Correlation Study between Modelled Bed Shear Stress and Fine Sediment Suspension from Dredging Operation Using MODIS Images

By

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14463

Dissertation submitted in partial fulfilment of

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CERTIFICATION OF APPROVAL

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Approved by,

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(Assoc. Prof. Ahmad Mustafa Hashim)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

SEPTEMBER 2014

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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(AARON KEITH PHILIP)

ABSTRACT

Lack in function in the well-known MIKE 21 Sediment Plume modelling for simulation of dredging scenarios had brought to a level of discrepancies between the model results and MODIS TSS measurement. This paper aims to determine the suspension of passive plume from dredging using MODIS images, in relation to the bed shear stress (BSS). MODIS images with 250m resolutions were used as standard for TSS measurement while BSS was derived from a calibrated model of the study area. Correlation study was conducted between MODIS and In-situ TSS and it shows an acceptable correlation of $?^2 = 0.5258$ and $?^2 = 0.2256$ at Seagrass and Paroo stations. Lower correlation between sediment suspension and modelled bed shear stress was achieved at $?^2 = 0.2519$, for BSS ranging from 0 to 0.3N/m^2 for BHD loading operation. However, strong correlation was observed for smaller bed shear stress range (from 0 N/m^2 up to 0.08 N/m^2) for TSHD loading operation with $?^2 = 0.9194$. It was found that the concerns due to the lower correlation coefficients achieved are because of factors such as MODIS resolution and the limitations to separate the long-term and short term sources.

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To my supervisors, Assoc. Prof. Ahmad Mustafa Hashim, Dr. Kim Parsberg Jakobsen, Dr. Claus Pederson and Amy Ling Chu Chu, I am truly humbled and grateful to have been able to work with such great people during the course of this project. The knowledge that I have gained through your guidance has evolved me and further defined my interest in field of Coastal Engineering.

I would also like to extend this credit to Mariaster Bt. Ham, Jennifer Chong and Hasmidah Bt. Hamzah for their kind assistance in providing me information regarding the project.

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CHAPTER 1 INTRODUCTION

Over the year, the scope and complexity for dredging is getting more and more advance with the assistance of the state-of-the-art engineering technologies available for mankind. Dredging is a human based activity that refers to the process of underwater soils or rocks removal from one point to the other by using dredger /1/. Dredger is defined as a floating vessel or plant equipped with mechanical tools suited for excavation /1/. Backhoe Dredger (BHD), Trailing Suction Hopper Dredger (TSHD) and Cutter Suction Dredger (CSD) are some of the popular type of dredgers used in many dredging project.

There are ranges of dredging applications such as excavation to build coastal structures' foundations and coastal defences; improving river hydraulic efficiency; to obtain sand for reclamation fill; and to improve the quality of environment at the vicinity of the project site by removal of contaminated bed materials to a safe dumping area /1/. The modern practice of dredging can be classified into two categories which are either capital or maintenance. A capital based dredging project deals with a one-time operation; whereas maintenance dredging relates to project that is being conducted repeatedly for a given contract.

During dredging operation, one of the critical elements is the generation of sediment plume. If the dredge derived sediment directly settle to the bed within a limited distance from the dredge source, the environmental impact would be easier to be assessed. However, the larger dispersion of these materials to nearby sensitive receptors surrounding the site may bring the attention of project proponents and authorities in terms of the further damages to the marine ecosystems. Therefore, detailed assessment on the environmental concerns due to the dredging works is at utmost important to prevent such catastrophe.

Therefore, consultants and contractors alike always opt for the use of sophisticated numerical modelling tools, such as MIKE 21 Mud Transport Module, to determine the fate of the transported dredge sediment. The result from the numerical modelling of the dredging operations can give primitive judgment on the potential environmental impacts to the vicinity and adjacent of the project site. Upon setting up the model, calibration and validation process needs to be conducted.

1.1 Project Background

Recent discoveries of an offshore gas field at the coast of Australia have brought to the construction of onshore facilities at the nearby coastline. To accommodate the economic demand subjected to the development, dredging for navigation channels to allow for freight transportation by vessels, construction of Material Offloading Facility (MOF) and laying of the oil and gas pipelines have been part of the master plan.

Construction of the navigation channel requires the assistance of dredgers such as Cutter Suction Dredger (CSD), Trailing Suction Hopper Dredger (TSHD) and Backhoe Dredger (BHD). Hopper barges were used together with the CSD for extra volume. During the dredging operations, there is a tendency for the dredger to overflow. At this stage, the dredge spoils were discharged back to the seabed through the valves system installed. As sediments were released from the dredger to the water column, some sediment may settle directly to the bed, while a very small amount be suspended and became passive plume. Source term may refer to the source of the suspended sediment or plumes from dredging work such as bed excavations, mooring, dredger overflow and disposal of the dredge spoils.

The surrounding project site is known to have high marine habitat densities which include sea grasses and tidal reefs. Thus, the plume dispersion from the source terms to the local map may impair these ecosystems if precaution and prevention actions were not taken.

