Delft3D-FLOW Model of the Yangon Port Area

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Abstract

Large sedimentation is observed in the Yangon port area in Myanmar and this sediment is blocking the entrance channel into the port. The entrance channel is dredged intensively to keep it navigable but insight into the sedimentation processes is limited. The sedimented area rises above the water level in dry season and is known as the Inner Bar. In this research the Delft3D modelling suite is used to reproduce the erosion and sedimentation patterns around the Inner Bar with a 2D depth averaged hydrodynamic model. Calibration of the model with measured water levels shows an underestimation of low water levels in the dry season. The model shows small sensitivity to the river discharge values and relatively large sensitivity to bed roughness. The model results do not clearly show a sedimentation pattern in the area according to bed shear stress results. This hydrodynamic model provides however a starting point for further numerical study into sedimentation in the Yangon area.

I. Introduction

Yangon is the former capital of Myanmar with a population of over 5 million. The port area is of large economical value and the entrance suffers extensive sedimentation issues. This sedimentation causes the least navigable depth of the river to be insufficient to continuously allow the largest approaching vessels to enter the Yangon River. The sedimentation area is known as the Inner Bar. The sedimentation issues in the area are described in studies by Nelson (2000), who conducted a study into the behaviour of fine-grained sediment in the Yangon River. Also research by Aung (2013) acknowledges sedimentation issues in the Yangon Port through the results of a 3D Princeton Ocean Model (POM).

The objective of this research is to set up a 2D hydrodynamic model and identify critical locations for sedimentation. The model can serve as a prerequisite for an adequate dredging strategy. In this study, the Delft3D numerical modelling suite is used. With adequate calibration and validation, Delft3D provides a strong tool to solve sedimentation issues in the harbour, which mainly cause an economical bottleneck. The same modelling suite however can be applied to problems regarding irrigation of farmland, sedimentation of river banks and erosion of shorelines.

Sloff et al (2012) acknowledge that 2D and 3D numerical models are valuable tools in studying river morphology. However, they state that the level of skill of researchers using the modelling tools has significant impact on the workability of the model. Calibration and verification of the model also requires sufficient detail in field data. Both skilled modellers and field data are scarce in Myanmar, revealing the most important knowledge gaps.

II. Materials and Methods

The modelling software used in this research is Delft3D-FLOW developed by Deltares in Delft, the Netherlands. Delft3D-FLOW is the hydrodynamic module of the Delft3D software package. The purpose of the FLOW module is simulation of multi-dimensional hydrodynamic flow and transport phenomena, including sediments (Deltares, 2014). The calculations are performed on a computational grid constructed by the user in a separate software module. The Delft3D-FLOW module solves the unsteady shallow water equations in either two dimensions or three dimensions. In a two dimensional calculation the properties are depth-averaged. The equations are either formulated in orthogonal curvilinear co-ordinates or in spherical co-ordinates on the globe (Deltares, 2014).

The calculations by Delft3D-FLOW provide insight in water levels, depth averaged velocities and bed shear stress. The calculations can increase in complexity by including additional processes like secondary flow, salinity and sediment transport (Deltares, 2014). The Yangon area in Myanmar is best described as an estuary and situations like these are suitable for modelling in Delft3D-FLOW.

The purpose of the model influences choices on grid density, time frame and level of detail in the bathymetry. The purpose of the model designed in this research is to locate large scale erosion and sedimentation patterns in the Inner Bar area. For this purpose a year-long simulation of the hydrodynamics is conducted to include influences of seasonal variations in discharge due to the present monsoon climate. The model is two-dimensional (2D) and therefore delivers depth-averaged results.

The location of the Inner Bar area is the basis for the model setup. The model setup includes a numerical grid, an imposed bathymetry and boundary conditions.

The model is extended beyond the Inner Bar area to provide necessary storage for the tidal wave moving in the domain. The total grid extends approximately $60\,\mathrm{km}$ upstream in the Yangon-Hlaing River direction and approximately $40\,\mathrm{km}$ upstream in the Bago River direction, as observed in Figure 1. Also hereby the negative effects of reflection of the tidal wave on the model boundaries are mitigated in the area of interest. The upstream part of the grid is less dense, since that saves in computational complexity of the model without affecting the results at the Inner Bar. The grid parameters 'Orthogonality' and 'Courant Number' around the area of interest in Table 1 meet requirements set up by Deltares (2014). Around the Inner Bar area the grid has the following specification:

Table 1: *Grid specifications*

Parameter	Value
Grid Type	Regular
Coordinate System	Cartesian
Grid Cell Size	$100 \times 100\mathrm{m}$
Orthogonality	< 0.003
Courant Number	< 13

The bathymetry of the area of interest is digitalized from a naval chart (NHO, 2007). This most recent map dates from 2007. The naval chart extends from the mouth of the river just upstream of the Yangon Port. The bathymetry for the remainder of the model domain is schematized with widths extracted from the digitalized land boundaries and constant depths between $16\,\mathrm{m}$ downstream to $10\,\mathrm{m}$ upstream.

