sediment transport will be discussed in section 3.4.

3.3 Phase of current at bifurcation Suriname and Commewijne River

At a bifurcation of two rivers it is possible that the turning of the tide (horizontal tide) just after at low or high water in one river is different than in the other river. The Suriname River, after slack of the vertical tide at low water, could continue to flow in upstream direction, while the Commewijne River starts to flow in downstream direction or the other way around after slack of the vertical tide at high water. Therefore, two current velocity measurements are compared to analyse the phase difference between the current velocity (horizontal tide) and the tidal elevation (horizontal tide). The two measurements are a measurement campaign at Zoelen in the Commewijne River and a measurement campaign at Leonsberg in the Suriname River. The campaign locations are visualized in Figure 3.11. Both measurement data of water levels and current velocity have been plotted in Figure 3.12.

The measurement campaign at Zoelen was located 4,5 km upstream of the bifurcation point (km 40) of the two rivers and the water level measurement location at Nieuw Amsterdam is located 1 km upstream of the bifurcation point. Therefore, a time difference between the measured water level and the measured current velocity is expected of 8 min (average water depth is 6 m), because it takes the tidal wave 8 min to travel the 3,5 km difference of the measurement location.
The velocity measurement at Leonsberg (km 43) is located 3 km upstream of the bifurcation point (km 40). The water level measurement has been executed at the same location.

At both measurement-campaigns, velocities at three different vertical profiles at several depths were measured. The data has been averaged to estimate a cross-section- and depth-averaged velocity during a tidal cycle as is presented in Figure 3.12.

The time difference between slack of the vertical tide at low water (minimum water level during tidal cycle) and the slack of current direction (horizontal tide) \( (U = 0 \text{ m/s}) \) is 1 hour and 30 minutes at Leonsberg. For Zoelen this difference is 1 hour and 32 minutes when the 8 min are subtracted for the location difference between water level measurement and current velocity measurement.

At the bifurcation of the two rivers, there is a phase difference of 2 minutes for the current velocity according to the available measurement data. 2 minutes compared to 1 hour and 30 minutes is a very small difference and can be neglected.

It is assumed that the water flowing in and out of the Suriname River and Commewijne River is equally flowing in upstream direction and equally flowing in downstream direction according to the measurement data.
3.4 Preliminary sediment transport analysis

Based on the measurement analysis, it is assumed that there is a balance between the sedimentary infilling due to tidal asymmetry, gravitational circulation and the flowing out of sediments due to the instantaneous river current.

Although it appears that the tidal asymmetry and the gravitational circulation in the Suriname River Estuary would cause a tendency to import sediment from the sea, the system has had the chance of importing sediments during previous decades. Apparently, the river discharge is strong and continuous enough to reduce the sediment import and cause the bed level to stay in an alternating equilibrium level.

Tidal asymmetry

Based on the tidal asymmetry, it is to be expected that the tidal movement causes a high instantaneous mud transport landward during the relatively short flood period and a low instantaneous mud transport seaward during the relatively longer ebb periods (visualized in Figure 3.13). Due to the high current velocity during the flood period, more sediment is eroded from the bed than during the ebb period. The higher current velocities during flood period result in higher sediment concentration in the water column, which are transported landward by advection. The lower current velocities during ebb periods result in a lower sediment concentration. However, the longer duration of the ebb period can cause the same amount of sediment transport during an ebb period than a flood period. This means that sediment transport due to tidal dominance during the whole tidal cycle can be:

- in upstream direction (resulting in a bed level increase),
- in downstream direction (resulting in a bed level decrease),
- or in equilibrium when the total transport during the flood period is the same as the total sediment transport during the ebb periods.

The tidal wave starts as a symmetric wave at the Ocean (km 20) and increases its asymmetry until Domburg (km 70) according to the measurements data. The tidal wave is assumed to keep its asymmetric shape further upstream. Whether this also accounts for an asymmetric shape of the current velocity is unknown, since no long term current velocity data is present. Therefore, it is impossible to define the impact of the tidal asymmetry on the sediment transport in longitudinal direction of the Suriname River Estuary.

Whether the Suriname River bed level is alternating around an equilibrium level is hard to prove. According to the measurements from the past 50 years, it seems that the bed level is increasing and decreasing over decades, in spite of the artificial regulation of the Suriname River discharge. The tidal dominance causes a tendency to transport sediment landward
but the residual river discharge causes a tendency to transport sediment seaward. Therefore, the tidal dominance has an impact on the balance of sediment transport. Without the tidal dominance the river would tend to transport sediment seaward, but on the other hand, without the river discharge the river would tend to be filled with mud from the Ocean.

![Diagram of sediment transport due to tidal asymmetry](image)

**Figure 3.13 Schematisation of sediment transport due to tidal asymmetry**
**Stratification**

The stratification of the estuary causes salt gradients between the surface layer and the bed layer, especially between the Ocean (km 20) and Paramaribo (km 54). This results in fluid density differences between surface and bed. Therefore, the lower dense water remains on top of the higher dense water at the bed due to buoyancy. This appears to be amplified by the high sediment concentrations in the water column, because the Hansen and Rattray parameters, calculated with the measurement data, show a higher stratification than the theoretical stratification from Prandle.

For non-stratified flows, the velocity $U$ does not vary strongly in depth, except for the lower part of the water column, close to the bed layer. This does not account for stratified flows, where the velocity can even change its sign (direction) in the vertical profile.

The velocity profile for a stratified flow is described with the following formula:

$$U = - \frac{u_0 \ln \frac{z}{z_0}}{\kappa} + \frac{1}{2} \frac{g \cdot h_0}{\kappa} \left( z - z_0 \right) \frac{1}{\rho} \frac{\partial \rho}{\partial x}$$

where:

- $U$ horizontal flow velocity
- $\kappa$ Von Karman coefficient
- $z_0$ roughness height
- $h_0$ water depth
- $\rho$ bulk density of fluid mixture
- $x$ longitudinal coordinate
- $u_*$ shear velocity
- $z$ vertical coordinate
- $g$ acceleration of gravity
- $\partial/\partial x$ longitudinal density gradient

The first part of the formula describes the well-known logarithmic velocity depth profile. The second part of the formula describes the velocity profile which is mainly defined by the longitudinal density gradient (salt gradient) $\partial \rho / \partial x$. The logarithmic velocity depth profile can change significantly due to the longitudinal density gradients, as is visualized in Figure 3.14.

![Figure 3.14 Schematisation of velocity depth profile due to residual river discharge and longitudinal density gradients](image)

A strong longitudinal density current can result in a residual flow at the bed in landward direction. This residual flow of two separated directions is called gravitational circulation.

If the average sediment concentration at the bed layer is higher than the sediment concentration at the surface layer, the residual flow transports more sediment landward at
the bed than seaward at the surface. In that case, the net transport of the system is thus in
landward direction.

This does not seem to be the case in the Suriname River Estuary, otherwise the river
estuary would have been completely filled with mud. But the longitudinal density gradient,
due to the difference of the salty sea and the fresh river water, causes the velocity depth
profile to be deformed in the section of the salt intrusion (km 20-54). The deformation of
the velocity depth profile is stronger if the density gradient is higher. The fluid density
difference between sea and river water is almost constant at approximately 32 kg/m³.
Hence, the deformation of the velocity depth profile is mainly depended on the length of
salt intrusion ($\Delta x$). During spring tide, $\Delta x$ is larger as during neap tide. This will be
discussed in section 5.2

**Bifurcation phase difference**

Since the current velocities (horizontal tide) of the Suriname River and the Commewijne
River does not appear to have a phase difference at the bifurcation of the two rivers (based
on the two measurement campaigns), it is assumed that the sediment transport capacity has
an equal contribution in and out of the two rivers.

The cyclic processes, such as gravitational circulation, density currents, mixing and tidal
asymmetry, but also erosion, sedimentation and consolidation, strongly affect the sediment
transport.

From the provided the measurement data present, it is not possible to estimate the
sediment transport in the Suriname River Estuary. The tidal asymmetry in relation to
sediment transport needs to be complemented by long term current velocity data. The
measurements of the salt and sediment stratification also should include long term data to
define the stratification during different tidal conditions. The salt and sediment
concentrations should also be measured at several depths in the water column to prove the
concentration differences between the layers in the water column.

To define the sediment transport one could measure the velocities, water levels, discharges,
salt concentrations and sediment concentrations in the Suriname and Commewijne River
for a long period and with small spatially intervals, including precise execution and proper
documentation. The cyclic processes occur all at the same moment in space and time,
making it difficult to distinguish the impact on the sediment transport of each individual
process.

To quantify the sediment transport, all these processes need to be included in model
calculations. Not only because of complexity, but also because of density difference
between surface and bed layer, a computer tool is required to simulate the currents, water heights and sediment and salt concentrations of the Suriname River Estuary. The 3D-computer tool Delft3D is used to simulate the present estuary situation, including the hydrodynamic and the morphodynamic processes in the river estuary.
4 Suriname River Estuary Delft3D model

From the previous chapter it is apparent, that the measurement data alone, is not sufficient to quantify the hydrodynamic and morphodynamic processes in the study area and certainly not sufficient to estimate the morphological development of the river bed. However, analyzing the data resulted in recognizing several hydrodynamic processes, which are potentially dominant for the mud transport in the Suriname River Estuary.

According to the tidal elevation measurements, the estuary seems to be flood dominant between the estuary mouth and Domburg (km 32-70). However, this is uncertain due to the shortcoming of velocity measurement data. According to the measurements, the estuary classification seems to be between partially mixed and well-mixed, resulting in stratification of the velocity and the salt distribution. This probably also accounts for the sediment distribution.

The computer tool Delft3D is used for further analysis of the hydrodynamic and morphodynamic processes, plus the estimation of the morphological development of the present situation and the effect of lowering the fairway.

This chapter is divided 5 sections. Section 4.1 explains why and how the computer model is being used for this study. Section 4.2 summarizes the characteristics of the model that has formerly been made by Alkyon. Section 4.3 describes the approach that is being used to achieve the objectives for this study. Section 4.4 describes the model layout as is used for analyzing the hydrodynamics and morphodynamics. Section 5.5 discusses the morphodynamic processes, which are computed with Delft3D.

4.1 The reason and the way of using the Delft3D model

To qualify the hydrodynamic processes and to quantify the mud transport more measurement data is needed or a tool can assist. Several tools are possible, for instance a physical scale model, a pilot channel in the present fairway of the Suriname River Estuary or several computer tools for simulating the characteristics of the Suriname River Estuary.

For this thesis a computer tool has been used in stead of scale models or pilot dredging. The choice of simulating with a computer tool is made, because it is more accessible for a graduation student than scale modelling or dredging a pilot trench.

Another reason to use the Delft3D computer tool is the fact that a previous study has been executed by engineering company Alkyon. Alkyon developed a 2D and a 3D simulation model for the Suriname River Estuary. The 2D model has been used to simulate the hydrodynamic processes and to estimate the boundary conditions for the 3D morphodynamic model computations. This study will use the 3D model of Alkyon to
analyze the hydrodynamic and morphodynamic processes that take place in the riverine part of the Suriname River Estuary. And this study will quantify the mud transport with a different approach for the morphology.

The computer tool is the Delft3D software, developed by WL Delft Hydraulics. It can simulate hydrodynamic and morphodynamic processes in 3-dimensions and in any chosen time-period. The three dimensions are of major importance due to the stratified conditions of salt and sediment in the estuary causing flow differences between bed and surface and due to the alignment of the estuary causing cross channel flow differences.

To achieve the goal of this thesis, the Suriname River Estuary needs to be simulated to resemble the present situation. As many hydrodynamic and morphodynamic processes are needed to be implemented in the simulation to achieve a simulation which will be comparable with the real-life dynamic river estuary.

For this study the wave module of Delft3D is not used in the simulation. It is expected that in the riverine section of the Suriname Estuary only small waves occur due to wind and navigation. The reason not to use the wave-module is because of the substantial additional calculation time of the computer model.

The model bathymetry and grid is made by Alkyon. The model was calibrated for the tidal elevation, velocities, currents, salt intrusion, river discharges, sediment supply and sediment characteristics. This Alkyon model will be reviewed in section 4.2.

For this study the model has been used to analyze the hydrodynamic and morphodynamic processes. The main objective was to quantify the dominant processes that impact the mud transport.

An attempt was made to simulate the present morphologic situation by trying to obtain an equilibrium sediment transport in time including the high sediment concentrations that occur in the river. The measurement data demonstrate these high sediment concentrations (see subsection 2.7.1).

The next study objective was to quantify the amount of erosion and sedimentation of the present situation and the erosion and sedimentation in the future lowered fairway. Alkyon has already defined the erosion and sedimentation; however this study will review their results and will use a different approach to estimate the mud transport including the behaviour of erosion and deposition of the mud in the riverine section.
4.2 Alkyon model

4.2.1 2-Dimensional model
Alkyon has set up a 2D flow model for the simulation of the tidal regime and a comparison with the existing data. This model simulates the flow regime between the 10 m depth contour (off shore) and 10 km upstream of Pararam and the first 10 km of the Commewijne River. At these upstream boundaries the model was provided with rectangular water buffer area, representing the upstream tidal storage capacities. These rectangular basins were adjusted to calibrate the propagation and attenuation of the tidal wave. At the upstream boundaries of these buffers, the river discharges have been set to an average value for the discharge in the Suriname River and the Commewijne River.

Not only the boundary conditions of the tidal regime of the Ocean were simulated, but also the Guyana current was set as one of the boundary conditions to calibrate the total flow regime of the Suriname River Estuary.

After calibrating the model, the tidal movement has been reproduced quite well however the flow velocities show some difference with the measurements. Apparently upstream of Paramaribo the model seems to simulate the flow velocities too low during flood periods (Alkyon, 2007). The reason for this difference is yet unclear and could not be solved by modifying the model parameters. It does not mean that the flow model is not accurate, the measurements can be inaccurate or the river discharge during the measurements was higher than the average river discharge.

4.2.2 3-Dimensional model
Alkyon also made a 3D model to study the sediment transport and to determine the future sedimentation volume and so the required maintenance dredging in the fairway channel.

The 2D flow model has been used to determine the upstream boundary conditions for the 3D model. The 3D model is modified compared to the 2D model. The grid resolution is larger, the grid cell dimensions are longer and wider, however the grid is distributed in 10 horizontal sigma-layers in stead of 1 (see subsection 4.4.5).

Within the model a mean cohesive sediment fraction is specified with input of a fall velocity. The yearly sedimentation and erosion rate has been calculated from a simulation period of three days using a morphological multiplication factor. The sedimentation and erosion of three days within a spring-neap tidal cycle of 1 month should represent the sediment transport for a full year after multiplying with the morphological factor.
The future sedimentation and erosion because of dredging the fairway channel has been studied with two layouts of the lowered fairway and several dumpsites of the dredged material. The dredged material will be dumped at the shallow bank areas close to the dredged fairway.