Therefore, DHI Water and Environment had been granted to launch numerical modelling studies to assess potential environmental hazards to the surrounding marine environment associated with the dredging activities. Their work applies DHI’s MIKE series of numerical models which include MIKE 21

HD, MIKE 21 MT, MIKE 3 HD and MIKE 3 MT models. From this point onward, MIKE 21 MT module may also be regarded as Sediment Plume Model; and sediment refers to the fine cohesive sediment.

1.2 Problem Statement

Modelling the dredging scenarios using numerical approach requires certain inputs in the Sediment Plume Model as described briefly below:

1. Hydrodynamic Input
2. Advection and Dispersion Input
3. Boundary Conditions
4. Sediment Characteristics
5. Bed Characteristics
6. Dredges Logs
7. Spill Rates Data

Based on the list above, items six (6) and seven (7) are the key elements for any modelling of dredging operations. Dredge Logs data refer to the daily operations by the dredgers that consist of the source location. Spill Rates data, in the unit of mass flow rate (?? /?), are the estimated value of the source strength for each of the operation i.e. mooring, dredging or trailing, dredger overflow, dredge material dumping, or any combination of these processes.

Technically, when sediment is being released to the water column, there is a significant time lag before the generated suspended sediment would settle to the bed. Within the duration, the numerical model would assess the dispersion and transport of the material. It would also investigate the deposition, as well as the re-suspension of the materials to the water column. However, the MIKE model could not determine the amount of initial suspension if a given load (spill rate) is discharged to the sea from the dredger. The initial amount of suspension, hereinafter, refers to the percentage of spill. Currently, engineer has to manually define the percentage of spill value in the model setup.

To date, there were limited studies have yet been conducted to give guidelines on the percentage of spill. According to Bray, R et al (1997), quantifying the dredging spill from an operating dredger at higher degree of accuracy would be impossible regardless of the number of research to be conducted in the future. This is because of the complexity involved in the process of conducting physical works due to the effect of background turbidity from the previous generated plume, and because of the intricate behaviour of the fine sediment itself, which limits the requirement for water sampling for laboratory analysis purpose.

Therefore, in order to proceed with the Sediment Plume Modelling, assumptions have to be made on the amount of suspension of the fine sediment, regardless of the hydrodynamics condition at the spill area. The assumption was that 40% of the fine sediments would go into suspension regardless of the hydrodynamics and wave conditions (DHI Malaysia). Figure 1-1 shows an illustration of the dredger overflow and the respective sediment suspension and deposition conditions based on the assumed value. The assumed percentage of spill was constantly used throughout the model time domain and the numerical results were obtained.

Moderate-resolution Imaging Spectroradiometer (MODIS) data with 250m resolutions were used to validate the modelled result. MODIS is an instrument on board the Terra (EOS AM) and Aqua (EOS PM) satellites, respectively, to captures the trends occurring at the Earth's surface up to the troposphere level /16/. The MODIS images stores the actual Total Suspended Solid (TSS) data in the form of Tag Image File Format (TIFF) files and the data were processed using an extension of ArcGIS tool.

When the modelled results were compared to the measured data, there were discrepancies between the two sets of data especially in term of the spatial distribution of the plume generated at the source term – see Figure 1-2. It is expected that suspension of fine cohesive sediment cannot be constant throughout the temporal and spatial scales, but varies according to parameters such as flow of water, grain characteristics and many more.

Based on the above, there is a need to assess the suspension the moment the fine sediments are released to the water column due to dredging operations i.e. removal of bed material by cutting or suction, overflow and disposal. The current study is trying to relate the suspension to the bed shear stress parameter which was derived from the calibrated model.