The model includes a total of seven boundaries. On all of the boundaries a boundary condition is imposed. The boundary at the river mouth is a tidal signal, extracted from the numerical model of the Ayeyarwady delta by Attema (2013). This signal is calibrated with a tidal signal at Elephant Point near the ocean mouth. The other boundaries are river discharges of which five are directed into the domain and one, the Twante Canal, is directed outward of the model domain. The model domain with applied bathymetry and boundaries is shown in Figure 1.

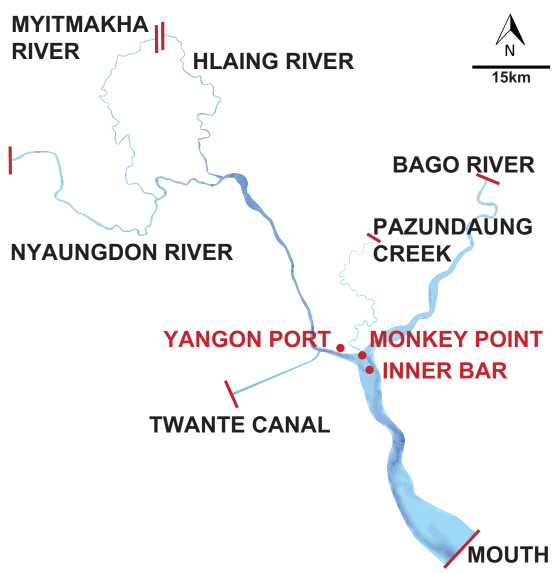

Figure 1: *Model area*

The river discharges on the model boundaries are calculated from a discharge dataset with a yearly minimum and maximum discharge for the Yangon River (downstream), Pazundaung Creek and Bago River from research by Aung (2013) and a maximum value for the Twante Canal (UN, 1976). This dataset is translated to a discharge curve with monthly values over the span of a year. A standardized discharge distribution curve is obtained by standardizing and averaging discharge data from catchments from the Bago River, Ayeyarwady River and Sittaung River, as shown in Figure 2.

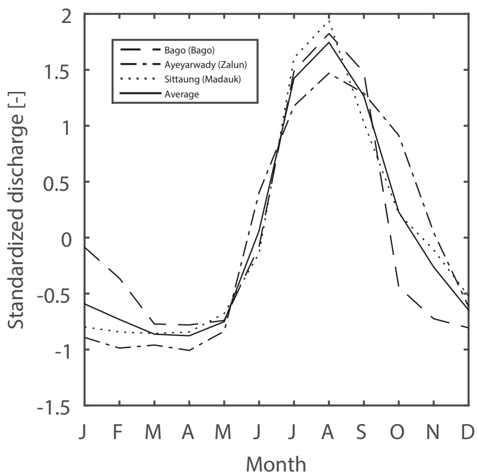

Figure 2: *Standardized discharge data*

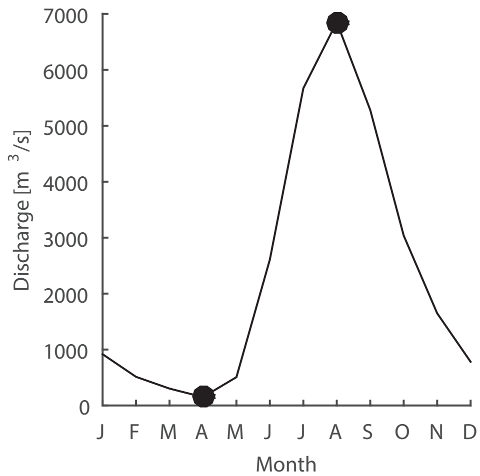

Figure 3: *Discharge curve Yangon River*

This curve is subsequently forced through the minimum and maximum discharge values. This process produces a dataset with monthly discharge values for the Yangon River, Pazundaung Creek and Bago River. To obtain river discharges at the model *boundaries* the discharge distributions over different branches are calculated by means of continuity laws. Figure 3 shows the discharge curve for the Yangon River. The final output gives a discharge distribution per month for the rivers Nyaungdon, Myitmakha, Hliang, Twante Canal, Pazundaung Creek and Bago River, corresponding with the model boundaries shown in Figure 1.