The effect of sedimentation and erosion through both layouts is in general small. The water levels are hardly affected; the velocities are only very locally affected. Mainly the deeper fairway channel causes higher depth averaged velocities in the fairway channel. (Figure 5a, b, c and d).

‘The average annual sedimentation volume in the navigation channel between 0 and 90 km is approximately 1.0 Mm$^3$/y for the present situation. Deepening the fairway in the Suriname River (layout 1) increases the annual sedimentation in the channel between km 0 and km 90 with about 400,000 m$^3$/y to a total of about 1.4 Mm$^3$/y.’ (Alkyon, 2007, p.65).

This thesis will use a different approach to study the mud transport of the Suriname River Estuary. The study will try to define the transport processes which are dominant in the Suriname River Estuary and will try to review the Alkyon approach by using different parameters for the calculations. The main difference will be the sediment concentrations, Alkyon focused on the correct simulation of the sedimentation and erosion of the present situation. This study will focus simulating the sediment concentrations as measured and will focus on the hydrodynamic processes such as gravitational circulation, tidal asymmetry, and damped turbulence.

4.3 Approach of adjusting the existing model

First an attempt was made to increase the sediment concentrations in the vertical water column. To increase the sediment concentrations it was thought to do it by excluding the erosion and deposition of the sediment and implementing the effect of the sediment density on the fluid mixture. The sediments are therefore not able to erode during high velocity conditions and not able to deposit during low velocity conditions, therefore the sediments were totally kept in suspension. The effect of the sediment density on the fluid mixture should cause damped turbulence and therefore less mixing hence more stratification of the salt and sediment concentration. The more stratification the larger the effect of gravitational circulation can occur. Due to higher sediment concentration at the bed than at the surface, the residual flow at the bed layer imports (landward) more sediment than the residual flow (seaward) at the surface.
The simulation needs to start with an initial sediment concentration in the water column because the simulation cannot pick up sediment from the bed due to disabled erosion and deposition. The sediments will be transported by currents, turbulence and gravity directly after the start of the computation and distributes through the river estuary according to the hydrodynamic and morphodynamic processes.

At first the results appeared to be very successful, and high sediment concentrations indeed occurred and the cumulative sediment transport seemed to confirm the expected sediment influx at the start of the study area. However through restarting the computations with initial conditions from former computations it appeared that the sediments where all transported outward in the direction of the Ocean.

The simulation period has been adjusted to 15 days, namely a complete spring-neap tidal cycle of 29 tides. The longer simulation period is desired because the computations do not have to be restarted several times before an equilibrium state has been reached and because the spring-neap tidal cycle of 15 days is enables the analysis the sediment transport during spring tidal cycles and during neap tidal cycles. For the three day simulation period the differences between spring and neap tidal conditions could not be analysed.

A longer simulation period did logically not solve the problem of the outward transport of sediments in the direction of the Ocean. Therefore a beta version of Delft3D was used to try to solve this problem. This beta-version is TRANSPOR2004 from Van Rijn. The new general prediction method is severely tested against field data of river and coastal flows, showing reasonable good results. The method is universal in the sense that it can be applied to the full size range of 8-2,000 μm and the full hydrodynamic regime of quasi-steady river and tidal flow and coastal flow. A new simplified transport formula is presented, which can be used to obtain a quick estimate of suspended transport in river and coastal flows. (Van Rijn, 2007, p. 668).

The reason to try the TRANSPOR2004 version was because this version implements the fact that the fall velocity of the sediment increases due to increasing sediment concentration before decreasing due to hindered settling. The regular Delft3D version only takes into account the decreasing fall velocity (hindered settling) due to very high sediment concentrations.

By using the TRANSPOR2004 version it was thought to increase the stratification of the sediment concentration and therefore the sediment transport due to gravitational currents. The fall velocities in the surface layers will increase due to high sediment concentrations and as a result the sediment rains down the water column faster, causing much higher sediment concentrations at the bed layer as at the surface layer.
The TRANSPOR2004 results indeed showed higher sediment concentrations (still not as high as desired) and also the sediments where not all exported into the Ocean on the long term. The reason was not the stratification of sediment concentration, but it appeared that this version calculates its own critical bed shear stress. The critical bed shear stress for erosion and deposition from the regular Delft3D version where overruled by the calculated critical bed shear stress. Therefore the TRANSPOR2004 computations enabled erosion and deposition on the bed.

Enabling erosion and deposition on the bed causes the sediments not to be transported out of the riverine section on the long term. During low velocity conditions the sediments can settle down on the bed not participating in the flow regime, which indeed is the case if deposition is disabled. Keeping all the sediments in suspension causes the sediments to be transported out of the study area because even during low velocity conditions the sediments take part in the flow regime. Due to advection of the fluid mixture, the residual river discharge is transporting the sediments out of the study area into the Ocean.

The TRANSPOR2004 version is not further used to simulate the hydrodynamics and morphodynamics for this study. This version is a beta version and not a commercial version, but more importantly this version calculates the critical bed shear stress for deposition and erosion based on the mean sediment diameter. The fall velocity is also calculated based on the sediment diameter.

Adjusting the sediment diameter affects the critical bed shear stress and the fall velocity. Adjusting the sediment diameter causes implicit changes of two parameters, which causes the calibrating process to be not explicit. Beside, this version calculates only one critical bed shear stress for the whole model area, local adjustments of the critical shear bed stress are impossible.

To keep the calibration process explicit it is decided to use the regular Delft3D version, but enabling erosion and deposition. The sediment concentrations are calibrated through adjusting the critical bed shear stress for erosion and the critical bed shear stress for deposition. This calibrated model will be described in the following section

### 4.4 General layout of model

The grid and bathymetry, the timeframe and boundary conditions, processes, parameters and calibration of the hydrodynamics and morphodynamics have all previously been set and defined by Alkyon. However for this study changes have been made and therefore a summary of the layout of the model is described in this section.
4.4.1 Software

The Delft3D software is developed by WL Delft hydraulics. This world leading computer tool is suited for 2D and 3D computations for coastal, river and estuarine hydraulic flows, waves, sediment transports, morphology changes, water quality and ecology.

For this study the module FLOW (version 3.56.01) has been used. Another version has been used as well, namely TRANSPOR2004 (Beta-version). The Beta version was very useful to understand several hydrodynamic and morphodynamic processes, but its way of computing the critical bed shear stresses was not convenient for further study.

Within the FLOW module the flow and the sediment calculations are coupled. The flow influences the sediment and the other way around.

4.4.2 Processes

With Delft3D it is possible to specify several processes that influence the hydrodynamic and morphodynamic simulation. The processes salinity and sediment are included for this study. It is possible to define several sediments (up to 99) with different sediment characteristics; however in this study only one mean diameter fraction was used.

Other processes such as temperature, pollutants and tracers, wind, waves, secondary flow and dredging and dumping have not been taken into account because their influence is assumed not to be significant for this study.

4.4.3 Grid and bathymetry

The grid and bathymetry has been set up by Alkyon and have not been adjusted for this study model. The resolution of the surveys (survey data from the MAS 2002-2004) is different as the grid resolution, therefore grid cell averaging of the survey data is applied to create depth points at the grid intersection points.

4.4.4 Horizontal grid

The 3D-grid contains rectangular cells varying in width and length per cell. The grid resolution varies between 30 by 30 meters at the fairway alignment, but at the Ocean cells of 200 by 200 m also occur. Figure 5a, b and c visualizes the grid-cells in top view. The maximum amount of grid-cells in M-direction (perpendicular to the fairway alignment) is 119 and in N-direction (along the fairway alignment) it is 279.

4.4.5 Vertical grid

Every horizontal grid cell is divided in 10 layers distributed as sigma layers. The thickness of each layer in each cell is a percentage of the water depth at that location of the grid. Since the water depth is location depended and time depended, the layer thickness is varying in time and place. The distribution of the layer thickness in vertical direction is constant as is presented in Table 4.1.
The layer at the bed is the thinnest and the layer at the surface is the thickest.

<table>
<thead>
<tr>
<th>layer</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>percentage of depth</td>
<td>20%</td>
<td>20%</td>
<td>15%</td>
<td>12%</td>
<td>12%</td>
<td>10%</td>
<td>8%</td>
<td>6%</td>
<td>4%</td>
<td>3%</td>
</tr>
</tbody>
</table>

*Table 4.1 Distribution of grid layer thickness in vertical direction.

4.4.6 Timeframe, boundary and initial conditions

Simulation period

The simulation period (15 days) of the study model is covering a larger period than the Alkyon model (3 days). The disadvantage of a longer simulation period is a much larger calculation time (in stead of ca. 12 hours it is ca. 48 hours). The main advantage is the possibility to analyze the sediment transport during spring tidal condition and during neap tidal conditions.

The simulation period of the study model calculation is set to 15 days covering exactly 29 tidal cycles, including spring and neap. The tidal forcing at the beginning of the simulation is similar as the tidal forcing at the end of the simulation period.

This spring/neap tidal cycle of 15 days repeats itself during the year; however in reality due to some tidal constituents with small frequencies the spring/neap tidal cycle also changes in time, however the effect on the total tidal elevation of these tidal constituents is relatively small. Figure 4.3 visualizes one spring-neap tidal cycle of 15 days followed by a second spring-neap cycle however the period is mirrored. Figure 6 shows measurement data from the station at MAS Paramaribo from the year 2004 day 23 till day 52.

The reference time for the computation is set at 1 January 2001 and the computation period is between 06 January 2001 02:40:00 (hh:mm:ss) and 21 January 2001 04:00:00. The simulation period resembles the 1st spring-neap period in Figure 4.3, including spring and a neap cycles.

The time step is set to 24 seconds, small enough to ensure the numerical stability of the computations.
Boundary flow conditions

At the boundaries of the grid model, flow conditions have been set at the ocean side of the model and at the most upstream side of the model, namely at the Suriname River boundary and at the Commewijne River boundary.

The Ocean side contains a tidal forcing at the north and the west side divided in 5 sections each section with the same tidal constituents but different phases and amplitudes. The tidal forcing is represented using 22 tidal constituents purchased from satellite data. 10 of these tidal constituents have been multiplied with a factor to calibrate the water levels in the 2D model. The 3D model uses the same tidal forcing as the 2D model.

The east side boundary is divided in 4 sections each with a constant current velocity between 0.1 m/s at the coast side and 0.2 m/s at the northern Ocean side. These values for the current velocity have been adjusted in the calibration process as well and seemed to simulate the Guyana current in the best possible way. Without the implementation of the Guyana current the salinity intrusion of the estuary was not simulated as desired.

The boundary condition for the Suriname and Commewijne River is set as a discharge condition specified as time-series. The time-series has been purchased from the 2D model computation. In the 2D model the discharge was set as a constant discharge of 300 m$^3$/s for the Suriname River and 150 m$^3$/s for the Commewijne River.

Boundary transport conditions

At the same boundaries of the grid model as the flow conditions, sediment and salt transport conditions have been set.

The salt transport conditions are the same as for the Alkyon model. At the Ocean boundary there is an influx of water containing a salt concentration of 32 ‰, at the
Commewijne River boundary it is set as 16 % and at the Suriname River boundary it is set as 0.1 %.

The sediment transport conditions of the study model at the Ocean boundary has been set as water influx containing a yearly mean value sediment concentration of 0.2 kg/m³ for all boundary sections. This value is assumed to represent the mean influx of sediment in the model area.

Both river boundary conditions have been set as zero. The sediment transport from upstream is assumed to be negligible. According to the literature hardly any sediments from the landside is transported into the river (river water influx containing a sediment concentration of 0.02 kg/m³ at Suriname River, (Nedeco, 1968)). The main sediments that are transported into the river are believed to be sand particles and not mud particles.

A Thatcher-Harleman boundary condition (described in Appendix C.5) has been set at 180 minutes for all transport boundaries.

Initial conditions
The initial conditions at the start of the computations can be set as a condition file containing water levels, velocities, salinity concentrations and sediment concentrations in every grid cell. The initial file has been created with the output from the 2D model for the velocities, salinities and the water levels at the same simulation time as the start of the 3D simulation.

The sediment concentration of the fluid mixture has been added to the initial file and set to a value of 0.5 kg/m³ for every grid cell.

Another initial condition is a bed layer thickness of 0.1 m, simulating a muddy layer at the bed to simulate a small layer of mud on the bed of the system area with a specified critical bed shear stress for erosion and deposition.

4.4.7 Physical parameters
In Delft3D a number of parameters can be selected which relate to the physical condition of the model area. The most parameters are set as default values such as the physical constants and background viscosity parameters; others have not been specified because several processes are not enabled.

The roughness, the viscosity parameters for 3D-turbulence, sediment and parameters are not set as default values.
Roughness
For this study the Alkyon roughness values from the 3D model have been adapted. The roughness parameter for the 2D model was set at a constant value specified as \( k_r = 0.001 \) m in the White-Colebrook formulation. To calibrate the 3D model Alkyon has adjusted these values to cause more turbulence and hence higher sediment concentrations. \( k_r = 0.003-0.004 \) m for the ocean and river mouth area, \( k_r = 0.001-0.002 \) m for the study area and a higher \( k_r = 0.01 \) m for the upstream part of the study area where the sediment diameter of the river bed is larger.

Viscosity parameters for 3D-turbulence
For a 3D simulation four turbulence models can be selected. This study model uses the k-epsilon model to determine the vertical turbulent eddy viscosity and the vertical eddy diffusivity additional to the background values. The default background values are:

- vertical eddy viscosity and diffusity \( 10^{-6} \) m\(^2\)/s.
- horizontal eddy viscosity is \( 1 \) m\(^2\)/s.
- horizontal eddy diffusivity is \( 10 \) m\(^2\)/s.

Sediment
The following parameters for specific density \( 2650 \) kg/m\(^3\), dry bed density \( 500 \) kg/m\(^3\) and sediment erosion rate \( 10^{-4} \) kg/m\(^2\)/s have been set as default values.

The reference density for hindered settling has been set at a constant value \( C_{gel}=50 \) kg/m\(^3\).

The settling velocity has been set to 0.5 mm/s. This value has not been changed compared to the Alkyon model. It is very difficult to define a general settling velocity, which represents the settling velocity of all sediment diameters and flocculated sediments.

According to some mud modelling specialists such as Dr. Ir. J.C. Winterwerp and Dr. Ir. D.S. van Maren this value seems to be a reasonable value for a mean settling velocity for comparable muddy environments.

During the study process several critical bed shear stresses have been set to enable the sediments to erode and deposit during the tidal cycles. The best value for critical bed shear stress for erosion seemed to be \( 0.2 \) N/m\(^2\) and for critical bed shear stress for deposition seemed to be \( 0.1 \) N/m\(^2\).

The choice and effects of these critical bed shear stresses will be discussed in section 5.2.
Morphology

For this study the bed changes will not be updated during the computations, causing the hydrodynamics not to be affected by eroded and deposited areas in the model.