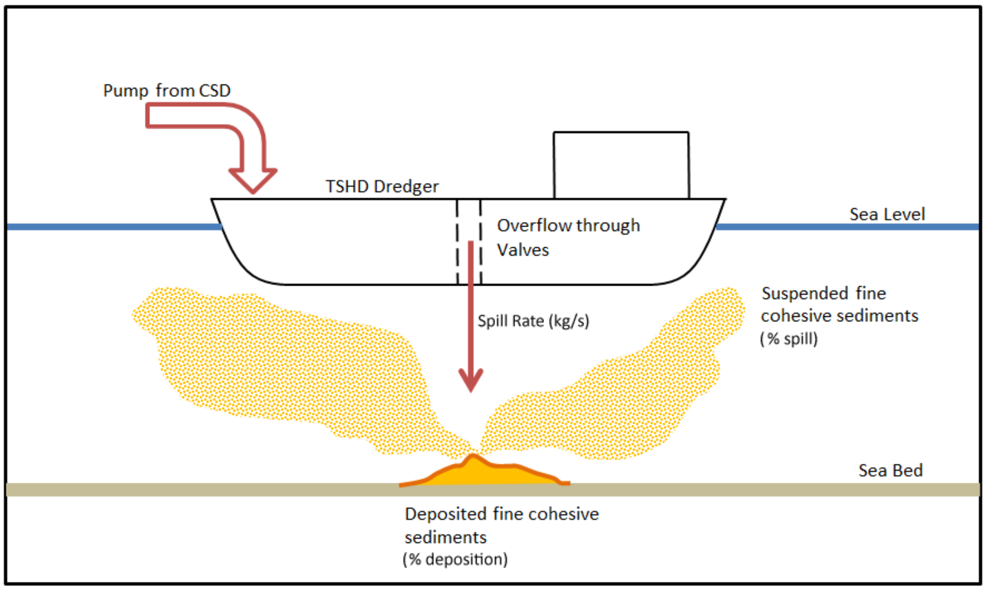


Figure 1-1 Illustration of TSHD dredger overflows through the valve system and the respective spill percentage used in the current model (regardless of the bed shear stress condition)

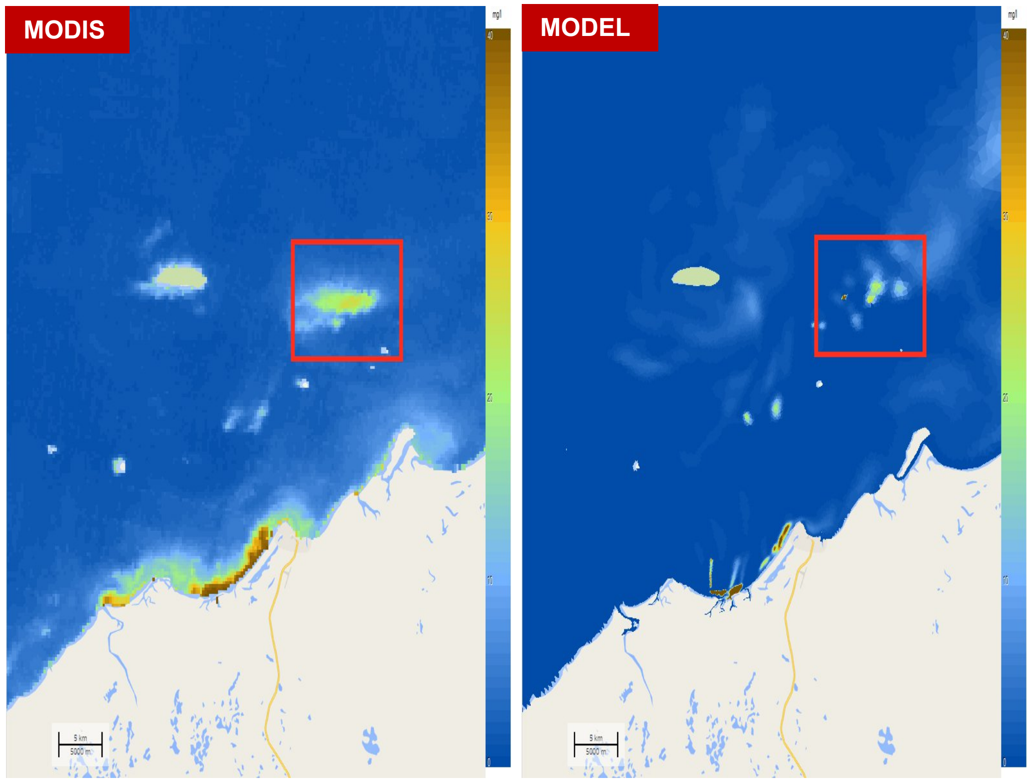


Figure 1-2 TSS data comparison (Left: MODIS, Right: Modelled).

1.3 Aim and Objectives

The aim of this research is to determine the correlation between the modelled bed shear stress and fine sediment suspension subjected to dredging, where the suspension values are obtained from MODIS images. To achieve this aim, the following objectives were defined:

1. To determine the suitability of MODIS as standard for TSS measurement by correlation analysis between MODIS TSS map and field measurement.
2. To determine the appropriate points for extraction of TSS, BSS and Source Strength used for the assessment.
3. To develop a relationship between bed shear stress and fine sediment suspension.

1.4 Scope of Study

The scope of study for this research focuses on the bed shear stress factor that contributes to the suspension of dredge materials. Only the TSS from MODIS will be used to provide the fine sediment suspension concentration from dredging work. The research may have used other TSS/Turbidity related data such as ADCP backscatter; and in-situ turbidity data, but it will only be used to determine how close MODIS TSS data are to the field measurement. The mentioned data were not used to plot the suspension-bed shear correlation graph. The general knowledge on dredging activity and the fundamental behaviour of fine sediment i.e. deposition and suspension that relates to the bed shear stress must also be known. The knowledge of modelling using MIKE 21 Mud Transport Model and ArcGIS software are also the important elements in executing the project.

1.5 Relevancy and Feasibility of Study

The correlation study aims to assist engineers, in constitutions or industries, to calibrate their MIKE sediment plume model to produce a sound model setup. Eventually, this will further improve the quality of judgement in Environmental Impact Assessment (EIA) and Environmental Monitoring Plan (EMP) stages. In term of the feasibility of the project with respect to Final Year Project (I and II) durations, the project can be manage within the time frame provided that only the BSS parameters are studied with respect to the sediment suspension.