Model parameters that serve as input for calculations carried out by Delft3D-FLOW (after calibration) are summarized in Table 2:

Table 2: *Model parameters*

Parameter	Value
Grid Points $\mathrm{m} \times \mathrm{n}$	706×524
Simulation Time	$1\text{-}1\text{-}2015$ to $31\text{-}12\text{-}2015$
Time Step	1 minute
Open Boundaries	7
Water Density	$1000\,\mathrm{kg\,m^{-3}}$
Horiz. Diffusivity	$1\,\mathrm{m^2\,s^{-1}}$
Roughness Formula	Manning
Roughness Value	0.014

Calibration of the model results is conducted by comparison of calculated water levels with measured water levels at *Monkey Point* tidal station at Yangon Port (see Figure 1). The bed roughness input parameter in the model is adapted accordingly to match the water level signals. The discharge boundaries are adapted to represent the seasonal cycle of water levels. The performance of the model is assessed by means of a sensitivity analysis. In the sensitivity analysis a deviation of the river discharges and bed roughness is applied, while the tidal forcing remains the same. The resulting deviation of the results is analyzed for output parameters *Water Level* and *Bed Shear Stress*. Bed Shear Stress is related to the flow velocity and is a measure for the initiation of motion of sediment described by van Rijn (1993). For the sensitivity analysis a simulation time of a tidal cycle is sufficient.

III. Results

Numerical Model Calibration

For calibration the numerical results are assessed with water level measurements at Monkey Point tidal station nearby the Yangon Port. The measurement data is provided by the Myanma Port Authority (MPA, 2015). The simulated results are assessed on daily time-scale and on monthly time-scale. The simulated water levels are affected by the imposed bottom roughness. Increasing the bottom roughness will decrease the amplitude of the tidal signal, and decreasing the bottom roughness vice versa. The effect of the bottom roughness is visible on daily scale. The bottom roughness value of 0.015 is adopted from the model by Attema (2013). This value is adapted to 0.014 to correctly represent the measured water levels. Figure 4 shows the results of calibration on daily scale.

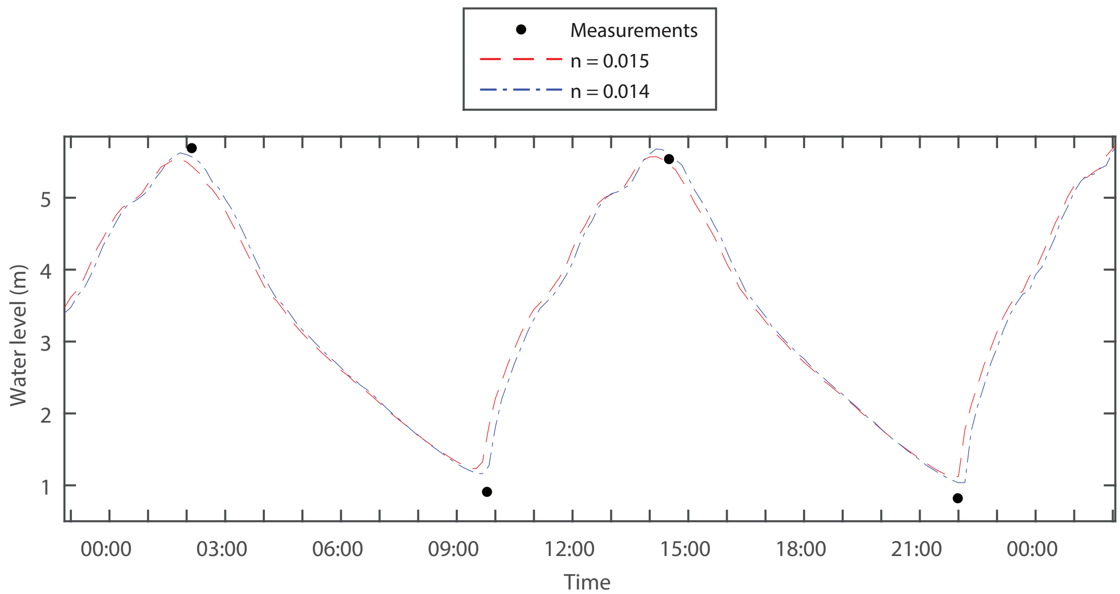

Figure 4: *Calibration: simulated versus measured water levels on daily scale at Monkey Point tidal station. Using roughness value Manning 0.014 shows an improved fit to the measured water levels.*