The effect of the sediment on the fluid density has been included for this study model. Because very high sediment concentrations occur in the Suriname River Estuary this feature is very important for simulating the mud transport. The effect of the sediment density on the fluid mixture will be discussed in section 5.2.

The morphological scale factor is set as 1 in stead of 118. Morphological developments take place on a time scale several times longer than typical flow changes. So a scale factor can be set to represent a morphological development longer than the period of the simulation period. The morphological scale factor is set as 1 to analyse the development of sediment transport during 1 spring-neap tidal cycle of 15 days.

4.4.8 Numerical parameters

The numerical parameters have been set to default values, except for the horizontal Forester filter. The horizontal Forester filter suppresses small negative sediment and salinity concentrations due to adding numerical diffusion.

4.5 Simulating the physical processes in Delft3D

The Delft3D numerical model computes the commonly used 3D hydrodynamic equations. The Delft3D-FLOW manual (WIT/ Delft3D Manual, 2006) describes all equations and assumptions used for the model flow calculations. The way Delft3D-FLOW is being build up with equations and assumptions will not be summarized in this report.

The descriptions of the processes and equations which are evident for this thesis project (defining the sediment transport in the numerical model), have been added as appendix C. A description of the modelled processes is discussed in this section.

Sediment transport

The Suriname River Estuary is assumed to transport the muddy sediments as suspended load. Bed-load transport as loose sediment particles or flocculated particles is not to be expected in this muddy environment. The only form of bed-load transport that is expected to occur, is a density current of fluid mud at the bed. The Delft3D-FLOW module is not able to simulate fluid mud.

The flows, in the modelled area, transport dissolved substances, such as salt and sediments. In Delft3D-FLOW, the transport of these substances is modelled by a three-dimensional
advection-diffusion equation (for sediment transport see appendix C.1). Basically, the computed sediment concentration in the fluid mixture in combination with the computed discharge at every computation grid cell defines the sediment transport. If the sediment concentrations and the fluid discharge are correctly simulated, then the sediment transport should also be correct.

Normally for other sediment studies a sediment transport relation (or equation) is used to simulate the sediment transport (often if the fluid contains coarser sediment, such as sand). That does not hold for the advection-diffusion equation. Simulating muddy environments, like the Suriname River Estuary, commonly uses the advection-diffusion equations, because there is not (yet) a transport relation.

Flocculation

The fall velocity of the sediments is set as a mean value, corresponding to a mean diameter of the flocculated muddy sediments. It is assumed that the sediment particles are flocculated, with particle diameters varying between 2 μm and 300 μm. The exact composition of the flocs is unknown and therefore the choice of a mean value for the fall velocity is the only option for simulating the composition of the flocs in Delft3D.

It is impossible to vary the conditions for flocculation in Delft3D-FLOW. Hence, the effect of salinity and sediment concentrations on the rate of flocculation is not possible to simulate.

It is known that flocculation of muddy sediments in salt water tends to be stronger than flocculation in fresh water. It could be, that the fall velocity of the flocs is higher in salt water than in fresh water. Whether this is the case for the Suriname River Estuary is unknown.

There is no data of flocculation in the Suriname River Estuary, therefore it is impossible to define a relation between the rate of flocculation and the salt content of the water. The lack of knowledge about the rate of flocculation in the Suriname River Estuary is a second reason to choose a mean value for the fall velocity.

The mean value for the fall velocity is therefore simulating a mean composition of the flocs and an average rate of flocculation of the loose sediment particles.

Hindered settling

Hindered settling is a process that is implemented in Delft3D-FLOW. The flocculated sediments rain down the water column due to gravity. The flocculated sediments hinder each other from raining down the water column due to very high sediment concentrations. The weight of a floc on top of another floc causes the water content of a floc to be pushed out in upward direction through the pores, hence causing extra buoyancy of the floc above.
The hindered settling process (appendix C.2) is set as a function of:

- mean fall velocity,
- hindered settling concentration (CSOIL),
- sediment concentration.

Erosion and deposition

Erosion and deposition of the sediments is simulated in Delft3D-FLOW with the commonly used Partheniades-Krone formulations (appendix C.3).

In these formulations the erosion of sediment is a function of:

- a default value of an erosion parameter,
- critical bed shear stress for erosion (see also subsection 4.4.8, sediment),
- the occurring bed shear stress calculated with the hydrodynamic equations.

The deposition of sediments is a function of:

- a mean value for the fall velocity,
- the occurring sediment concentration,
- a relation between the critical bed shear stress for deposition (see also subsection 4.4.8, sediments),
- the occurring bed shear stress calculated with the hydrodynamic equations.

Density of fluid mixture

The effect of the density of sediments on the fluid mixture is included for this simulation model. The sediment content in the fluid mixture causes a higher density of the fluid mixture. The density of the fluid mixture is calculated as a function of the occurring sediment concentration and the difference between the density of water and the density of sediments. (appendix C.4).

Including the effect of the density of the sediments on the fluid mixture enables density currents. Due to gradients of sediment concentrations, 3D turbulence is damped.

The effect of the density of salt particles on the fluid mixture is already included in the hydrodynamic equations.

Model boundary condition for transport

At the boundaries of the modelled area, the transport condition is set as described in section 4.4.6. This condition defines the concentration of salt and sediment on the edges of the simulated estuary. At the boundary of the model area this concentration is the content of the fluid mixture, which flows into the model area. In this way the salt and sediment is
transported in the modelled area. During the outflow of fluid at the boundary, the concentrations of the fluid mixture may be different from the inflowing transport. A smooth transition of these concentrations is set as a Thatcher-Harleman condition. In Delft3D-FLOW a half cosine transition is used. After the return time (180 minutes as described in section 4.4.6), the boundary value remains constant until outward flow begins. (appendix C.5).

Consolidation and settling
Consolidation of the settled sediments cannot be simulated with Delft3D-FLOW. The formation of a cohesive sediment bed is a combination of settling and consolidation processes. The settling and consolidation strongly influences the erodibility of the sediment bed. At low values of the bed shear stress suspended sediments (individual particles or flocs) deposit onto the bed. The weight of the deposited sediment expels the water from the underlying sediment bed, causing the underlying sediment bed to increase in density. The increasing density causes the sediment bed to decrease its erodibility as well. The top layer of the sediment bed is therefore more erodible than the denser layers beneath the top layer. In Delft3D-FLOW it is not possible to set a sediment bed layer with an increasing density in depth.

Another limitation of the simulation of the consolidation process, is the fact that the increasing density of the consolidating sediment bed layer is also time-dependent. If the sediment bed is not being eroded for a longer period of time, this causes an increase of the sediment bed density and hence a decrease of erodibility. In other words, when the flow is not strong enough to erode the top layer of the sediment bed for a long time, then the top layer has decreased its erodibility in contrast with a sediment layer which has just been deposited. Newly deposited sediment will therefore erode more easily.

The study model deals with this limitation by implementing a thin top layer (0.1 m) with a low critical bed shear stress, simulating a thin layer of muddy sediment, which can easily be eroded and deposited. Beneath this thin layer no sediment is available to be eroded.

Section 4.5 summarized:

- Delft3D model includes 3D hydrodynamic equations (including salinity).
- The transport of sediments is modelled by a 3D advection-diffusion equation.
- Due to lack of flocculation data the fall velocity is modelled as a fixed mean value.
- Hindered settling of sediments is included in the simulation.
The modelling of erosion and deposition of the sediments from and onto the bed is included in the simulation, using the Partheniades-Krone equations.

The effect of density of the sediment on the fluid mixture is also simulated.

Consolidation of settled sediments on the bed is not included in the numerical model. The numerical model is unable to set a depth-variable density of the bed. The numerical model is also not (yet) able to simulate the process of consolidation of newly deposited sediment in time.
5 Analyzing model results

Chapter 5 describes the Delft3D model results. Section 5.1 compares the Delft3D model results to the measurement data analysis from chapter 3. Section 5.2 describes the transport capacity of the study area and estimates the relation between the tidal asymmetry, gravitational circulation and the residual river discharge. Section 5.3 discusses the sensitivity of several model parameters on the model results. The final two sections (5.4 and 5.5) describe the present morphologic development and the future morphologic development according to the Delft3D model.

5.1 Compare model results with system analysis

5.1.1 Tidal characteristics

The conclusion of the system analysis for the tidal characteristics is that the Suriname River Estuary is flood dominant based on the long period measurements of the water levels and the short term measurement campaigns of the current velocity at a few locations in the study area.

Because only a few measurement campaigns for the current velocity have been executed, the dominance of the tide will be analyzed with the 3D-model again. The model can simulate the water level close to reality and the current velocities are calibrated close to reality as well. Therefore the water levels and the current velocities can be compared to check whether the earlier conclusion about the tidal dominance can be confirmed or not.

Four locations in the study area (km 41-83) have been analyzed using the Delft3D model results. The discharge, velocity and water level characteristics during spring tidal and during neap tidal conditions of two calendar days are visualized in Figures A1-A4.

Model results

- The duration of falling water (decreasing water level) is taking 1 to 3 hours longer (with an average of 2 hours) than the duration of rising water (increasing water level) in the whole study area for spring tidal conditions and for the neap tidal conditions.
- During a tidal period the water flowing in downstream direction is taking 1 to 3 hours longer (with an average of 2 hours) than the water flowing in upstream direction in the whole study area for spring tidal conditions and for the neap tidal conditions.
- The asymmetry of the tidal elevation (water level) during spring tidal conditions is increasing in upstream direction (Figure 5.1). The asymmetry of the tidal elevation
(water level) during neap tidal conditions is not increasing in upstream direction but constant.

- The asymmetry (difference in length of flood and ebb period) of the current velocity, during spring tidal conditions, is increasing in upstream direction (Figure 5.2). However the increasing asymmetry of the current velocity is reasonable less as for the asymmetry of the tidal elevation. The asymmetry of the current velocity during neap tidal conditions is not increasing in upstream direction but constant.

- During spring tidal conditions the absolute maximum flood current velocities are 10% higher than the maximum ebb current velocities at Leonsberg (km 43) (Figure 5.2). The maximum flood current velocities at Domburg (km 70) are only 2% higher than the maximum ebb current velocities.

- During neap tidal condition the maximum flood current velocities are lower than the ebb current velocities. Amplified with the longer duration of ebb periods it can be stated that the Suriname River Estuary is ebb dominated during neap tidal conditions based on the current velocities for all locations in the study area.

- The highest current velocities of a full spring/neap tidal cycle (15 days) appear during spring at flood periods for all locations in the study area.

- The maximum instantaneous flood discharge at Leonsberg is 35% higher than the maximum ebb discharge (Figure 5.3). The maximum instantaneous flood discharge at Domburg is only 20% higher than the maximum ebb discharge.
The average tidal prism during spring-neap tidal cycle for Leonsberg is 104 x 10^6 m³ and at Domburg it is 56 x 10^6 m³. The share of the river discharge is 6% of the tidal prism at Leonsberg and 12% at Domburg.

- The flood and ebb periods within two serial tidal cycles can differ significantly, because of daily inequality. Mainly the S2 constituent of the tidal elevation is partly causing the maximum elevation of one tidal cycle to be higher as the maximum elevation of the following tidal cycle during that same calendar day. The daily inequality is also influencing the tidal discharge and the depth averaged velocities.

The results from the Delft3D computation confirm the asymmetry of the tidal elevation (water level) from the system analysis in section 3.1.3. However the asymmetry of the current velocity is less pronounced as the asymmetry of the tidal elevation (water level).

The Suriname River Estuary still can be qualified as flood dominated based on the fact that the absolute highest current velocities occur during spring flood, however the assumption that the asymmetry of the tidal elevation results in very high current velocities during flood periods and reasonable lower current velocities during ebb periods does not seem to be true for the Suriname River Estuary.

The erosion of the estuary bed is directly related to the current velocity at the bed layer. It is expected that more erosion will occur during spring flood (higher current velocities) and less erosion will occur during the spring ebb. Therefore more eroded mud is coming in suspension during spring flood as during spring ebb. The higher concentrated fluid mixture will transport the mud land-/inward during flooding, settles down during slack of current direction (horizontal tide) before eroded again through the lower ebb current velocities.

---

3 The S₂ constituent has speed 30 degrees/hour, corresponding to twice the angular speed of the sun across the sky.
The lower ebb current velocities will erode less sediment from the bed and therefore less sediment is brought in suspension and causes a lower sediment transport rate in sea-/outward direction, however during a longer ebb period due to the tidal asymmetry. Especially during spring tidal conditions it can be expected that at the downstream side of the study area (km 43) the net sediment transport is land-/inward. At the upstream side of the study area (km 83) it can be expected that the net sediment transport is in downstream direction, because the peaks of flood current velocities are lower than the peaks of ebb current velocities causing the longer ebb period to be more dominant in transporting the sediments downstream.

The actual effect of the tidal asymmetry on the sediment transport is discussed in section 5.2.

### 5.1.2 Velocity and salinity structure of the vertical water column

The conclusion of the analysis of measurement data for the salinity and velocity structure is that the Suriname River Estuary is quantified between partially mixed and well mixed, based on the Hansen and Rattray parameters.

Only a few measurement campaigns for the velocity and salinity have been executed and the data is not sufficient for averaging over long periods. The Delft3D simulation enables to average the salinity and velocity profiles over a longer period (such as the spring neap cycle of 15 days). The current velocities and the salt concentrations will be analyzed to check whether the earlier conclusion about the velocity and salinity structure can be confirmed or not.

Two locations in the study area Leonsberg (km 43) and BEM Paramaribo (km 58) are analyzed using the Delft3D model results, because these locations resemble the location of the measurement campaigns. The current velocity and salinity characteristics during one spring tidal and during one neap tidal cycle are visualized in Figures B1 and B2

**Model results**

- On average the current velocities in the entire water column at Leonsberg (visualized in Figure 5.4a) are in downstream direction, however in the upper part of the vertical water column, current velocities are higher than in the lower part of the water column. The entire vertical column has a negative value indicating that there is no level of 'no motion' as would be expected for a partially mixed estuary (visualized in Figure 3.5 at subsection 3.2.1). Figure 5.4b visualizes the velocity profile from a computation without salinity process. The different
velocity profile at Leonsberg shows the influence of the longitudinal salt gradients between the high salt content of the sea water and the zero salt content of the upstream fresh water.

- On average the current velocities in the entire water column at BEM Paramaribo are also in downstream direction (visualized in Figure 5.4a), but different from Leonsberg the vertical profile is less stratified, indicating that the tidally averaged (time-integrated) current velocities at the surface and at the bed are a transition stage between the velocity profile of Leonsberg (km 43) and the laterally well-mixed velocity profile of Domburg (km 70) (visualized in Figure 5.4a).