CHAPTER 2 LITERATURE REVIEW

Understanding the general properties of fine sediment is crucial for this research. The mechanism of dredging i.e. on how the dredgers remove the sediment from the bed; how the sediments were released to the water column during overflow or disposal period from either a dredger (TSHD) or hopper barge; and how the sediment behaves as the they were released from a vessels are some other important elements that need to be apprehended to help in the analysis of data. These components are briefly explained in this literature review to allow for better understanding of the project.

The use of MODIS images for assessment of TSS distribution in an open channel i.e. lake, river mouth and ocean have been extensively used by most researchers such as in /9/, /16/ and /19/. With respect to dredging operation, /16/ had attempted to study the spatial distribution of resuspended sediment from dredging operation using MODIS and numerical data, which to some extend relates to the current study. Although, the paper did not quantitatively studied the amount of sediment released to the water column soon after the discharged of material from the dredger and relates to the bed shear stress during the event. Nevertheless, the research suggested that the strength of the dredging source and the wind-induced current will affect the concentration level and dispersion of the suspended sediments /16/.

The study of fine sediment suspension, re-suspension and deposition in relation to bed shear stress are usually conducted in laboratory such are the work by /2/, /10/ and /11/. The experiments conducted were by using equipment such as annular channel and ring and straight open flume. The following section describes the findings:

2.1 Properties of Cohesive Sediments

Sediment, as defined by Van Rijn, is the fractions of rocks resulted from the physical and chemical weathering processes that occurs continuously at the surface of the Earth. The sizes may range from as small as colloidal particles to pebbles and boulders /17/. Cohesive sediments, such as silt and clay, are those particles with sizes less than 63 micron. For most cases, this sediment combines with additional organic matters and waste materials in the open channel (Mehta, & Partheniades, 1982) /11/.

2.1.1 Factors Affecting Sediment Resuspension

Resuspension is a term that refers to the process of reintroduction of deposited and consolidated sediment from the bed to the water column /12/. Since sediment resuspension are dependent on external forces, to be able to lift its own weight, it may also be defined as the:

"*…response to wave energy expressed by the velocity and measured in terms of sediment load or sediment concentration related to the local erosion rate or rate of material transfer at a point in the system.*" /12/

On the other hand, deposition is a process of settling of sediment to the bottom bed for a period of time before it will be resuspended to the water column /12/. The factors affecting the sediment erosion and resuspension process are summarized in Table 2-1. Although there were many elements influencing the erosion, resuspension and deposition processes, this document will focus on the effect of bed shear stress to the suspension of dredge spoils.

Table 2-1 Factors contributing sediment erosion and resuspension. Source /12/.

1.	Hydrodynamics	Bed Shear Stress	• Current and Waves • Boundary Layer Roughness
2.	Bed Resistance	Sediment Composition and Texture	• Organic Content • Clay Mineralogy • Cation Exchange Capacity (CEC) • Grain Size and Clay/Sand Percentage

		Pore Water Character	• Cation and Anion Composition • Sodium Adsorption Ratio (SAR) • Temperature • pH
		Eroding Fluid Character	• Salinity • Temperature • pH • Chemical Composition
		Bed Structure	• Sediment Density and Depth • Sedimentation/Consolidation Rate • Stress History

2.1.2 Effect of Bed Shear Stress

Bed shear stress refers to the shear induced by the velocity of currents to the bed. The erosion and deposition rates of sediments are strongly dependant to the bed shear stress in the system. In general, as the rate of flow of water increases, it increases the bed shear stress magnitude. Higher bed shear stress will leads to higher suspension. The concepts are as follow:

2.1.2.1 Concept of Sediment Deposition

Sediment depositions occur when bed shear stress is lower than the critical bed shear stress for deposition. The individual particles are able to resist the hydrodynamic forces, increases the fall-velocity and stick to the bed. For deposition, a full deposition was achieved when the bed shear stress is less than the critical shear for full deposition. Partial deposition was expected when half of the heavier flocs deposited to the bed while the remaining lighter flocs remained suspended. No sediment is deposited when the bed shear stress is higher than the critical shear for deposition. The following relationships represent the scenarios /17/:

For full deposition:

$$? \ = ? ? \ ?_{?,?} \qquad ??? \ ?_{?} \ < \ ?_{??,???}$$

For partial or hindered deposition:

$$? \ = ?? - ?_{??} ?? \ ?_{?,?} \qquad ??? \ ?_{??,???} < ?_{?} \ < ?_{??,????}$$

For no deposition:

$$? \ = 0 \qquad ??? \ ?_{?} \ > \ ?_{??,????} \ ?? \ ?_{??,???}$$

$$? \ h???: ? \ = ????????????? \ ?? \ ????? \ ???$$
$$?_{?,?} \ = ????????? \ ????????? \ ??????????? \ ?? \ ?????? \ ????$$
$$? \ = ??????????? \ (????????? \ ??????)$$