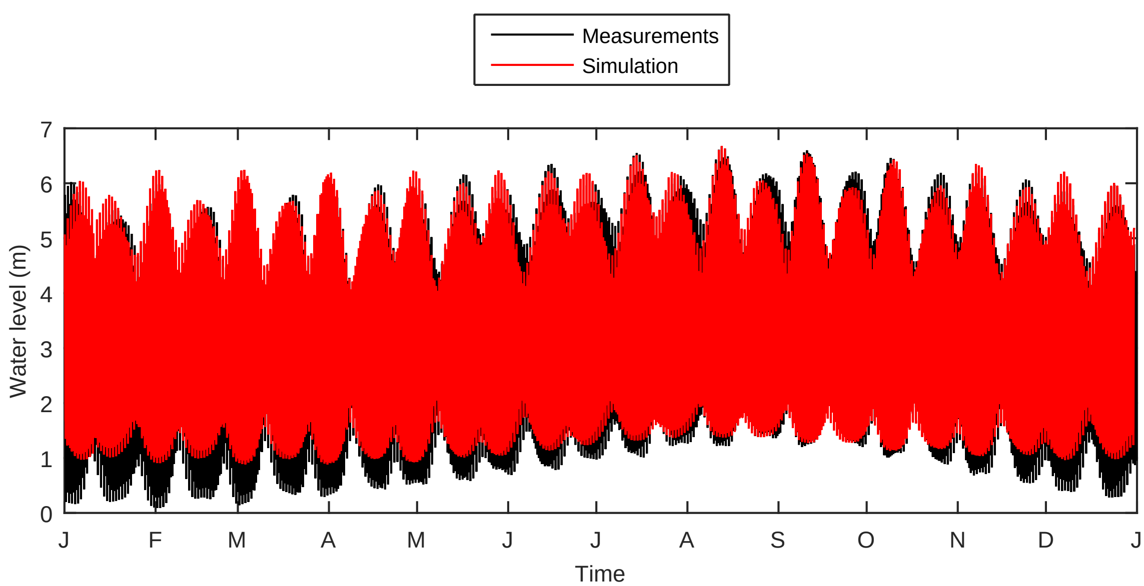

Figure 5: *Calibration: simulated versus measured water levels on monthly scale at Monkey Point tidal station. The seasonal variation in water levels is less pronounced in the simulated signal.*

In Figure 4 the bullets resemble the measured data by MPA (2015). The bullets are disconnected since the dataset uses only a registration of the high water and low water per day. The manning value n=0.014 shows that the peaks of the simulated signal give a closer fit to the measured values. The simulated results show that the tide rises faster than that the tide falls. This behaviour is an indication of a flood dominant location, which is prone to importing sediment (Bosboom & Stive, 2013).

Figure 5 presents the results of calibrating the discharge boundary conditions. The imposed discharges on the model boundaries show variation on a monthly scale. As the river discharges increase when the monsoon season prevails, the mean water level in the Yangon River basin rises accordingly. This effect is visible in Figure 5, showing the simulated and measured water levels over the course of the year.

The *minimum* discharge values adopted from research by Aung (2013) are a factor ± 25 higher than in research by Nelson (2000) and the seasonal cycle is barely visible. The discharges on all boundaries in the dry season are lowered by this factor to increase the effect of the wet-dry seasonal cycle. The discharge values are generated following the same method described in Section II. Despite the large difference in dry season and wet season discharges, the yearly variation of the mean water level is not as pronounced as in the measured signal. For the months June through November however there is a good fit of the water level elevation. The peaks of the tidal signal follow the measured values neatly, after a manual shift of the simulated water levels by $2.9\ \mathrm{m}$. This shift is necessary since there is no reference level provided with the measured signal.

The remaining underestimation of low-water levels in the dry season indicates that the discharge boundaries are not the only factor influencing the simulated water level signal. The results are discussed in Section IV. In Table 3 the discharge values per month on the different model boundaries are presented. The calculated discharge of the Yangon river is shown in Figure 3.