- The salinity characteristics show a considerable difference between the model and the measurements. At Leonsberg tidally averaged salt concentrations have been measured between 3.7‰ at the surface and 6.6‰ at the bed. The model simulates tidally averaged salt concentrations between 8.6‰ at the surface and 9.6‰ at the bed during the whole spring/neap cycle and respectively 6.5‰ and 7.4‰ during the neap cycle (Figure 5.5a). The stratification simulated with the model is smaller as the measurement data indicate. At BEM Paramaribo tidally averaged salt concentrations have been measured between 0.9‰ at the surface and 1.4‰ at the bed. The model simulates tidally averaged salt concentrations between 0.2‰ at the surface and 0.17‰ at the bed during the whole spring/neap cycle.
cycle and respectively 0.4‰ and 0.5‰ during the spring cycle. The stratification simulated with the model is smaller as the measurements and the salt concentrations at the surface are even higher as the bed concentrations averaged over the whole spring-neap cycle.

![Salinity profile diagrams](image.png)

- Figure 5.5a visualizes the tidally averaged salinity profiles from a computation without the effect of sediment density on the fluid mixture. The conclusion from the measurement analysis was that the high sediment concentrations amplify the stratification of the salinity profile. The model results confirm this conclusion. The salinity profiles from Figure 5.5a are more stratified than the profiles from Figure 5.5b.

- The depth averaged salt concentrations at Leonsberg (km 43) including the sediment process are higher as the depth averaged salt concentrations without the sediment process. The high sediment concentrations amplify the salt intrusion.

- The depth averaged salt concentration at Leonsberg according to the model for spring tidal conditions and for neap tidal conditions is higher as the measurement data indicate. The depth averaged salt concentration at BEM Paramaribo according to the model for spring tidal conditions and for neap tidal conditions is lower as the measurement data indicate.
The results from the Delft3D analysis do partly confirm the conclusions from the system analysis. According to the model results the Suriname River Estuary can be qualified as a well-mixed estuary at Leonsberg based on the Hansen-Rattray parameters like in subsection 3.2.4 in stead of partially mixed according to the measurement data analysis. But, the sediment concentrations in the Suriname Estuary indeed amplify the salt stratification at Leonsberg.

Several reasons for this difference can be thought of:

- The measurement campaign interval of measuring the current velocities and the salt concentrations are of the order of hours. The calculated Hansen and Rattray parameters are tidally averaged and therefore time-integrated values. The larger the time interval the more inaccurate these time-integrated values can be. The measurement campaign is also covering only one tidal period at random in the spring neap tidal cycle of 36 days. The conditions during that specific tidal cycle can differ from the long term averaged values.

- The Suriname River discharge during the day of the measurement campaign could be different from the mean Suriname River discharge of the model. A higher river discharge during that specific day could lead to lower salt concentrations affecting the calculated Hansen-Rattray parameters.

- The calibration of the salt concentrations in the Delft3D model could be incorrect; however it seems according to appendix D1 that the salt intrusion of the model in longitudinal direction of the estuary is in line with literature knowledge and measurements.

- The calibration of the salt concentrations in vertical direction should be executed as well. Since no long term data of the vertical salinity is present, it is not possible to calibrate the vertical salinity profile.

The gravitational circulation according to the Delft3D model results is less dominant as was assumed due to the results from the measurement data and the Hansen and Rattray diagram. The tidally averaged velocity at Leonsberg (Figure 5.3) shows a reasonable difference between the surface velocity and the bed layer velocity, but not resulting in a land- / inward current velocity at the bed as would be expected for a partially mixed structure (Figure 3.5). Nevertheless the presence of gravitational circulation at Leonsberg weakens the sediment advection due to the river current in sea- / outward direction at the bed where the sediment concentrations are reasonably higher as at the surface.
The tidally averaged velocity at BEM Paramaribo (Figure 5.3) does not show a reasonable difference between the surface velocity and the bed layer velocity, confirming the behaviour of a well-mixed structure (Figure 3.6). Therefore it can be assumed that gravitational circulation does not reach the location Domburg (km 70).

The tidally averaged currents appear to be influenced by the salt and the sediment concentrations and gravitational circulation occurs in the study area. The numerical effect of the gravitational circulation on the cumulative sediment transport is hard to separate from the other processes such as tidal dominance and residual river discharge. The Delft3D model computes the sediment transport including all these processes as will be discussed in section 5.3.

5.2 Sediment transport capacity analysis

Before the sediment transport of the Delft3D computations will be analyzed it is believed to analyze the transport capacity of the hydrodynamic model results first. Estimating the transport capacity clarifies the impact of the tidal discharge, river discharge and the current velocities on sediment transport through the study area. This transport capacity does not take into account the longitudinal density gradient and thus no gravitational current transport. The transport capacity is only fulfilled if a continuous supply of sediment in the fluid mixture is present due to erosion of the bed layer. If no sediment is present at the bed to be eroded, than the transport capacity is not fulfilled. In that case the actual transport capacity is less than the sediment transport capacity.

The sediment transport computed by the Delft3D model is mainly due to advection of the sediment in the fluid mixture. In other words; the fluid mixture including a certain sediment concentration is flowing in and out of the river estuary. Therefore the discharge through every computational cell times the sediment concentration at the same time and place in the water column defines the sediment transport in kg/s.

In reality the fluid mixture residual discharge and the residual sediment concentrations are not evenly distributed over the vertical water column as is shown in Figure 5.6a and 5.6b causing the sediment transport also not to be evenly distributed over the water column.
To define sediment transport due to the tidal asymmetry and the residual river discharge excluding the longitudinal density gradient, the cross-section discharge has to be multiplied by a depth averaged sediment concentration \( \bar{c} \).

The carrying capacity of a turbulent flow laden with noncohesive sediment is different as the carrying capacity of the flow laden with cohesive sediment. The noncohesive sediment deposit grains during calm flow conditions, form a rigid bed immediately, at which full turbulence production is possible. The cohesive sediments deposit as flocs, forming a fluid mud layer onto the bed, because of the floc's high water content. Thus a two layer fluid system develops in which the lower layer is the denser one. The higher density of the lower layer decreases the turbulence, and damping of the vertical mixing occurs, decreasing the carrying capacity. Thus the concentrations profile, referred to as the saturation concentration \( C_s \) (Winterwerp, 2006).

A relation for the saturation concentration \( C_s \), which is the depth-averaged value of the local saturation concentration \( c_s \), was derived (Winterwerp, 2001):

\[
C_s = \frac{1}{h} \int c_s dz = K_s \frac{\rho}{\Delta g h w} U^3
\]

Figure 5.6a Computed (T525c) tidally averaged (15 days) discharge depth profile at Leonsberg (km 43)

Figure 5.6b Computed (T525c) tidally averaged (15 days) sediment concentration depth profile
Therefore a sediment capacity of the fluid mixture is solely based on a theoretical relation between discharge \((Q)\) through a cross section of the river and the depth averaged current velocity \((U)\). A very simplified relation \(S = Q \cdot c \cdot Q \cdot U^3\) approximates the sediment transport capacity \((S)\) through a cross section.

The transport capacity analysis is not aiming for an estimation of the sediment transport. The Delft3D model already computes the sediment transport in three dimensions including the morphodynamic processes as mentioned above. However the theoretical transport capacity will demonstrate the capacity of the flowing water transporting sediments in or out of the study area. The capacity indicates whether the currents through a cross section have a tendency to import or export sediments during the simulated spring-neap cycle of 15 days.

The theoretical instantaneous transport capacity based on the hydrodynamic model results have been plotted in the upper graph of Figures C1 till C5 for five cross sections, namely Leonsberg (km 43), MAS Paramaribo (km 51), BEM Paramaribo (km 58), Dijkveld bank (km 62) and Domburg (km 70) indicated in Figure 5.7.
The time integration of the instantaneous transport capacity has been plotted in the lower graph of Figures C1 till C5 and equals the cumulative sediment transport capacity. For the cross section of Leonsberg (km 43) the transport capacity is plotted in Figure 5.8.

An increasing cumulative sediment transport indicates a net sediment land-/ inward capacity through the cross section and a decreasing cumulative sediment transport indicates a net sediment sea-/ outward capacity through the cross section. In both graphs the sediment transport direction for a positive value is upstream (landward) and for a negative value it is downstream (seaward).

The sediment transport capacity of the Suriname River Estuary system indicates to import sediments (landward) during spring tidal conditions and export sediments (seaward) during neap tidal conditions in the entire study area. The sediment transport capacity confirms the conclusions on the tidal dominance. During spring tidal conditions the flood dominance causes an increasing sediment transport and during neap tidal conditions the ebb dominance causes a decreasing sediment transport. The cross section at Leonsberg (Figure 5.8) is the only cross section which indicates to net import (landward) sediment into the study area, due to a higher cumulative sediment import (landward) during spring tidal conditions as the cumulative sediment export (seaward) during neap tidal conditions.

The other cross section also indicate to import (landward) sediment during spring tidal condition, however the ebb dominance during neap tidal conditions causes a higher cumulative sediment export (seaward) indicating a net export (seaward) of sediment out of
the upstream section. For example cross section at BEM Paramaribo (km 58) is visualised in Figure 5.9.

Whether the cross sections actually are importing or exporting sediment is dependent on the supply of sediments. If there are no sediments in suspension or on the bed to fulfil the capacity, the flowing water is unable to import or export the sediment.

The transport capacity of the system indicates that the supply from Ocean side of the system is plausible if there is enough supply of sediments and could cause a net import of muddy sediments into the study area due to the flood dominance into the study area.

5.3 Morphodynamic modelling of the study area

The modelling of the Suriname River Estuary with the Delft3D computer tool was a process of adjusting the model parameters and model processes to achieve the simulation of the sediment transport according the present morphology of the Suriname River Estuary.

The impact of these model parameters on the simulation of the sediment transport is discussed in this section.

5.3.1 Effect of critical bed shear stress on the cumulative transport

According to the measured sediment concentrations described in section 2.7.1 very high concentrations (in the order of 10-15 kg/m³) can occur in the water. The sediment concentrations in the vertical water column are induced by the erosion of the sediments from the bed due to turbulent current velocities. Apparently the muddy bed is easily eroded by the turbulent current velocities causing the high sediment concentrations.

To simulate the measured sediment concentrations of the same order of magnitude, the critical bed shear stress for erosion is set as 0.2 N/m² and the critical bed shear stress for deposition is set as 0.1 N/m². The tidally mean sediment concentrations according the simulation results resemble the mean sediment concentrations in longitudinal direction of the study area visualized in Figure 5.10a and D1.
The computed tidally averaged bed shear stresses (Figure 5.11) are higher than these critical bed shear stresses, except for the shallow banks and the shallow river boundaries. Only during the moment of changing the flood current into the ebb current (depth averaged velocity is zero) and the other way around, the computed bed shear stress is lower than the critical bed shear stresses (Figure 7a). The maximum computed bed shear stresses are very high and can even reach values of 3 N/m² (Figure 7b and c), during slack of the vertical tide at high water and during slack of the vertical tide at low water, when the current velocities also reach the maximum value.

![Image of bed shear stress distribution](image)

**Figure 5.11:** Tidally averaged (15 days) computed bed shear stress [N/m²]

The maximum sediment concentrations do not resemble the maximum measured sediment concentrations (Figure D1). In reality, the top layer of the bed will erode more easily than the model simulates. Apparently, the top layer of the muddy bed has a lower critical bed shear stress than is chosen for in the model. A small layer of loosened mud due to bioturbation (observed by Nedeco and Heuvel, see end of section 2.1.2), could clarify the
extremely high mud concentration, which occasionally occur in the water. The bed shear parameters have not been set lower, to increase the maximum sediment concentrations.

Due to consolidation, the strength of the bed is variable; the top layer of the bed is less consolidated than the sediment layer underneath the top layer. The density of the bed is increasing in depth. From the top layer the density increases to a certain maximum, until consolidation of the muddy sediment also has reached its maximum. The lower density at the top of the bed layer is enabling the sediment to be eroded more easily than the underlying layers with higher densities. Delft3D is unable to set a parameter to simulate the variable consolidated bed strength.

The variable strength of the bed in depth had to be simplified, by simulating two layers. One layer of sediment (0.1 m) lies on top, with 1 value for the critical bed shear stress of erosion and deposition and a layer without sediment, with a very infinite high strength to erosion. The top layer simulates the fluffy mud layer and the lower layer simulates an extremely consolidated clay bed.

Of course a model including the option to simulate the variable bed strength is desired, but such a model is not available yet.

Higher parameters for the critical bed shear stresses result in mean sediment concentrations too low compared to the measured concentrations and the maximum sediment concentrations do not even come close to the maximum sediment concentrations as have been measured. For example, the tidally averaged sediment concentration of run T533 (critical bed shear stress for erosion is 0.6 N/m²) is visualised in Figure 5.10b.

![Comparison between measured and computed (T533) mean sediment concentration in longitudinal direction](image)

The higher sediment concentrations in the water column due to the lower critical bed shear stress result in higher instantaneous sediment transport during the tidal cycles as is visualised in Figure 5.12. Both simulations (T524b and T533) show a cumulative sediment transport landward, but this is overestimated because of the initial sediment layer of 0.1 m.

The effect of this initial layer is discussed in section 5.3.3.

Eventually, the instantaneous sediment transport is simulated correctly using the lower critical bed shear stresses for erosion and deposition (0.2 N/m² and 0.1 N/m²).
5.3.2 Effect of sediment density in the fluid mixture on the cumulative transport

Within Delft3D-FLOW it is possible to enable the effect of sediment density on the fluid mixture. The reason to enable this option within Delft3D is the presence of very high sediment concentrations in the fluid mixture. The sediment concentration cause an increase of the fluid mixture density, which damps the turbulence (less mixing) thus amplifies the stratification of salt and sediment concentrations and amplifies the gravitational currents.

The cumulative sediment transport, including the sediment density effect (run T524b) is compared to a cumulative sediment transport, without the density-effect (run T526) reasonable different (Figure 5.13). The simulation without the density effects (T526) results in a net seaward transport of sediments out of the study area. The simulation including the density effects (T524b) results in a net landward transport of sediments into the study area with sediments originating from downstream side of the system (Ocean side).

The high sediment concentrations impact the 3D turbulence in such a way, that the higher fluid mixture density causes damping of the turbulent flows. This means that mixing of the sediments through the water column is less than without the density effects. The decreased mixing causes the sediment stratification to be higher, resulting in higher sediment concentrations at the bed than at the surface layers. This was already visualised in Figures 5.5a and 5.5b.
Without the density effect on the fluid mixture the sediment concentrations are less stratified and the residual river discharge causes the sediment to transport out of the study area.

The effect of the sediment density on the cumulative transport is decreasing in more upstream direction (visualized in Figures F1 till F6). This is due to the decreasing mean sediment concentrations. The higher the sediment concentrations the more impact the density effect has on the on the cumulative transport.

It appears from the model computations, that the density of the fluid mixture due to the sediment is important for the sediment transport in the study area (km 43-83).