The reduction factor,? , can also be termed as probability, ? (Krone, 1962) /2/. Therefore, the resultant equation can be expressed as:

$$? \ = -???_{?,?} \qquad ??? \ ?_{?} \ < \ ?_{??,???}$$

$$? \ h???? \ = \frac{?_{??} - ?_{?}}{?_{??}} = 1 - \frac{?_{?}}{?_{??}}$$

According to the formulae above, the concentration of sediment in the water column is one of the governing factors controlling the deposition rate other than the bed shear condition. The result of Krone's study on the deposition of sediment is shown in Figure 2-1. The figure clearly implied that lower bed shear stress would promote higher deposition rate. Based on Figure 2-2, linear deposition rate increments occur in the region of flocculation with increasing concentration. Further increase in concentration ($? > 10 \ ??/?^{3}$), however, leads to hindered settling that reduces the deposition rate (partial deposition).

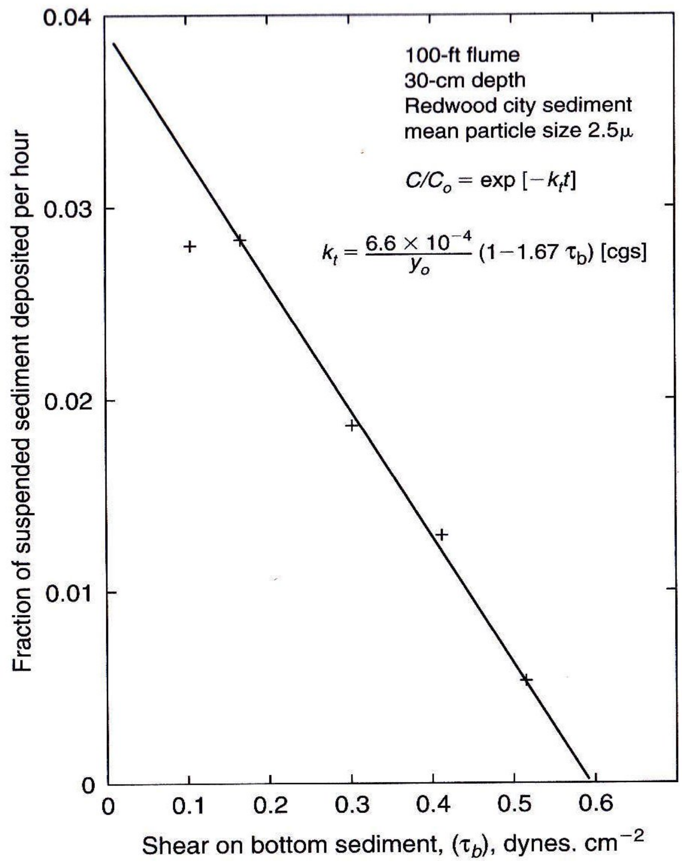


Figure 2-1 Experimental result for deposition of material in response to the bed shear stress /2/.

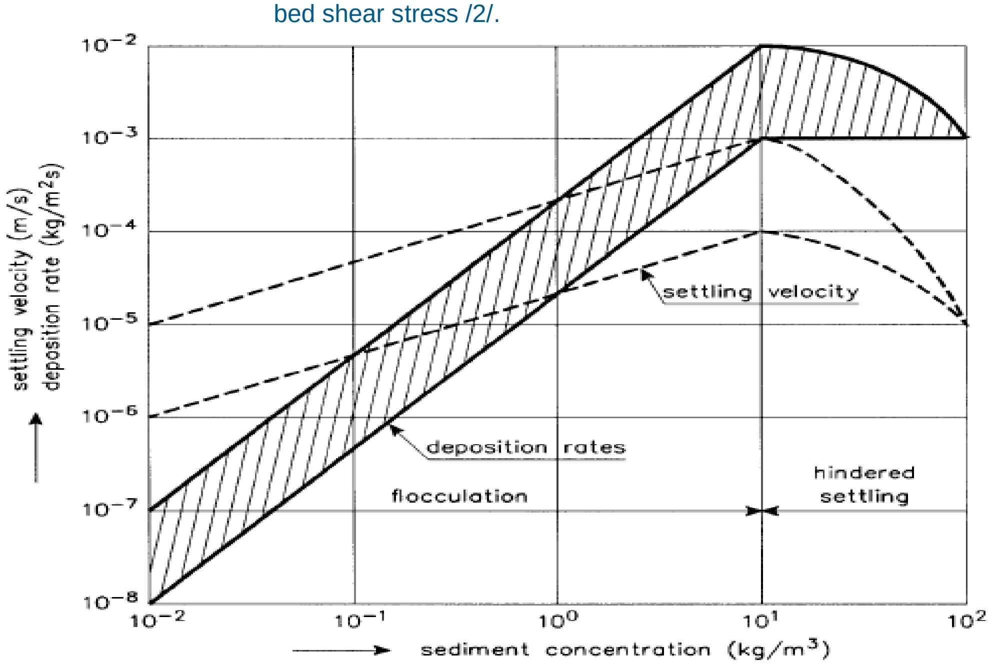


Figure 2-2 Deposition rate as a function of concentration during slack tide (maximum deposition will occur). /17/