Table 3: *Imposed discharges on boundaries in* m^3/s

Month	Bago River	Pazundaung Creek	Twante Canal	Hlaing	Nyaungdon	Myitmakha
JAN	188	103	140	488	391	179
FEB	94	51	78	272	218	100
MAR	45	24	46	161	129	59
APR	10	5	23	80	64	29
MAY	93	51	78	269	216	99
JUN	580	321	400	1388	1111	508
JUL	1291	714	869	3018	2416	1105
AUG	1566	866	1050	3648	2920	1335
SEP	1201	664	809	2811	2251	1029
OCT	680	376	465	1617	1295	592
NOV	358	197	252	877	702	321
DEC	156	86	120	416	333	152

Sensitivity Analysis

The sensitivity of the model results is assessed with a deviation in the imposed river discharges and with a deviation in the imposed bed roughness. The discharge curve is based on two single data entries, which limits the accuracy of the curve (see Section II). The sensitivity of the results is assessed for output parameters *Water Level* and *Bed Shear Stress*. Assessing water levels establishes a link with the calibration of the model. Bed shear stress is used as indicative parameter for erosion and sedimentation and the reliability of this output is therefore vital for interpretation of the model results. Figure 6 shows the sensitivity of the water level output with a deviation of $\pm 10\%$ over the values in Table 3.

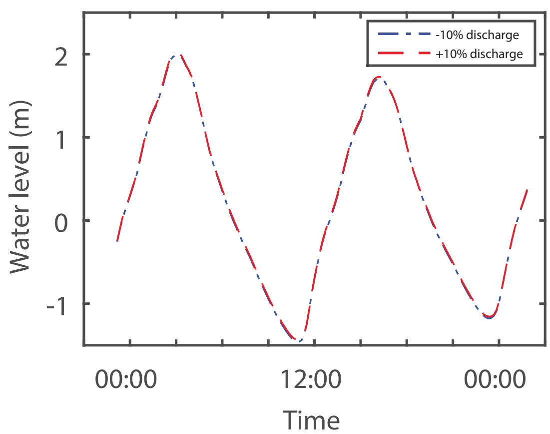

Figure 6: *Sensitivity analysis: deviated discharge to water level*

The resulting water levels in the Yangon Port area after adding or subtracting 10% discharge on the boundaries are indistinguishable. This shows that the model is not sensitive to changes in discharge in this order and at the same time shows that the influence of the tide on the water level signal is highly significant. The limited impact of a deviation of the discharge on the model results makes a comparison of the resulting Bed Shear Stress unnecessary.

The bed roughness value of the model (n=0.014) is deviated by $\pm 10\%$ to assess the influence of this parameter. With a deviated bed roughness value, the effect on water levels becomes clearly visible. As expected a lower roughness value results in a larger water elevation and a higher roughness value vice versa. Contrary to the discharge boundary conditions the roughness value is a sensitive model parameter. Figure 7 shows the sensitivity of deviated roughness to water level output. The output deviates in the order of 10% at the peaks.

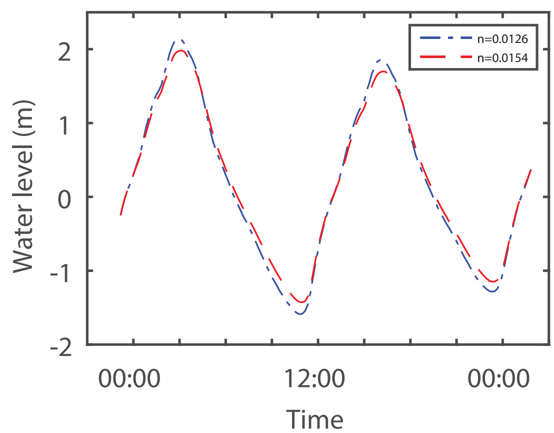

Figure 7: *Sensitivity analysis: deviated roughness to water level*

Figure 8 shows the difference between the occurring bed shear stresses after deviating the roughness parameter. The signal is calculated quadratically from the flow velocity and roughness. The negative values in the graph correspond with a land inward direction. The peaks land inward are lower than the peaks land outward. Land outward the discharges of the river and the tide are in the same direction, resulting in a higher flow velocity thus resulting in higher bed shear stresses.