![Cumulative transport at Leonsberg km 43](image)

**Figure 5.13** cumulative sediment transport at Leonsberg (km 43); difference in- and excluding sediment density effect

### 5.3.3 Effect of salinity in the fluid mixture on the cumulative transport

When the process salinity is disabled, the computation does not involve the salinity concentrations, thus the density due to the salt concentrations is not affecting the fluid mixture, as the other computations including salinity.

The effect of the salinity concentrations on the cumulative transport resembles the effect of disabled sediment densities on the fluid mixture. However the decrease of salt concentrations in the study area in longitudinal direction is stronger as the decrease of sediment concentrations.

The salt concentrations at MAS Paramaribo (km 52) and BEM Paramaribo (km58) and further upstream are too low to affect the density due to the salt concentrations.

Between Leonsberg (km 43) and MAS Paramaribo (km 52) and of course downstream of the study area where the salt concentrations are even higher, the high salt concentrations...
affect the mixing of the fluid mixture and the gravitational current and therefore the cumulative sediment transport as well (Figure 5.14).

![Figure 5.14 cumulative sediment transport at Leonsberg (km 43); difference in- and excluding salinity effect](image)

Figure 5.14 cumulative sediment transport at Leonsberg (km 43); difference in- and excluding salinity effect

It appears from the model computations, that the salinity is important for the sediment transport in the study area (km 43-83).

### 5.3.4 Effect of Suriname River discharge on the cumulative transport

An increased river discharge in the Suriname River causes the cumulative sediment transport to decrease at every cross section in the study area (visualized in Figures F1 till F6). The residual outflow due to an average river discharge of 500 m³/s (T528) causes the study area to become a sediment exporting system (seaward), compared the importing (landward) sediment transport of simulation T524b (Figure 5.15).

![Figure 5.15 cumulative sediment transport at Leonsberg (km 43); River discharge of 300 and 500 m³/s](image)

Figure 5.15 cumulative sediment transport at Leonsberg (km 43); River discharge of 300 and 500 m³/s
Therefore the impact of variable river discharge is not to be neglected for the long term cumulative sediment transport. A mean river discharge of 500 m³/s is not expected to occur in the Suriname River as is described in section 3.2, however during the year 1972 and 1976 a mean river discharge at the Afsbakka dam of 420 m³/s has been measured.

The sediment concentrations in the vertical water column during the spring-neap tide cycle are hardly affected through the higher river discharge. On contrary, the salt concentrations are affected through the higher residual river discharge and thus the supply of fresh water from upstream direction. The higher discharge of fresh water from upstream causes the salt concentration to decrease. The fresh water pushes the salt front in downstream direction. Therefore not only the residual river discharge is exporting the sediment out of the study area (seaward), but the gravitational current, driven by the longitudinal density gradient, is also shifted in downstream direction.

5.3.5 Effect of sediment supply from Ocean boundary on the cumulative transport

A lower sediment supply from the Ocean east side boundary does not have impact on the cumulative sediment transport. The sediments importing at the Ocean boundary are not directly transported into the estuary mouth, but are deposited at the bed of the Ocean or at the shallow bank in front of the estuary mouth (Vissersbank). After deposition on the bed the sediment is picked by strong tidal currents and then transported in and out of the study area. The sediment supply from the Ocean impacts the cumulative sediment transport on the long term, if the supply is not enough to keep that small layer of erodible sediment at the bed of the Ocean in front of the river mouth. But these simulation runs (15 days) are too short to define the impact of sediment supply due to the Guyana current.

5.3.6 Effect of initial conditions on the cumulative transport

The simulation run (T524b), starting with the initial sediment layer thickness of 0.1 m in the entire model area (Figure 5.16a), causes very high instantaneous sediment transport (Figure 5.17) due to the very high supply of sediments from the bed of the river.
Just downstream of the study area between Braamspunt (km 32) and Leonsberg (km 43) the computed (T524b) high current velocities caused this area to be entirely eroded, except for the shallow river boundaries. This means that the initial sediment layer thickness of 0.1 m has almost been completely washed away, exposing the non erodible bed layer underneath the initial sediment layer.

Apparently, the bed shear stresses in the estuary mouth (km 32-43) and in the two sharp bends (Leonsberg km 43 and Paramaribo km 54) are high enough to wash away the 0.1 m sediment layer during whole spring and neap tidal cycle of 15 days. The critical bed shear stress for erosion of this muddy layer is low, therefore at these locations erosion of the top layer prevails.

The shallow sections of the study area, where the current velocities are less pronounced, collect the sediments due to the deposition of the sediments (Figure 5.16b).

As is stated before, the actual distribution of the variable bottom strength is unable to be simulated with the Delft3D-FLOW module. But the computed sediment bed layer thickness (Figure 5.16b) after 15 simulation days including springs and neaps, reveals which areas of the bed are more liable to erosion than other parts. The areas which are completely eroded, represent a bottom with a higher strength to erosion, such as strongly consolidated clay. And the areas which are accreting sediment, represent a bottom with fluffy mud on the bed and maybe even with fluid mud on the bed. It is assumed that the computed sediment layer thickness (Figure 5.16b) represents the bed layer as in reality.

The established sediment layer thickness after 15 days (Figure 5.16b and 5.17a) is used to restart the simulation (T525c).
Due to the erosion of the area between Braamspunt (km 32) and Leonsberg (km 43) not enough sediment is present on the bed of the channel to fulfil the sediment transport capacity. This causes not enough availability of sediment on the bed at the beginning (downstream) of the study area. The cross section at the beginning of the study area (Leonsberg km 43, Figure 5.18) is no longer importing (landward) sediment during spring tidal condition.

The initial sediment layer of 0.1 m is providing enough sediment at the bed to fulfil the transport capacity, resulting in a landward transport of sediment. However the bed layer of 0.1 m with the low critical bed shear stress is in reality not present in the areas as previously stated. Therefore the simulation of the present situation (T525c) uses the computed sediment bed layer thickness after 15 simulation days as the initial condition for bed layer thickness.
Wave-action at the Ocean is not taken into account for in this thesis project, but could be a cause of mixing sediment in the fluid mixture at the mouth of the estuary resulting in higher sediment concentrations in the fluid mixture at the mouth of the estuary.

Implementation of the Delft3D-WAVE module is possible; however it doubles the computation time. Since the Delft3D-FLOW computation already takes 48 hours it was decided to simulate the mixing of the sediments in Delft3D-FLOW module.

The mixing is simulated by disabling deposition of sediments in the Ocean area of the model. The critical bed shear stress for deposition is set to an infinite high value at the estuary mouth (run T542).

The model results show, that for this run, the cumulative sediment transport at the beginning of the study area is in equilibrium over 15 simulation days (Figure 5.19). During spring tidal conditions there is an export (seaward) of sediment and during neap tidal conditions there is an import (landward) of sediment and for the whole spring neap tidal cycle no import or export of sediments after 15 days.
It is believed, that this run (T542) simulates the yearly averaged sediment transport in the Suriname River Estuary.

- The run simulates a balance of sediment import and export alternating around an equilibrium level (Figure 5.19).
- The computed mean sediment concentrations are comparable to the measured sediment concentrations (Figure 5.10).
- The cumulative sediment transport of 1 flood period, during a spring tide, is approximately 55,000 m$^3$ (dry sediment). The cumulative sediment transport of 1 flood period, during neap tide, is approximately 10,000 m$^3$ (dry sediment). The simulated amounts of sediment transport (approximately 40% higher) are comparable to the amounts defined by Nedeco (1968), as is described in section 2.7.2.

However, during a year and during decades of years, situations can occur differently from the yearly averaged computed sediment transport. For instance:

- The fluctuation of the discharge; a large river discharge causes a net seaward sediment transport and a low river discharge a net landward sediment transport.
- The wave-action is weather related; extremely high wave-action causes extra mixing of the sediment in the fluid mixture at the mouth of the estuary causing a net landward transport of sediments. For calm wave conditions the net sediment transport is more seaward.
- The sediment supply from the Ocean side, depended on the passing mud bank, can increase causing a net landward sediment transport.
- The critical bed shear stress can increase due to decreasing ship movement in the fairway channel, causing consolidation of the mud layer. The consolidated mud is
less liable to erosion and tends to remain in the artificial fairway channel until a new equilibrium of sediment transport is reached. Eventually, the sediment transport will decrease, because the ships will not loosen the mud layer on the bed. The mean sediment concentration of the water will decrease.

The computed sediment transport (T542) of the present situation is in balance. The processes causing its balance are discussed in the following subsection.

5.3.7 The simulated cumulative transport compared to the transport capacity

According to the Delft3D model results it is clear that the effect of the sediment and salt density on the fluid mixture in the Suriname River Estuary is important for the cumulative sediment transport. The four most important processes that influence the cumulative sediment transport are:

- Tidal asymmetry (between km 32-83)
- Gravitational circulation (between km 32-54)
- Damped turbulence (entire area)
- Residual river discharge (entire area)

The tidal asymmetry causes a net landward sediment transport, but only if enough sediment is provided to bring the sediment from the bed in suspension. The computed depth averaged sediment concentrations at Leonsberg (Figure 5.20) show a high sediment concentration during ebb periods but a lower sediment concentration during flood period. This opposes the theoretical saturation concentration (Figure 5.21) showing a high sediment concentration during flood period and a lower sediment concentration during ebb period.

Figure 5.20 Computed depth averaged sediment concentration at Leonsberg (km 43)
Therefore, the cumulative sediment transport (Figure 5.22) based on the theoretical saturation concentration is overestimated. The theoretical cumulative transport shows a net sediment landward transport during spring tides and a net sediment seaward transport during neap tides. The model computation shows an opposite cumulative transport during spring tides and neap tides (Figure 5.24).
The simulation of the present situation includes the four most important processes. The damped turbulence due to the density gradients within the fluid mixture causes stratification of the sediment concentrations (see Figure 5.5a and 5.5b). The longitudinal density gradient of the salt gradient causes deformation of the velocity depth profile (Figure 5.4). The combination of the stratified sediment concentrations and the deformed velocity depth profile results in gravitational circulation. The tidal asymmetry tends to import sediment during spring tides and tends to export sediment during neap tides (Figure 5.22), but only if enough sediments are present on the bed to be eroded by the current velocities. The residual river discharge tends to export the sediment seaward due to advection of the fluid mixture (Figure 5.15).

These processes are simulated within the model, resulting in a balance in sediment transport during one spring neap cycle of 15 days, but it was not succeeded to separate the impact of the sediment transport of each individual process. The following sections describe the morphology of the present situation.
5.4 Erosion and deposition of the present situation

In the present situation of the river estuary no extreme variations in bathymetry occur. The bed level seems to be quite stable based on the historic survey data as discussed in section 2.2.

The fairway channel is believed to be created by the passing vessels, causing turbulence at the bed and preventing the bed sediments to consolidate. The unconsolidated mud at the bed of the fairway channel is therefore more liable to erosion than the surrounding river bed, creating the artificial navigation channel.

In Figure 5.24 (run T542) the sedimentation and erosion of the Delft3D study model after 15 days is presented.

Most of the sedimentation occurs at the shallow zones along the boundaries of the Suriname River. The shallow zones comply with the river banks like Vissersbank, Resolutie bank, Jagtlust bank and Dijkveld bank.

The Delft3D model seems to simulate a realistic sedimentation and erosion pattern like Alkyon also concluded in a previous study.

This thesis project enabled to qualify the sediment transport processes. The combination of gravitational circulation and tidal dominance cause an inward sediment transport and at the same time the residual river discharge causes a sediment transport in outward direction. These sediment transport processes seem to be in balance, amplified with the fact that the bed level of the river channel can be stated as stable (especially within 15 days).
Therefore, it is assumed that the sedimentation on the shallow river banks cannot continuously deposit sediment, otherwise these shallows would tend to become reclaimed as land and the river would become narrower.

The present morphology of the river estuary is not narrowing; therefore it is believed that the deposits in the shallow areas accumulate as an emulsion, called fluid mud. The fluid mud disperses as a density current over the whole width of the river and settles in the deeper fairway channel.

This also explains the erosion pattern of the Delft3D model. According to the simulation, the deeper sections around the navigation channel tend to erode due to strong tidal currents. However, erosion is not expected, because the bed level of the current estuary seems to be in a stable level, especially within 15 days.

Since fluid mud is an emulsion of mud with a high viscosity it is resistant to strong currents before the fluid mud is eroded. The fluid mud can resist the strong current in the deeper section. This could be a reason why the deeper sections do not erode further as would be expected based on the high bed shear stresses due to tidal currents.

Unfortunately it was unable to simulate the fluid mud behaviour with the Delft3D-FLOW module.
5.5 Erosion and deposition due to lowering of the fairway

Not only the present situation is simulated, but one of the future lowered fairway channel layouts is simulated with the model as well. The layout of this channel is according to the conceptual design of the new channel as generated by Lievense (Lievense, 2007a). In Figure 5.25 the differences between the present situation and future layout is presented.

The channel layout includes the lowering of the fairway channel at places where increasing of the navigable depth is needed, but also three dumping sites, namely at the Ocean side (west side of the navigation channel), at the river boundary of Jagtlust bank and at the river boundary of Dijkveld bank.

The previous study of Alkyon studied the hydrodynamic effects of the channel layout and concluded that the effect of the channel layout in general is small.
The tidal elevation along the river trajectory does not change significantly (< 0.01 m) (Alkyon, 2007).

The effect on the current velocities is also relatively small with an increase of velocities (in the order of 0.1 m/s) along the lowered sections and a decrease of velocities on the adjacent shallow sections (Alkyon, 2007).

The sedimentation in the fairway channel due to the lowering of the fairway channel according to the Delft3D study model results is relatively small. According to the model results (Figure 5.28) only very small amounts of maintenance dredging are required to keep the bed of the fairway channel on the required navigable depth.

The sedimentation at km 53 and at km 67 is even located in a deep section of the fairway channel, meaning no maintenance dredging is required until the sedimentation reaches a certain level, above the required navigable depth.

The model does not show a significant increase of sedimentation due to lowering the fairway channel.
The erosion in the fairway channel due to the lowering of the fairway channel according to the Delft3D study model is less as for the present situation. Less erosion due to a lower bed level could be caused by lower bed shear stresses at the bed due to the increased depth, despite increased depth-averaged current velocity at the fairway channel zone.

As stated before in section 5.4 erosion is not expected in the fairway channel because the bed level has been stable for the last decades.

The sedimentation and erosion pattern of the future layout (Figure 5.29) is comparable to the sedimentation and erosion pattern of the present situation (Figure 5.24). The shallow section tends to deposit sediments and the deeper sections around the navigation channel tend to get eroded. This is what the study model computes but does not comply with the fact that the bed seems to be quite stable, as was stated for the present situation the previous section 5.4.