2.1.2.2 Concept of Sediment Erosion

The erosion described in this section refers to the surface erosion of the bed. For most cases regarding dredger overflow and material disposal, surface erosion may not be as significant as compared to dredge spoil deposition rate, since the sources of dredge spoils came from the dredger to the bottom bed. Nevertheless, understanding the concept of fine sediment erosion at the bed could help in the development of the relationship between spill amount and bed shear stress. Surface erosion is a process of removing sediment from the soil to the water column due to the actions of the hydrodynamics forces.

The mechanism of erosion starts when the bottom shear velocity is slightly higher than the critical shear for initiation of motion. At this stage, the bed materials will start to rolls and/or slides from its original location with longer contacts with the bed. For increasing Reynolds number, saltation will occur whereby the particles jumps further above the sea bed. When subjected to turbulence flow, the particles are no longer in contact to the bottom bed, but instead remain in suspension state within the water column. This is because the turbulence uplift forces are equal or of higher order as compared to the submerged weight of the particles. /17/

There were many versions of empirical formulae describing the magnitude of erosion. Ariathurai (1974) presented the relationship between erosion rates in response to the change in the local bed shear stress by fitting Partheniades (1962) experimental outcomes as stated below. /7/

$$?_{?} = ?^{?\ ?} \; ?\frac{?_{?} - ?_{??}}{?_{??}}? , \quad ?_{?} > ?_{??}; \qquad 0 , \quad ?_{?} < ?_{??}$$

$? h???,\quad ?_{?} = ??????? ??????? ????$

$?_{?} = ??????? ???? ????????$

$?_{?} = ??? ?h??? ??????$

$?_{??} = ?????????h??? ??? ???????$

The accuracy of describing the erosion rate using the relationship above is more accurate for constant critical shear throughout the spatial domain (bed with constant density). /11/ had compared the erosion rate between a stratified beds and uniform beds. The studies concluded that the rate of erosion in stratified bed decreases with time and depth, whereas those in uniform beds were independent to the temporal and spatial variations. It was also founded that the rate of erosion is inversely proportional to the consolidation time. Van Rjin also stated that the degree erosion is greatly dependant on the deposition and consolidation history.

Taking into account for changing bed density (varying critical shear for erosion), Parchure and Mehta (1985) (described in /7/) developed the relationship below assuming the increase in erosional magnitude to the change in the depth, z, from the surface:

$$\ln \frac{?_?}{?_?} = ?(?_? - ?_{??})^{0.5} \qquad ?_? > ?_{??}(?)$$

$$? h???,\ ?_? = ? ??? ?????? ??????? \ ? h?? \ ?_? \ ????? ?? \ ?_{??}$$

$$? = ????? ?? ?????? ??????? ????? ?h? ??????? ??$$

The flocs erosion can be determine by plotting $\ln ?_?$ versus $(?_? - ?_{??})^{0.5}$, where $?_?$ is the intercept of the y-axis. /7/

The term $?\frac{?_? - ?_{??}}{?_{??}}?$ is a dimensionless parameter that either magnifies or reduces the erosion rate constant $?_?$ that affect the erosion rate. In short, it is a probability that determines the amount of eroded material in a given temporal scales.

Figure 2-3 shows the experimental results by /11/ using kaolinite to determine the erosive properties on consolidated soil. The experiment was conducted using annular flume-ring whereby the sediment concentrations were firstly mixed with highest shear stress over a period of time before the shear stresses were reduced to allow for deposition of materials. The flow of water then stopped to allow for further deposition of the remaining suspensates to the bed and to allow for consolidation of the soil. Afterwards, the bed was applied with increasing shear stress over a period of time /11/. Based on the result, it shows that with increasing shear stress applied to the bed, the concentration within the water column increases. The rate of concentration increment is observed to increase as the shear stress magnitude increases. There are three significant increment observed which are between $?_0$ to $?_{?1}$; $?_{?5}$ to $?_{?6}$; and $?_{?7}$ to $?_{?8}$. This indicates the existence of the required shear to initiate particle motion, saltation and suspension.