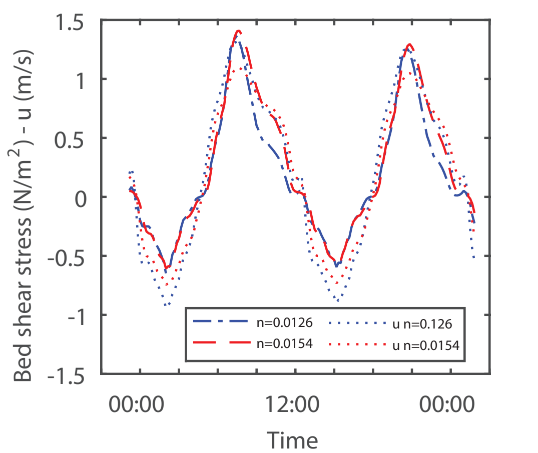

Figure 8: *Sensitivity analysis: deviated roughness to bed shear stress and depth averaged flow velocities*

The peak of the bed shear stress signals are higher for a higher roughness value. A higher roughness value results in lower flow velocities, and a lower bed shear stress is expected. However the roughness value itself is also included in the bed shear stress formula, wherein a higher Manning value can lead to a higher bed shear stress (Deltares, 2014).

Numerical Model Results

To identify erosion and sedimentation in the model the bed shear stress output values are used. The interpretation of the results rely on the assumption that sedimentation occurs with bed shear stress values lower than $0.2\,\mathrm{N}\mathrm{m}^{-2}$ and erosion occurs with values between $1\,\mathrm{N}\mathrm{m}^{-2}$ and $2\,\mathrm{N}\mathrm{m}^{-2}$ (Deltares, 2015).

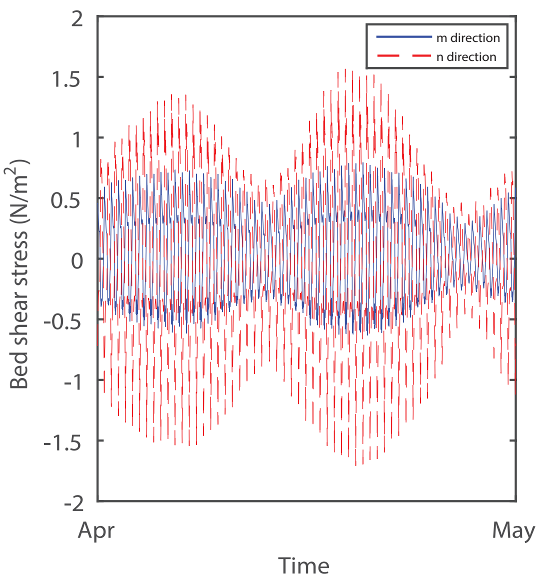

Figure 9: *Simulated bed shear stress at the Inner Bar in dry season*

Figure 9 shows a graph of the bed shear stress in the Inner Bar area. The smaller amplitude line is in the m direction of the model (east-west) and the large amplitude line is in the n direction (north-south). In the n direction the shear stresses are above $0.5\,\mathrm{N}\mathrm{m}^{-2}$ most of the time. The n direction is the main direction of the tidal flow, which explains the higher values. The m direction shows much smaller values, only for short times above $0.5\,\mathrm{N}\mathrm{m}^{-2}$. In the m direction the flows of the Yangon River and the Bago River come together from opposite direction, which may result in the lower bed shear stress amplitude. The values in the m direction are low, but however do not indicate sedimentation with certainty. The graph is shown for the month April in the dry season, a plot in wet season would be almost identical following small influence of the discharges observed in the sensitivity analysis.

The spatial representation of the bed shear stresses in the Inner Bar area in Figure 10 clearly show a drop of the bed shear stresses where the river flows come together. This again may indicate sedimentation at the Inner Bar area, but the same pattern does not show for all time steps.

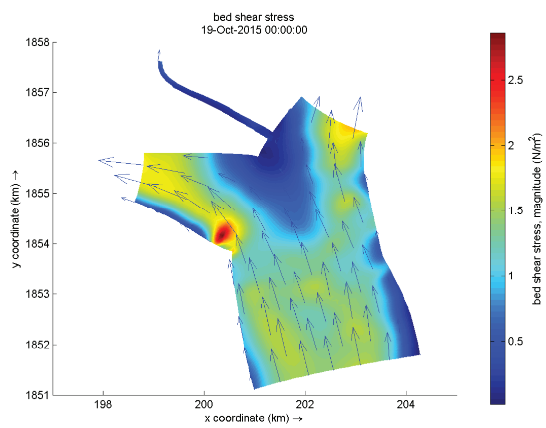

Figure 10: *Spatial representation of bed shear stress with vectors*

IV. Discussion and Recommendations

Computational Grid

A recommendation to reduce computation time and increase workability of the model is to reduce the grid resolution in the upstream region of the domain. The most effective approach is to rebuild the grid in the Flexible Mesh module of Delft3D. This module enables the coupling of different mesh types, simplifying the process of creating areas with a high resolution grid coupled to areas with a low resolution grid.