![Figure 5.29 Sedimentation (positive) and erosion (negative) pattern of future situation after 15 days computation (run T543).](image)

The difference between the sedimentation and erosion pattern in the study area due to the lowering of the fairway is presented in Figure 5.30.

Due to lowering of the fairway the Delft3D model computes sedimentation at the beginning and end of the two dumpsites located in the study area.

This sedimentation is extra on top of the sedimentation that occurs at these shallows in the simulation of the present situation.

As explained in section 5.4 it is believed that the deposited extra sediment in these shallow zones could accumulate as fluid mud at the bed and will spread out over the entire width of the river as a density current.
If this is the case the eroded deeper sections could be filled with this fluid mud causing the bed level of the system to maintain its current level.

Figure 5.30 Sedimentation (positive) and erosion (negative) difference between present situation and future situation
6 Conclusions and recommendations

6.1 Conclusions

Due to the construction of the Afbakka dam, the bed level of the river estuary seems to have risen; however the last two decades show a decrease of the bed level indicating that the regulation of the river flow at the dam is no longer causing the bed level to increase. The upper 2 m layer of the river bed and the estuary bed consist of mud until km 62. A transition zone of sandy mud is present between km 62 and km 85. A sandy/gravel bed is present more upstream from km 85. The presence of mud in the upper layer of the bed until far upriver (km 62) indicates the system to be a mud importing system since no indication of upstream mud supply is present and more than enough mud is present at the Ocean side of the system.

The long term water level measurements indicate an increasing asymmetry of the propagating tidal wave (sine shape) in upstream direction of the Suriname River. The asymmetry of the tidal wave results in short flood period and thus long ebb periods. The amount of water flowing in the system during flood period as the same as the amount of water flowing out of the system during ebb period, however during a shorter time period. It is expected that the discharge and current velocities during the shorter flood periods are reasonably higher as during the ebb periods. The average water level during the flood period is higher than the average water level during the ebb period causing the water to flow through a larger wet surface during flood period affecting the current velocity. Therefore it is not possible to assume the system to be flood dominated based on the water level elevation.

Since no long term current velocity data is present, the Delft3D software was used to analyse the tidal dominance. The Delft3D model simulation confirmed the tidal asymmetry based on the water level elevation but the expected high current velocities during flood periods seem to be less dominant as was expected.

The absolute maximum current velocity during flood period at the beginning of the study area is 10% higher as the absolute maximum current velocity during ebb period, indicating flood dominance based on the current velocities. The difference between the maximum flood currents and ebb currents decreases linearly to zero at upstream end of the study area, indicating that the flood dominance in upstream direction is fading away. During neap tidal conditions the system becomes even ebb dominated since the maximum ebb currents are higher than the maximum flood currents in the same tidal period.
The measurement campaigns including the measured velocities and salt concentrations indicate the system to have a velocity/salinity structure between well-mixed and partially mixed and both campaigns show high salt stratification. The measurement data even indicate to be more stratified as would be expected according to the theoretical defined stratification, indicating an enhanced stratification due to the presence of very high sediment concentrations in the water column.

The measurement data for the velocity/salinity structure is not sufficient enough to determine a tidally averaged and long term averaged velocity/salinity structure; therefore the Delft3D model has been used to analyse the structure.

The results from the Delft3D model simulation do not confirm the conclusion from the system analysis. According to the model results the Suriname River estuary can be qualified as highly stratified and well-mixed estuary based on the Hansen-Rattray parameters.

The gravitational circulation according to the Delft3D model simulation is less dominant as was assumed due to the results from the measurement data. The tidally averaged velocity is not resulting in a net inward current velocity at the bed as would be expected for a partially mixed structure.

The measurement data that are present for the Suriname River Estuary appeared to be insufficient to determine the sediment transport in the system. It is recommended to execute more measuring as will be discussed in the following section.

The Delft3D model simulation shows us an interaction of several processes that define the sediment transport in the system;

- gravitational circulation,
- tidal asymmetry,
- damped turbulence,
- residual river current.

The presence of gravitational circulation and the flood dominance in combination with the supply of sediments from the Ocean weakens the sediment advection due to the residual river current in outward direction.

The Delft3D model simulation did not achieve to simulate a long term sediment influx of sediments at the beginning of the study area, but long term equilibrium of net sediment transport was achieved. Extreme conditions such as extraordinary low river discharges or extreme supply of muddy sediments from the Ocean side could be a reason for an occasional import of sediment in the study area. On the other hand, extreme conditions such as extraordinary high river discharges or no supply of muddy sediments from the Ocean side could be a reason for an occasional export of sediment.
Although the model shows a long term balance of sediment transport in the longitudinal direction of the system, the erosion and sedimentation pattern does not show a balance within the cross section of the study area between km 43 and 83. The erosion and sedimentation pattern of the study area between km 43 and 83 according to the model shows us in the deeper sections such as the artificial fairway a tendency to erode these deeper sections due to strong currents and thus high shear stresses at the bed. On the other hand the shallow sections (at the river banks) in the same cross section tend to accumulate sediments due to low currents and thus low shear stresses at the bed.

According the calculated currents and shear stresses this erosion and sedimentation pattern seems plausible, and one would expect further erosion of the deeper parts and narrowing of the river. In reality there is a different erosion and sedimentation pattern, namely a river channel which is quite evenly shallow in the whole cross section and a very wide cross section compared to the depth.

The bed level measurements of the last decades do not show any tendency of erosion of the deeper sections and accumulations of the shallow section. Something is opposing the accumulation of the shallow section and erosion of the deeper section.

The Delft3D-FLOW model does not contain a fluid mud simulation and the consolidation process. These two processes should have been implemented in this thesis project to be really conclusive about the actual feasibility of the dredging project.
6.2 Recommendations

If an estimation or calculation of the sediment transport and morphology of the river estuary is needed again in the future, it would be very helpful if the quantity and quality of the measurement data is better than the present measurement data. The achievement of the Suriname River dredging project, which probably will start this calendar year 2008, offers an ideal chance to execute extra measurements (for instance monitoring the fairway bed level) to collect more data for studying the complex muddy system and possibly calibrate the existing computer model and assist other studies in comparable muddy environments.

Except for the water level data no other long term measurement data are available, which cover more than one tidal cycle and preferably cover spring tidal conditions and neap tidal conditions. Long term data of current velocities, upstream river discharges (Commewijne and Suriname River) and salt and sediment concentrations can be very helpful. Since the system is rather stratified, the velocity, salt concentrations and sediment concentrations measurements should be executed at several depths in the water column to define the tidally averaged structure of these components. Especially for the current velocity it would be wise to measure the current direction as well or to measure with a small time-interval between the measurements to define the transition between flood and ebb current.

Another point of attention is keeping record of the conditions during the execution of the measurements and to include them with the measurement data. Conditions such as: measurement equipment, river discharge, water level and reference level are important to use the measurement data for further analyse.

The fall velocity of the sediments has been set as a mean value in the Delft3D model, representing a mean diameter of the flocculated muddy sediments. For this study it is assumed that the sediments are flocculated containing several different sediment diameters in one floc. The composition of the flocs is unknown and therefore the choice of a mean value for the fall velocity seemed the only option for simulating the composition of the flocs.

For future morphology studies or for validation of the computer model it should be investigated how the flocculation process behaves in the Suriname River and what fall velocity belongs to those flocs and what composition of sediments those flocs contain. During investigation main questions should be:

- What is the average floc size? and what fall velocity belongs to that floc size?
- Do floc sizes vary in longitudinal direction of the estuary?
• Do solely flocs occur in the water column or in combination with loose sediment particles?

The consolidation of the settled sediments was not able to be simulated with the Delft3D-FLOW module. The settling and consolidation strongly influences the erodibility of the sediment bed. At low values of the bed shear stress, suspended sediments (individual particles or flocs) deposit onto the bed. The weight of the deposited sediment expels the water from underlying sediment bed causing the underlying sediment bed to increase its density. The increased density causes this layer to decrease its erodibility. The top layer of the sediment bed is therefore more erodible than the denser layers beneath the top layer.

If the present trial-versions of Delft3D or other morphodynamic calculation tools implementing the consolidation process become available in the future, it would provide the possibility to significantly improve the current simulation of the Suriname River Estuary. Implementing the consolidation process should significantly improve the erosion and sedimentation pattern of the muddy river estuary simulation.

Another process not being implemented in the Delft3D model is the presence of fluid mud at the bed of the river estuary. Possible density cross current of fluid mud could be an explanation for the dispersion of mud over the entire cross section in stead of deposits at the shallow sections at the river banks. Whether this can occur in the system should be checked with field measurements.

Past studies have proven the presence of fluid mud but did not prove the mobility of the fluid mud as a density current. One of the characteristics of fluid mud is that it gains strength and is therefore less erodible than loose sediments at the bed, which could explain why the mud is liable to the higher bed shear stresses when it flows to the deeper section within the cross section.

This thesis study did not include the impact of the waves in the simulation due to the fact that the study area is not affected by the waves from the Ocean. However these waves seem to influence the supply of sediments into the river mouth and increase the sediment concentrations due to wave turbulence. Therefore it is advised to implement the wave activity in the computer model if it ever will be used again.
 References


Appendices
Figure 1 Schematisation of migrating mud banks along Guyana coast, after Allersma 1968.
Figure 2 Bathymetry of Suriname River Estuary after Nedeco 1968
Figure 3 Bathymetry of Suriname River Estuary after MAS 2002-2004
Figure 4 Wind roses from an offshore location near the Suriname Coast
Figure 5a Top view Delft3D model area (grid cells)
Figure 5b Top view Delft3D model area (grid cells) km 35-60
Figure 5c: Top view Delft3D model area (grid cells) km 60-83
Figure 6a Velocity differences between present situation and future situation (lowered fairway) during flood, after Alkyon 2007
Figure 6b Velocity differences between present situation and future situation (lowered fairway) during ebb, after Alkjon 2007
Figure 6: Velocity differences between present situation and future situation (lowered fairway) during flood, after Alkyon 2007
Figure 6d: Velocity differences between present situation and future situation (lowered fairway) during flood, after Alkyon 2007.
Figure 7a computed bed shear stress during current slack (flood current changing into ebb current).
Figure 7b computed bed shear stress during low water slack (ebb).
Figure 7c computed bed shear stress during high-water slack (flood).
Table 1 Tidal constituents for four measurement stations in the Suriname River Estuary