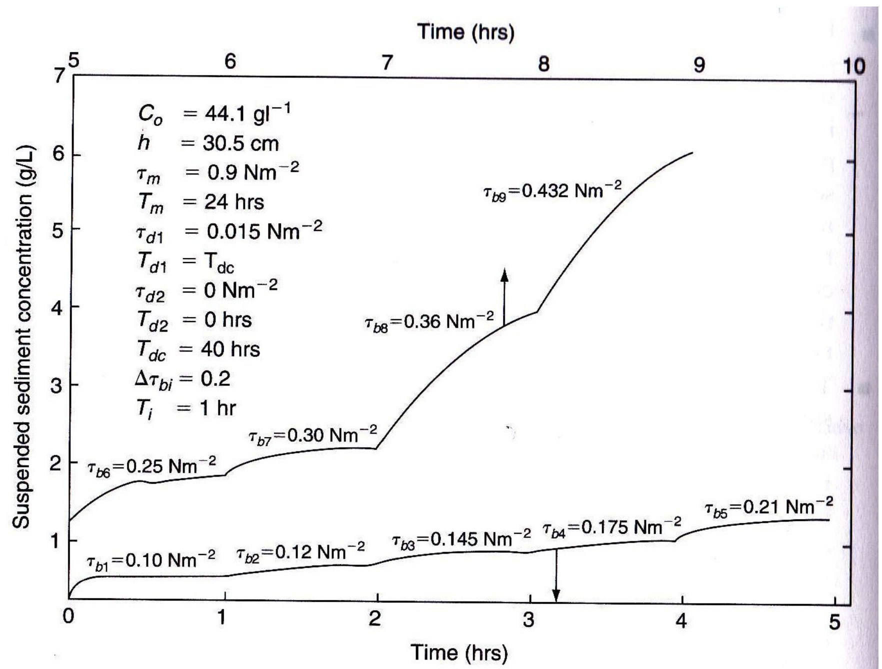


Figure 2-3 Suspended sediment concentration-time plot for kaolinite in salt water with varying shear stress applied across the bed /11/.

2.2 Sediment Behaviour during Dredging Operation

When sediment is discharged from a dredger, the generated plume will either be in dynamic phase or passive phase. Dynamic plume refers to plume that can moves naturally under its own volition. Reportedly, the concentration within the plume could reach more than 1 g/L. The factor that contributes to the generation of dynamic plume is mainly due to the type of dredger and its mechanism of dredging i.e. on how the overflow was conducted; and how the disposal of dredge material was carried out. The higher density provided by the mixture of sediment and water drives the plume rapidly to the bed. During this period, part of the dynamic plume will be stripped off from the system (especially the smaller particle sizes) and became passive plume as it is advected by the ambient current. The dynamic plumes that interact with the bed tend to move radially outward as dense plume with decreasing velocity due to the kinetic energy use to overcome the friction. Consequently, it forms weak deposits that could be easily eroded by a small magnitude of bed shear stress. (/8/, /13/)

The zone of influence of dynamic plume is usually within the range of 100m – 200m from the source /8/. This however varies according to the factors such as initial density and momentum of dredge spoil at the outflow; and the strength of the current /13/.

Passive plume, which is the main scope for this research, refers to the loss of sediment, during dredging operations and the loss from the dynamic system. The main factor contributing to the loss is due to external force such as the hydrodynamic environment. The concentration within the plume is observed to be very low in the order of hundreds of mg/L within the dredge area and reduces to tens of mg/L as it disperses to the adjacent surrounding /8/. This natural concentration level is very crucial if the suspended sediment mixture to behave as Newtonian fluid /14/.

While the deposition of sediment in dynamic plume can occur instantly upon contact with the bed, the deposition rates for fine particles within the passive plume may take hours to take into effect /13/. This, in turn, creates a very weak layer of erosive bed surface (mud layer), weaker than the bed properties derived from the deposition of dynamic plume's sediment. The dispersion may take kilometers away from the source depending on the magnitude and direction of the current /8/.

The general descriptions of the forces inducing sediment suspension are given in Table 2-2 based on /9/ and /14/. For more information of how each dredger generates different amount of suspensates can be found in /1/.

Table 2-2 Factors generating sediment suspension (/8/, /13/)

1.	Fluid Force	Shear Stress	• current • waves
2.	Dredging Technique	Dredger Type and Technique	• TSHD • CSD • BHD • Hopper barge disposal method
3.	Material	Properties of Sediment	• Particle size • Concentration • Flocculation/ Aggregation

Previously, a brief discussion had been given on the types of plumes the discharged sediment can exhibit. /18/ further classifies the negative buoyant plume into three categories as described below:

1. Density Current: Spreading of plume on the sea floor upon contact with visible radial of dispersion
2. Mixing: The released plume will follow the main flow of water and dissipate over the water depth.
3. Transitional: Possesses the characteristics of both density current and mixing partly because the processes occurred simultaneously.

Since the behaviour of the dredge plume is very similar with that of the buoyant gas plume released to the air e.g. factory smoke released to the open air as described by /18/, therefore the characteristic of the plume can be expressed in terms of Richardson number, R, and velocity ratio, ζ. /18/

$$? = \frac{???}{?^{2}}$$

$$\zeta = \frac{U}{W}$$

? h???, ? = ??????? ?????? ??????? ?? ??????? ???? ?

? = ????????????????????????????

? = ????????? ???? ?? ???? ? (???? ???? ?? ???????? ????)

? = ????????? ?? ?? ?????? ???? ???????? ?? ?ℎ? ?ℎ??′? ?????

? = ??????? ???????? ?? ???? ?