The model area around the Inner Bar is captured in approx. 500 grid cells, assuming the same grid cell dimension. The area of interest can be expanded downstream to include the whole access route to the Yangon Port. This area can be captured in approx. 2000 grid cells. The grid is set up to create space for the tidal wave, essential to represent physical processes correctly. The grid outside the area of interest is built up out of approx. 20000 grid cells, consequently taking up over 75% of the computation time of the model. The model results outside the area of interest are based on schematized bathymetries and therefore of little importance. This inefficient use of computation power is a limitation of the grid creation module in the Delft3D modelling suite. A favourable situation is a drastic decrease of grid density upstream of the area of interest without losing resolution in the area of interest.

Model Processes

The current model is hydrodynamic, which implies that only flow phenomena are described by the model. The erosion and sedimentation pattern is described through the hydrodynamics since the parameters are closely linked. This is sufficient for a *qualitative* analysis. Delft3D-FLOW is however also capable of doing *quantitative* analysis of transport phenomena by including their processes in the calculation. The processes sediment, salinity and secondary flow can be added to the calculation.

A recommendation for including sediment into the model is not easily drawn. With the sediment module it is possible to expand the model into a sediment budget study and it will also enable the study of bed level changes. Delft3D-FLOW is able to include bed load and suspended load sediments, both of non-cohesive and cohesive types Deltares (2014). With the salinity module the interaction between the fresh water discharge and the salt water tide can be studied. As a consequence of the density difference between fresh and salt water a salt wedge is moving over the river bed. This salt wedge reacts with sediment particles on the bed causing flocculation. This flocculation is increasing the particle size of the sediment and causes settling of sediments (Nelson, 2000).

Including the sediment and salinity processes enables the study of more complex sedimentation processes around the Inner Bar that a qualitative analysis does not allow. Including the additional processes however comes at a price. Adding processes has a negative influence on the computational complexity of the model. Also they require additional data as input for the model. The sediment module requires data about suspended sediment concentration on all boundaries throughout the year and it also requires data about bed material, while data availability is low in Myanmar. Also the sediment module will drastically increase the computation time of the model (Deltares, 2014). Including it requires a more efficient computation of the model or a major increase in computation power. A complete morphological study also requires a 3D domain to include vertical processes like density currents and (turbulent) interactions between the current and the river bed, which will increase the model complexity even more.

Salt intrusion of the Ayeyarwady delta is studied by Attema (2013) and a more detailed continuation of this study is recommended. The salinity module requires readily available data about salinity concentrations and it is recommended to include it in further study. Apart from sedimentation the salinity module can also study the salt intrusion in the model domain. How far inland the salinity values rise above 1ppt is an important measure for the usability of water for irrigation of farmland.

It is also recommended to include the secondary flow process in continued study. The process is an addition to the momentum equation solver of Delft3D-FLOW and can be added to the 2D model to include transverse flow effects in bends and may therefore increase the model accuracy in the complex flow situation at the Inner Bar (Deltares, 2014). The process increases the computation time of the model, but it requires no additional data or input.

Data and Boundary Conditions

A strong recommendation is to increase efforts into data collection in Myanmar. The amount of data sets should increase and the quality of the data sets should improve. The quality of the model output relies on the quality of the model input. The model data and boundary conditions for the hydrodynamic model consist of the bathymetry, bed roughness, river discharges and a tide signal. The bathymetry of the model around Yangon is implemented from a naval chart which had its last update in 2007. No other maps were available. The upstream reach of the model area relies on a schematization of bathymetry and cross section dimensions. This schematization may reflect the amount of water and the filling and emptying of the branches incorrectly.

The bed roughness is imposed as a constant value over the domain which is a conservative simplification of reality. The bed roughness may have considerable spatial variations in the domain, which has an impact on the movement of the tidal wave and subsequently the flow patterns. This simplification is one of the reasons that the calculated water levels are not matching with the measured water levels.