<table>
<thead>
<tr>
<th>Station</th>
<th>NAME</th>
<th>FREQUENCY (OM)</th>
<th>AMPLITUDE</th>
<th>PHASE (G)</th>
<th>AMPLITUDE</th>
<th>PHASE (G)</th>
<th>AMPLITUDE</th>
<th>PHASE (G)</th>
<th>AMPLITUDE</th>
<th>PHASE (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brama punt</td>
<td>SA</td>
<td>0.04106684</td>
<td>4.409</td>
<td>221.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SSA</td>
<td>0.08213728</td>
<td>3.684</td>
<td>97.3</td>
<td>3.684</td>
<td>192.4</td>
<td>3.684</td>
<td>204.3</td>
<td>2.006</td>
<td>217.7</td>
</tr>
<tr>
<td></td>
<td>MSM</td>
<td>0.471521083</td>
<td>0.624</td>
<td>192.4</td>
<td>0.624</td>
<td>204.3</td>
<td>0.624</td>
<td>217.7</td>
<td>2.006</td>
<td>217.7</td>
</tr>
<tr>
<td></td>
<td>MM</td>
<td>0.544374695</td>
<td>1.465</td>
<td>121.8</td>
<td>1.465</td>
<td>234.4</td>
<td>1.465</td>
<td>246.4</td>
<td>5.046</td>
<td>234.4</td>
</tr>
<tr>
<td></td>
<td>MF</td>
<td>1.09803306</td>
<td>1.469</td>
<td>351.3</td>
<td>1.469</td>
<td>351.3</td>
<td>1.469</td>
<td>351.3</td>
<td>2.006</td>
<td>217.7</td>
</tr>
<tr>
<td></td>
<td>SIGMA1</td>
<td>12.9271398</td>
<td>0.103</td>
<td>250.0</td>
<td>0.103</td>
<td>250.0</td>
<td>0.103</td>
<td>250.0</td>
<td>2.006</td>
<td>217.7</td>
</tr>
<tr>
<td></td>
<td>M1</td>
<td>14.49660588</td>
<td>0.566</td>
<td>238.2</td>
<td>0.566</td>
<td>223.8</td>
<td>0.566</td>
<td>223.8</td>
<td>2.006</td>
<td>217.7</td>
</tr>
<tr>
<td></td>
<td>K1</td>
<td>15.04106684</td>
<td>11.451</td>
<td>207.4</td>
<td>11.451</td>
<td>207.4</td>
<td>11.451</td>
<td>207.4</td>
<td>2.006</td>
<td>217.7</td>
</tr>
<tr>
<td></td>
<td>JT</td>
<td>15.5894334</td>
<td>0.599</td>
<td>199.6</td>
<td>0.599</td>
<td>232.3</td>
<td>0.599</td>
<td>232.3</td>
<td>2.006</td>
<td>217.7</td>
</tr>
<tr>
<td></td>
<td>MN2</td>
<td>27.4233374</td>
<td>0.419</td>
<td>139.1</td>
<td>0.419</td>
<td>243.4</td>
<td>0.419</td>
<td>243.4</td>
<td>2.006</td>
<td>217.7</td>
</tr>
<tr>
<td></td>
<td>SN2</td>
<td>27.8953485</td>
<td>2.807</td>
<td>126.3</td>
<td>2.807</td>
<td>143.1</td>
<td>2.807</td>
<td>143.1</td>
<td>2.006</td>
<td>217.7</td>
</tr>
<tr>
<td></td>
<td>MU2</td>
<td>27.9682084</td>
<td>2.456</td>
<td>118.4</td>
<td>2.456</td>
<td>143.1</td>
<td>2.456</td>
<td>143.1</td>
<td>2.006</td>
<td>217.7</td>
</tr>
<tr>
<td></td>
<td>N2</td>
<td>28.4391255</td>
<td>18.497</td>
<td>135.4</td>
<td>18.497</td>
<td>158.6</td>
<td>18.497</td>
<td>158.6</td>
<td>2.006</td>
<td>217.7</td>
</tr>
<tr>
<td></td>
<td>MU2</td>
<td>28.5128314</td>
<td>3.563</td>
<td>135.3</td>
<td>3.563</td>
<td>163.9</td>
<td>3.563</td>
<td>163.9</td>
<td>2.006</td>
<td>217.7</td>
</tr>
<tr>
<td></td>
<td>L2</td>
<td>29.5847042</td>
<td>89.007</td>
<td>150.0</td>
<td>89.007</td>
<td>163.3</td>
<td>89.007</td>
<td>163.3</td>
<td>2.006</td>
<td>217.7</td>
</tr>
<tr>
<td></td>
<td>LABD2</td>
<td>29.4508253</td>
<td>0.904</td>
<td>157.6</td>
<td>0.904</td>
<td>164.7</td>
<td>0.904</td>
<td>164.7</td>
<td>2.006</td>
<td>217.7</td>
</tr>
<tr>
<td></td>
<td>K2</td>
<td>30.08213728</td>
<td>8.455</td>
<td>170.9</td>
<td>8.455</td>
<td>186.5</td>
<td>8.455</td>
<td>186.5</td>
<td>2.006</td>
<td>217.7</td>
</tr>
<tr>
<td></td>
<td>MSN2</td>
<td>30.5493747</td>
<td>0.373</td>
<td>335.4</td>
<td>0.373</td>
<td>323.3</td>
<td>0.373</td>
<td>323.3</td>
<td>2.006</td>
<td>217.7</td>
</tr>
<tr>
<td></td>
<td>ZSM2</td>
<td>31.0148978</td>
<td>0.454</td>
<td>335.9</td>
<td>0.454</td>
<td>323.3</td>
<td>0.454</td>
<td>323.3</td>
<td>2.006</td>
<td>217.7</td>
</tr>
<tr>
<td></td>
<td>MO3</td>
<td>42.9271398</td>
<td>0.386</td>
<td>163.3</td>
<td>0.386</td>
<td>246.6</td>
<td>0.386</td>
<td>246.6</td>
<td>2.006</td>
<td>217.7</td>
</tr>
<tr>
<td></td>
<td>M3</td>
<td>43.4761835</td>
<td>3.565</td>
<td>302.5</td>
<td>3.565</td>
<td>313.8</td>
<td>3.565</td>
<td>313.8</td>
<td>2.006</td>
<td>217.7</td>
</tr>
<tr>
<td></td>
<td>MK3</td>
<td>44.0251288</td>
<td>0.471</td>
<td>270.6</td>
<td>0.471</td>
<td>288.8</td>
<td>0.471</td>
<td>288.8</td>
<td>2.006</td>
<td>217.7</td>
</tr>
<tr>
<td></td>
<td>MN4</td>
<td>57.4233374</td>
<td>0.906</td>
<td>110.7</td>
<td>0.906</td>
<td>197.8</td>
<td>0.906</td>
<td>197.8</td>
<td>2.006</td>
<td>217.7</td>
</tr>
<tr>
<td></td>
<td>M4</td>
<td>57.9682084</td>
<td>2.165</td>
<td>133.0</td>
<td>2.165</td>
<td>212.4</td>
<td>2.165</td>
<td>212.4</td>
<td>2.006</td>
<td>217.7</td>
</tr>
<tr>
<td></td>
<td>MS4</td>
<td>58.9841042</td>
<td>1.199</td>
<td>161.9</td>
<td>1.199</td>
<td>247.6</td>
<td>1.199</td>
<td>247.6</td>
<td>2.006</td>
<td>217.7</td>
</tr>
<tr>
<td></td>
<td>MK4</td>
<td>59.0698215</td>
<td>0.406</td>
<td>162.1</td>
<td>0.406</td>
<td>256.8</td>
<td>0.406</td>
<td>256.8</td>
<td>2.006</td>
<td>217.7</td>
</tr>
<tr>
<td></td>
<td>S4</td>
<td>60</td>
<td>0.533</td>
<td>260.1</td>
<td>0.533</td>
<td>297.0</td>
<td>0.533</td>
<td>297.0</td>
<td>2.006</td>
<td>217.7</td>
</tr>
<tr>
<td></td>
<td>MN6</td>
<td>86.4078370</td>
<td>0.639</td>
<td>191.1</td>
<td>0.639</td>
<td>243.3</td>
<td>0.639</td>
<td>243.3</td>
<td>2.006</td>
<td>217.7</td>
</tr>
<tr>
<td></td>
<td>M6</td>
<td>86.9521265</td>
<td>0.845</td>
<td>114.6</td>
<td>0.845</td>
<td>208.5</td>
<td>0.845</td>
<td>208.5</td>
<td>2.006</td>
<td>217.7</td>
</tr>
<tr>
<td></td>
<td>MN6</td>
<td>87.9682084</td>
<td>0.915</td>
<td>135.2</td>
<td>0.915</td>
<td>223.3</td>
<td>0.915</td>
<td>223.3</td>
<td>2.006</td>
<td>217.7</td>
</tr>
<tr>
<td></td>
<td>MN6</td>
<td>88.9503421</td>
<td>0.215</td>
<td>123.7</td>
<td>0.215</td>
<td>244.0</td>
<td>0.215</td>
<td>244.0</td>
<td>2.006</td>
<td>217.7</td>
</tr>
<tr>
<td></td>
<td>MS8</td>
<td>116.9521372</td>
<td>0.866</td>
<td>168.1</td>
<td>0.866</td>
<td>229.0</td>
<td>0.866</td>
<td>229.0</td>
<td>2.006</td>
<td>217.7</td>
</tr>
</tbody>
</table>

Table 1 Tidal constituents for four measurement stations according to Delft3D-TIDE analysis results
<table>
<thead>
<tr>
<th>Simulation run</th>
<th>Simulation period</th>
<th>Delft3D version</th>
<th>Initial conditions</th>
<th>cr. sh. stress</th>
<th>other deviations from final study model</th>
</tr>
</thead>
<tbody>
<tr>
<td>T505</td>
<td>3.5</td>
<td>FLOW</td>
<td>500 0</td>
<td>0.002 0.002</td>
<td>Cgel=100 kg/m^3; Forrester filter OFF</td>
</tr>
<tr>
<td>T506</td>
<td>3.5</td>
<td>FLOW</td>
<td>500 0</td>
<td>0.002 0.002</td>
<td>Cgel=100 kg/m^3; Forrester filter OFF</td>
</tr>
<tr>
<td>T507</td>
<td>3.5</td>
<td>FLOW</td>
<td>200 0</td>
<td>0.002 0.002</td>
<td>Forrester filter OFF</td>
</tr>
<tr>
<td>T513</td>
<td>15.0</td>
<td>FLOW</td>
<td>500 0</td>
<td>0.002 0.002</td>
<td>Forrester filter OFF</td>
</tr>
<tr>
<td>T514</td>
<td>3.5</td>
<td>FLOW</td>
<td>500 0</td>
<td>0.002 0.002</td>
<td>Forrester filter OFF</td>
</tr>
<tr>
<td>T515</td>
<td>3.5</td>
<td>FLOW</td>
<td>restart T514 0</td>
<td>0.002 0.002</td>
<td>Forrester filter OFF</td>
</tr>
<tr>
<td>T516</td>
<td>15.0</td>
<td>FLOW</td>
<td>500 0</td>
<td>0.002 0.002</td>
<td></td>
</tr>
<tr>
<td>T517</td>
<td>15.0</td>
<td>FLOW</td>
<td>restart T516 0</td>
<td>0.002 0.002</td>
<td></td>
</tr>
<tr>
<td>T518</td>
<td>15.0</td>
<td>FLOW</td>
<td>500 0</td>
<td>0.002 0.002</td>
<td>Cgel=500 kg/m^3</td>
</tr>
<tr>
<td>T518BG</td>
<td>15.0</td>
<td>TRANS2004</td>
<td>500 0</td>
<td>calculated by model</td>
<td>Cgel=500 kg/m^3</td>
</tr>
<tr>
<td>T518BGs</td>
<td>15.0</td>
<td>TRANS2004</td>
<td>500 0.1</td>
<td>calculated by model</td>
<td>Cgel=500 kg/m^3</td>
</tr>
<tr>
<td>T519</td>
<td>15.0</td>
<td>TRANS2004</td>
<td>restart T518 0</td>
<td>calculated by model</td>
<td>Cgel=500 kg/m^3</td>
</tr>
<tr>
<td>T520</td>
<td>15.0</td>
<td>TRANS2004</td>
<td>500 0</td>
<td>calculated by model</td>
<td>Cgel=100 kg/m^3</td>
</tr>
<tr>
<td>T521</td>
<td>15.0</td>
<td>FLOW</td>
<td>not applicable</td>
<td>not applicable</td>
<td>sediment process OFF</td>
</tr>
<tr>
<td>T522</td>
<td>15.0</td>
<td>FLOW</td>
<td>500 0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>T523</td>
<td>15.0</td>
<td>FLOW</td>
<td>500 0.1</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>T524</td>
<td>15.0</td>
<td>FLOW</td>
<td>500 0.1</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>T525</td>
<td>15.0</td>
<td>FLOW</td>
<td>restart T524b 0</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>T526</td>
<td>15.0</td>
<td>FLOW</td>
<td>500 0.1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>T527</td>
<td>15.0</td>
<td>FLOW</td>
<td>500 0.1</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>T528</td>
<td>15.0</td>
<td>FLOW</td>
<td>500 0.1</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>T529</td>
<td>15.0</td>
<td>FLOW</td>
<td>500 0.1</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>T530</td>
<td>15.0</td>
<td>FLOW</td>
<td>500 0.1</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>T531</td>
<td>15.0</td>
<td>FLOW</td>
<td>500 0.1</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>T532</td>
<td>15.0</td>
<td>FLOW</td>
<td>500 0.1</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>T533</td>
<td>15.0</td>
<td>FLOW</td>
<td>500 0.1</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>T534</td>
<td>15.0</td>
<td>FLOW</td>
<td>500 0.1</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>T535</td>
<td>15.0</td>
<td>FLOW</td>
<td>500 0.1</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>T536</td>
<td>15.0</td>
<td>FLOW</td>
<td>restart T524b 0</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>T537</td>
<td>15.0</td>
<td>FLOW</td>
<td>restart T524b 0</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>T538</td>
<td>15.0</td>
<td>FLOW</td>
<td>restart T524b 0</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>T539</td>
<td>15.0</td>
<td>FLOW</td>
<td>restart T524b 0</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>T540</td>
<td>15.0</td>
<td>FLOW</td>
<td>restart T524b 0</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>T541</td>
<td>15.0</td>
<td>FLOW</td>
<td>restart T524b 0</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>T542</td>
<td>15.0</td>
<td>FLOW</td>
<td>restart T524b 0</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>T543</td>
<td>15.0</td>
<td>FLOW</td>
<td>restart T524b 0</td>
<td>0.1</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Delft3D simulation runs
Hydro- and morphodynamics of the Suriname River Estuary

Leonsberg km43

Run=T524

Tidal dominance

Fig. A1
Tidal characteristics during SPRING tide at Jaglust bank km47 Run=T524

Tidal characteristics during NEAP tide at Jaglust bank km47 Run=T524

Current velocity (negative value = outflow) in station Jaglust bank km47

Waterlevel in station Jaglust bank km47

Hydro- and morphodynamics of the Suriname River Estuary

Fig. A2
Tidal characteristics during SPRING tide at BEM Paramaribo km58 Run=T524

Tidal characteristics during NEAP tide at BEM Paramaribo km58 Run=T524

Current velocity (negative value = outflow) in station BEM Paramaribo km58

Waterlevel in station BEM Paramaribo km58
Tidal characteristics during SPRING tide at Domburg km70 Run=T524

Tidal mean -312 m³/s

Tidal prism [m³]

11-Jan-2001
12-Jan-2001

inst. discharge cross-section [m³/s]
→
time

Tidal characteristics during NEAP tide at Domburg km70 Run=T524

Tidal mean -313 m³/s

Tidal prism [m³]

17-Jan-2001
19-Jan-2001

inst. discharge cross-section [m³/s]
→
time

U- and V-current

→
time

current velocity (negative value = outflow) in station Domburg km70

tidal mean -0.10 m/s

U-cross [m/s] V-longitudinal [m/s]

11-Jan-2001
12-Jan-2001

17-Jan-2001
19-Jan-2001

Waterlevel in station Domburg km70

vertical lines correspond max/min water level

waterlevel [m]

11-Jan-2001
12-Jan-2001

17-Jan-2001
19-Jan-2001

Hydro- and morphodynamics of the Suriname River Estuary

Domburg km70 Run=T524

Tidal dominance

Fig. A4
Velocities during 1 SPRING tidal cycle for every 10 minutes at Leonsberg km 43 Run=T524b

Velocities during 1 NEAP tidal cycle for every 10 minutes at Leonsberg km 43 Run=T524b

Salinity during SPRING tide for every 10 minutes at Leonsberg km 43 Run=T524b

Salinity during NEAP tide for every 10 minutes at Leonsberg km 43 Run=T524b

Waterlevel in station Leonsberg km 43

Leonsberg km 43
Run=T524b
Cross section
velocity/salinity structure

SURINAME RIVER ESTUARY

Fig. B1
Theoretical sediment transport capacity \([Q'U^3]\) at Leonsberg km 43 Run=T525c

cumulative time-integration of \([Q'U^3]\) at Leonsberg km 43 Run=T525c

Hydro- and morphodynamics of the Suriname River Estuary

Cross section Run=T525c
Leonsberg km 43
sediment transport capacity analysis

Fig. C1
Theoretical sediment transport capacity \(Q'U^3\) at MAS Par’bo km 51 Run=T525c

- **Instantaneous sediment transport**
- **Cumulative time-integration of** \(Q'U^3\)

Hydro- and morphodynamics of the Suriname River Estuary

Fig. C2
Theoretical sediment transport capacity \([Q'U^3]\) at BEM Par`bo km 58 Run=T525c

- Instantaneous sediment transport
- Cumulative time-integration of \([Q'U^3]\)

Cumulative sediment transport trendline

Hydro- and morphodynamics of the Suriname River Estuary

Fig. C3
Theoretical sediment transport capacity \( [Q^*U^3] \) at Dijkveld bar km 62 Run=T525c

Cumulative time-integration of \( [Q^*U^3] \) at Dijkveld bar km 62 Run=T525c

Hydro- and morphodynamics of the Suriname River Estuary
Theoretical sediment transport capacity \([Q^*U^3]\) at Domburg km 70 Run=T525c

- Instantaneous sediment transport
- Zero

Cumulative time-integration of \([Q^*U^3]\) at Domburg km 70 Run=T525c

- Cumulative sediment transport
- Trendline
- Zero

Hydro- and morphodynamics of the Suriname River Estuary

Cross section Run=T525c
Domburg km 70
Sediment transport capacity analysis

Fig. C5
Cumulative transport at Leonsberg km 43

Run T524b (present situation; initial layer 0.1 m)
Run T525c (restart present situation; initial layer T524b)
Run T526 (effect density on fluid OFF)
Run T527 (salinity process OFF)
Run T528 (Higher Suriname River discharge (500 m³/s))
Run T529 (Tau_cr_ero = 0.6 / Tau_cr_dep = 1000)
Run T542 (Sediment supply from Ocean due to Wave-action)

Hydro- and morphodynamics of the Suriname River Estuary

Cumulative sediment transport

Cross section Run T524b-T542
Leonsberg km 43
Fig. F1
Cumulative transport at MAS Paramaribo km 51