The river discharges are determined with a cumbersome procedure (see Section II) since only a handful of data points were available to calculate discharge values for every month for six rivers. The tidal signal at the river mouth is adopted from a different numerical model since the measurements are hard to obtain, their origin and measurement method is unclear and the measurements are lacking a clear reference level. For these reasons calibration of the model results with water levels still leaves a large uncertainty. Proper validation of model results requires a second data set, apart from the data set to which the calibration was conducted. This data is unavailable and therefore a validation is, at this moment, impossible. Also when one uncertain parameter interacts with another uncertain parameter, the result will have even more uncertainty. This makes it hard to obtain solid conclusions from the current model results.

If the model is expanded into a morphological model the sediment properties of the bed and the sediment supply at the model boundaries will have to be added. The availability of this data is low and therefore the reliability of the available data is questionable. Research by Nelson (2000) and Aung (2013) provide insight, but for example their discharge data contradict each other. An elaborate study into hydrodynamics dates from 1976 (UN, 1976).

Measuring campaigns require large funding and adequate policy and therefore the research into low-cost and easily executable measurements is a promising domain of development. Parallel to the set-up of this model a low-cost flow velocity meter is studied, see Janssen & de Koning (2015).

2D or 3D Model

A recommendation for continuation of the study is to keep the model in 2D (including morphology). Expansion into a 3D domain will have to be carefully considered. Only if the required data and efforts for calibration and validation and the increased computation time weigh up to the accuracy of results obtained by a 3D model it is worth doing so. Sloff et al (2012) states that it cannot be said in general that a 3D model is better than a 2D model and it needs to be evaluated on a case-to-case basis.

The model is set up in 2D and therefore uses depth-averaged quantities in the calculations. Expansion into a 3D domain and thus introducing vertical layers into the model provides a higher level of detail in the model. However the introduction of a 3D domain has specific implications, especially if the model is expanded into a 3D morphological model.

In a 3D domain the vertical layers are coupled through a hydrostatic pressure assumption and the use of mass conservation through the layers. For every layer added to the model, another set of equations is added to the calculation. Also morphological calculations are required to recalculate the flow field after an update of the bed levels. The height of the near-bed grid cells needs to be sufficiently small to correctly correspond to the three dimensional flow and morphodynamics. This greatly increases the model complexity and the computation time. Overall model performance improves with a fast calculation of the flow field (Sloff et al, 2012).

Specifically when the influence of sedimentation as a consequence of a salt wedge moving over the seabed is to be included, a 3D domain will be necessary in the model. The 2D depth averaged model is unable to reproduce the phenomena of flocculation in front of the salt wedge.

Additional Yangon Sedimentation Hypothesis

A recent theory into the sedimentation uses data of dredged volumes in the entrance channel. This theory is not used in this research but can be used as background information about the developments of the subject. The theory is nor tested thoroughly nor proven yet.

A review of data of dredged volumes revealed that there is three times more dredged material in the dry season than in the wet season. This seems contradictory to the large amounts of sediments that are carried by the rivers in the wet season. The hypothesis is that suspended sediments pass the Inner Bar without settling in the high-discharge period. The sedimentation is then caused by a dense mud layer floating just above the river bed moving with the sea water up and down the river. In the wet season this layer cannot move inland because of the strong momentum of the flow downstream, and the sedimentation can not reach the Inner Bar. In the dry season however this layer is able to move further inland and sediments are settling in the entrance channel (Yamamoto, 2015).

A more detailed calculation with additional model processes and higher quality data, as described in the subsections above, may reveal this theory to be well-grounded.

V. Conclusion

The model presents the hydrodynamics of the Yangon delta area where three rivers come together at a large confluence and interact with a strong tidal signal. The model is set up to reproduce the hypothesis that at the confluence, the Inner Bar area, intensive sedimentation takes place. The model is set up in 2D with depth averaged properties and through the bed shear stress parameter an indication of sedimentation and erosion is studied. The bed shear stress values around the Inner Bar do not show clear values that indicate sedimentation. However a spatial gradient between the bed shear stresses in the area is visible where the Inner Bar area shows smaller values than the deeper areas.

Calibration of the model with a water level time series at Monkey Point shows that the model underestimates the low-water levels, especially in the dry season. Surprisingly, the model does not seem sensitive to the discharge values imposed on the model boundaries. The tide signal and its corresponding discharge is completely dominant over the river discharges.

The model provides a starting point for further study into the sedimentation in the Yangon port area, using the recommendations set up in Section IV.

VI. Acknowledgements

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