Run T524b (present situation; initial layer 0.1 m)
Run T525c (restart present situation; initial layer T524b)
Run T526 (effect density on fluid OFF)
Run T527 (salinity process OFF)
Run T528 (Higher Suriname River discharge (500 m³/s))
Run T533 (τ_cr_ero = 0.6 / τ_cr_dep = 1000)
Run T542 (Sediment supply from Ocean due to Wave-action)

Hydro- and morphodynamics of the Suriname River Estuary

Cross section Run T524b-T542
MAS Paramaribo km 51
Cumulative sediment transport

Fig. F2
Cumulative transport at BEM Paramaribo km 58

- Run T524b (present situation; initial layer 0.1 m)
- Run T525c (restart present situation; initial layer T524b)
- Run T526 (effect density on fluid OFF)
- Run T527 (salinity process OFF)
- Run T528 (Higher Suriname River discharge (500 m³/s))
- Run T533 (Tau_cr_ero = 0.6 / Tau_cr_dep = 1000)
- Run T542 (Sediment supply from Ocean due to Wave-action)

Hydro- and morphodynamics of the Suriname River Estuary

Cross section BEM Paramaribo km 58
Cumulative sediment transport

Fig. F3
Cumulative transport at Dijkveld bar km 62

Run T524b (present situation; initial layer 0.1 m)
Run T525c (restart present situation; initial layer T524b)
Run T526 (effect density on fluid OFF)
Run T527 (salinity process OFF)
Run T528 (Higher Suriname River discharge (500 m³/s))
Run T533 (Tau_cr_ero = 0.6 / Tau_cr_dep = 1000)
Run T542 (Sediment supply from Ocean due to Wave-action)

Cumulative sediment transport

Fig. F4
Cumulative transport at Domburg km 70

Run T524b (present situation; initial layer 0.1 m)
Run T525c (restart present situation; initial layer T524b)
Run T526 (effect density on fluid OFF)
Run T527 (salinity process OFF)
Run T528 (Higher Suriname River discharge (500 m³/s))
Run T533 (Tau_cr_ero = 0.6 / Tau_cr_dep = 1000)
Run T542 (Sediment supply from Ocean due to Wave-action)

Cross section Run T524b-T542
Domburg km 70 Cumulative sediment transport

Hydro- and morphodynamics of the Suriname River Estuary

Fig. F5
Cumulative transport at Upstream boundary km 83

- Run T524b (present situation; initial layer 0.1 m)
- Run T525c (restart present situation; initial layer T524b)
- Run T526 (effect density on fluid OFF)
- Run T527 (salinity process OFF)
- Run T528 (Higher Suriname River discharge (500 m³/s))
- Run T533 (Tau_cr_ero = 0.6 / Tau_cr_dep = 1000)
- Run T542 (Sediment supply from Ocean due to Wave-action)

Cross section Run T524b-T542
Upstream boundary km 83
Cumulative sediment transport

Hydro- and morphodynamics of the Suriname River Estuary

Fig. F6
Hydro- and morphodynamics of the Suriname River Estuary

Run=T542
Fairway channel km 43-83
sedimentation along axis fairway

Fig. H1
Hydro- and morphodynamics of the Suriname River Estuary

Run=T543
Fairway channel km 43-83
sedimentation along axis fairway

Fig. H2
Appendix A; List of measurement data

The following measurement data:

Tidal elevation during several years:
- Water level time series at Braamspunt 2002-2006
- Water level time series at Nieuw-Amsterdam 2002-2006
- Water level time series at Paramaribo (MAS-pier) 2002-2006
- Water level time series at Domburg 2002-2006
- Tidal characteristics (LW and HW) during the years 1983, 1984 and 1985 by WLA

Current velocity during one tidal cycle:
- Resolutie 1982 from Heuvel
- Leonsberg 1982 from Heuvel
- Near the bridge at Paramaribo 1981 by WLA
- Near the bridge at Paramaribo 2007 from Naipal (AdK university of Suriname)
- Zoelen (Commewijne River) 2006 by WLA
- Overbridge 2006 by WLA
- Suzanna’s Daal 2002 from Khudabux

Salinity measurements during one tidal cycle:
- Resolutie 1982 from Heuvel
- Leonsberg 1982 from Heuvel
- Near the bridge at Paramaribo 2007 from Naipal (AdK university of Suriname)

Sediment concentration measurements during one tidal cycle:
- Resolutie 1982 from Heuvel
- Leonsberg 1982 from Heuvel
- Near the bridge at Paramaribo 2007 from Naipal (AdK university of Suriname)

River discharge:
- Near Brokopondo 1983 by WLA

Bottom and water samples:
- MOS 2006
Appendix B; plots of velocity and salinity measurements

B.1 plots of current velocity measurements
B.2 plots of tidally averaged current velocities at measurement locations
B.3 plots of salinity distribution at measurement locations
Appendix C ; Delft3D-FLOW manual content for sediment simulation

C.1 Simulating transport of salt and sediment

The sediment transport equation in Delft3D-FLOW:

\[
\frac{\partial c^{(i)}}{\partial t} + \frac{\partial uc^{(i)}}{\partial x} + \frac{\partial vc^{(i)}}{\partial y} + \frac{\partial (w - w_s^{(i)})c^{(i)}}{\partial z} + \]

\[
- \frac{\partial}{\partial x} \left( \varepsilon_{xz}^{(i)} \frac{\partial c^{(i)}}{\partial x} \right) - \frac{\partial}{\partial y} \left( \varepsilon_{yz}^{(i)} \frac{\partial c^{(i)}}{\partial y} \right) - \frac{\partial}{\partial z} \left( \varepsilon_{zz}^{(i)} \frac{\partial c^{(i)}}{\partial z} \right) = 0
\]

‘The local flow velocities and eddy diffusivities are based on the results of the hydrodynamic computations. Computationally, the three-dimensional transport of sediment is computed in exactly the same way as the transport of any other conservative constituent, such as salinity, heat, and constituents. There are, however, a number of important differences between sediment and other constituents, for example, the exchange of sediment between the bed and the flow, and the settling velocity of sediment under the action of gravity. These additional processes for sediment are obviously of critical importance. Other processes such as the effect that sediment has on the local mixture density, and hence on turbulence damping, can also be taken into account. In addition, if a net flux of sediment from the bed to the flow, or vice versa, occurs then the resulting change in the bathymetry should influence subsequent hydrodynamic calculations. The formulation of several of these processes (such as, settling velocity, sediment deposition and pickup) are sediment-type specific, this especially applies for sand and mud. Furthermore, the interaction of sediment fractions is important for many processes, for instance the simultaneous presence of multiple suspended sediment fractions has implications for the calculation of the local hindered settling velocity of any one sediment fraction as well as for the resulting mixture density.’ (Delft3D-Flow manual, 2006, p. 11-2).

C.2 Fall velocity and settling

‘In high concentration mixtures, the settling velocity of a single particle is reduced due to the presence of other particles. In order to account for this hindered settling effect we follow Richardson and Zaki (1954) and determine the settling velocity in a fluid-sediment mixture as a function of the sediment concentration and the non-hindered settling fall velocity:’ (Delft3D-FLOW manual, 2006, p. 11-2).

\[w_s^{(i)} = \left( 1 - \frac{C_{zo, i}}{C_{SOIL}} \right) w_{s0}^{(i)} \]

‘As the fall velocity is now a function of the sediment fractions concentration, this implies that each sediment fraction has a fall velocity which is a function of location and time.’ (Delft3D-FLOW manual, 2006, p. 11-2).
C.3 Cohesive sediment erosion and deposition

`For cohesive sediment fractions the fluxes between the water phase and the bed are calculated with the well-known Partheniades-Krone formulations (Partheniades, 1965); (Delft3D-FLOW manual, 2006, p. 11-2).

\[
E^{(t)} = M^{(t)} S \left( \tau_{cw}, \tau_{cr,d}^{(t)} \right),
\]

\[
D^{(t)} = w_0^{(t)} c_{b}^{(t)} S \left( \tau_{cw}, \tau_{cr,d}^{(t)} \right),
\]

\[
c_{b}^{(t)} = c^{(t)} \left( z = \frac{\Delta z_b}{2}, t \right),
\]

where:

- \( E^{(t)} \) : erosion flux [kg/m²/s]
- \( M^{(t)} \) : user-defined erosion parameter EROUNI [kg/m²/s]
- \( S \left( \tau_{cw}, \tau_{cr,d}^{(t)} \right) \) : erosion step function:

\[
S \left( \tau_{cw}, \tau_{cr,d}^{(t)} \right) = \begin{cases} 
\frac{\tau_{cw}}{\tau_{cr,d}^{(t)}} - 1, & \text{when } \tau_{cw} > \tau_{cr,d}^{(t)}, \\
0, & \text{when } \tau_{cw} \leq \tau_{cr,d}^{(t)}.
\end{cases}
\]

- \( D^{(t)} \) : deposition flux [kg/m²/s]
- \( w_0^{(t)} \) : fall velocity (hindered) [m/s]
- \( c_{b}^{(t)} \) : average sediment concentration in the near bottom computational layer

- \( S \left( \tau_{cw}, \tau_{cr,d}^{(t)} \right) \) : deposition step function:

\[
S \left( \tau_{cw}, \tau_{cr,d}^{(t)} \right) = \begin{cases} 
1 - \frac{\tau_{cw}}{\tau_{cr,d}^{(t)}}, & \text{when } \tau_{cw} < \tau_{cr,d}^{(t)}, \\
0, & \text{when } \tau_{cw} \geq \tau_{cr,d}^{(t)}.
\end{cases}
\]

- \( \tau_{cw} \) : maximum bed shear stress due to current and waves as calculated by the wave-current interaction model selected by the user; see Section 9.7 for full details
- \( \tau_{cr,d}^{(t)} \) : user-defined critical erosion shear stress TCEUNI [N/m²]
- \( \tau_{cr,d}^{(t)} \) : user-defined critical deposition shear stress TCDUNI [N/m²]

The calculated erosion or deposition flux is applied to the near bottom computational cell by setting the appropriate sink and source terms for that cell. Advection, particle
settling, and diffusion through the bottom of the near bottom computational cell are all set to zero to prevent double counting these fluxes.

**C.4 Density effect on fluid**

In its standard form Delft3D-FLOW uses an empirical relation (Eckart, 1958) to adjust the density of water in order to take into account varying temperature and salinity. For sediment transport this relation is extended to include the density effect of sediment fractions in the fluid mixture. This is achieved by adding (per unit volume) the mass of all sediment fractions, and subtracting the mass of the displaced water. As a mathematical statement this translates as: Delft3D-FLOW manual, 2006, p. 11-2). 

\[ \rho_{\text{mix}}(S, c^{(i)}) = \rho_w(S) + \sum_{i=1}^{\text{sed}} c^{(i)} \left(1 - \frac{\rho_w(S)}{\rho_s^{(i)}}\right) \]

‘Horizontal density gradients (now also due to differences in sediment concentrations) can create density currents. Vertical density gradients can also have a significant effect on the amount of vertical turbulent mixing present.’ (Delft3D-FLOW manual, 2006, p. 11-3).

‘This option is included as it has been found that a secondary effect of including sediment in the density calculations is a reduction of the flow velocity in the lower computational layers (when compared with a standard logarithmic velocity profile) and a consequent reduction in the computed bed shear stress. This reduction in bed shear stress is particularly pronounced when the k-epsilon turbulence closure model is used, and leads to an increase in overall flow velocity and a consequent lowering of the free surface. Our experience shows that this change in the free surface level (even if very slight) can lead to calibration problems when converting an existing 2DH model to 3D if the model is driven using water level boundary conditions.’ (Delft3D-FLOW manual, 2006, p. 11-3).

**C.5 Transport boundary condition**

The transport of dissolved substances such as salt, sediment, and heat is described by the advection-diffusion equation. The horizontal transport is advection dominated and the equation is of hyperbolic type. At inflow, one boundary condition is needed and the concentration is specified. At outflow, no boundary condition is allowed. The concentration is determined by pure advection from the interior area:

\[ \frac{\partial C}{\partial t} + \frac{U}{\sqrt{G_{zz}}} \frac{\partial C}{\partial \xi} = 0. \]

In Delft3D-FLOW the dispersive fluxes through the open boundaries at both inflow and outflow are zero:
\[
\frac{D_{H}}{\sqrt{G_{\xi}} \frac{\partial C}{\partial \xi}} = 0.
\]

If the concentration at outflow differs from the boundary condition at inflow, there is a discontinuity in the concentration at the turn of the flow. The transition of the concentration at the boundary from the outflow value to the inflow value may take some time. This depends on the refreshment of the water in the boundary region. The transition time is called the return time. The functional relationship describing the variation in concentration from the slack-water value to the present value is arbitrary. In Delft3D-FLOW, a half-cosine variation is used. After the return time, the boundary value remains constant until outward flow begins (Leendertse and Gritton, 1971), (Thatcher and Harleman, 1972). The mathematical formulation of this memory effect is given as follows:

\[
C(t) = C_{\text{out}} + \frac{1}{2} (C_{\text{bnd}} - C_{\text{out}}) \left[ \cos \left( \pi \frac{T_{\text{ret}} - t_{\text{out}}}{T_{\text{ret}}} \right) + 1 \right], \quad 0 \leq t_{\text{out}} \leq T_{\text{ret}}.
\]

where \(C_{\text{out}}\) is the computed concentration at the open boundary at the last time of outward flow, \(C_{\text{bnd}}\) is the background concentration described by you, \(t_{\text{out}}\) is the elapsed time since the last outflow and \(T_{\text{ret}}\) is the constituent return period. When the flow turns inward \((t_{\text{out}} = 0)\), the concentration is set equal to \(C_{\text{out}}\). During the interval \(0 \leq t_{\text{out}} \leq T_{\text{ret}}\), the concentration will return to the background concentration \(C_{\text{bnd}}\). After that period, the concentration will remain \(C_{\text{bnd}}\). The mechanism is illustrated in Figure C1.1.

![Figure C1.1 Illustration of memory effect for open transport boundary](image-url)
For a stratified flow the return time of the upper layer will be longer than for the bottom layer. Delft3D-FLOW offers the opportunity to prescribe return times for the surface layer and the bed layer. For the intermediate layers the return time is determined using linear interpolation:

$$T_{TH_i} = T_{TH_{bottom}} + (1 + \sigma_k) \left( T_{TH_{surface}} - T_{TH_{bottom}} \right),$$

or similarly for the Z-grid:

$$T_{TH_i} = T_{TH_{bottom}} + \left( \frac{d + z_k}{d + \zeta} \right) \left( T_{TH_{surface}} - T_{TH_{bottom}} \right)$$

with:

- $T_{TH_{bottom}}$ return time bed layer.
- $T_{TH_{surface}}$ return time surface layer.
- $z_k, \sigma_k$ vertical position, respectively in Z- and $\sigma$ co-ordinate system.
- $d$ local depth value