Figure 2-5 shows the relationship between velocity ratios to the Richardson number. At higher R, the dredge spoil will behave as density current and mixing process predominates at lower R region. It can be seen that dynamic plume possesses the density current due to its radial of dispersion and higher density. Passive plume classified as mixing as it directly mix easily with the ambient current upon its release to the water.

The experiment conducted, however, lacks in accounting the water depth as a parameter of concern – refer to Richardson number and velocity ratio equation. At larger depth, the released sediment plume might have longer time to mix with the ambient water before it reaches the sea floor. /18/

Figure 2-4 Density-driven plume dispersion. /18/

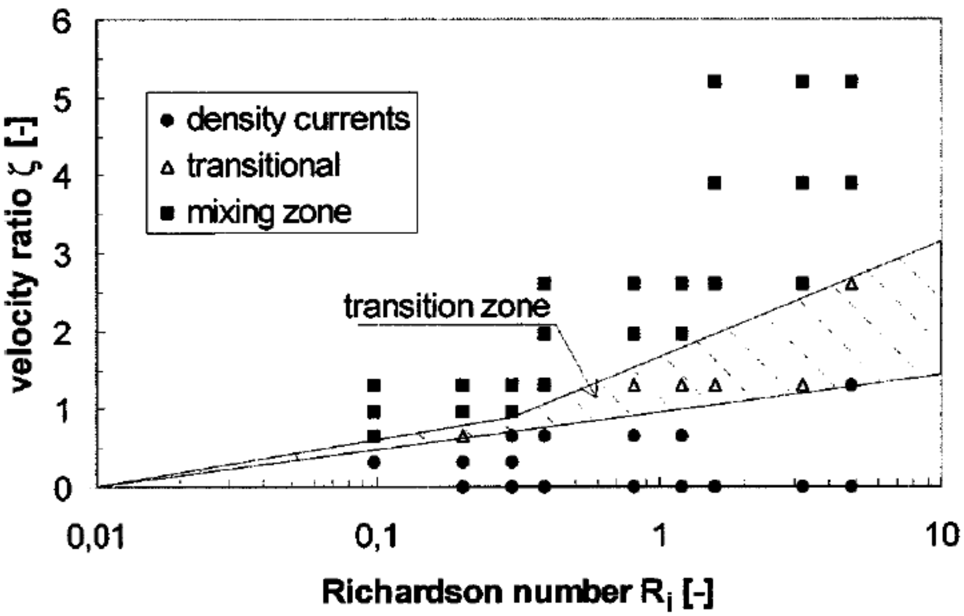


Figure 2-5 Classification of near-filed dispersion f dredging spill from TSHD in shallow water. /18/

CHAPTER 3 METHODOLOGY

This chapter discussed the principle idea on the method used to conduct the assessment in order to achieve the aforementioned research aim and objectives. This includes the description on the type of data used, selection of extraction points, and the analysis of the extracted data using suitable statistical tool. These elements, as well as the interpretation of data in the later part, require such high engineering skills in order to reduce the error of assessment. The extracted data includes the estimated spill rate, Total Suspended Solid (TSS) and Bed Shear Stress (BSS).

3.1 The Data

Although the main data used for the assessment are derived from MODIS (TSS), sediment plume model (BSS) and dredge logs (estimated spill), other types of data were also used to assist in the derivation of TSS and BSS from respective source file. The list below describes the overall data used for the assessment.

1. **MODIS TSS map**

   Remote Sensing data captured by the MODIS instrument on board the Terra and Aqua satellites that store the surface Total Suspended Solid (TSS) concentration and distribution at the vicinity of the project site. This research uses the MODIS with 250m resolutions. For more detail on MODIS data will be explained in section 3.1.1.

2. **MIKE 21 Sediment Plume Model**

   A numerical model of the study site has been developed by DHI Water and Environment Malaysia in which the hydrodynamics and wave conditions had been calibrated soundly. The calibration plots could not be provided due to confidential issue. However, according to DHI, the calibrated hydrodynamics and wave model are sufficient enough to provide the BSS parameter for the computation of plume deposition and re-suspension in the MIKE 21 MT model. This research will also use the generated BSS from the model to determine its relationship to the sediment suspension.

3. **Dredger Operation Logs**

   The data (i.e. date, time, location and estimated spill rates) of the daily operations (i.e. mooring, dredging/loading, overflow and disposal) of each working dredgers and its respective barges are summarized in the log file.

4. **Dredgers and Barges Coordinates Logs**

   File consists of the specific geographical coordinates of each working dredgers and hopper barges. The coordinates will be used to extract the TSS and BSS from respective sources.

5. **In-Situ Turbidity Measurement**

   In-Situ measurements of turbidity (NTU) measured at selected water quality stations. The measurements were taken at water depth ranging from 5 to 14 meters.

6. **ADCP Backscatter Data**

   Backscatter data obtained from transect survey that shows the sediment profile in the water column.

3.1.1 MODIS TSS Data

Usually, there are two (2) images available each day; morning from Terra EOS AM (hereinafter denoted as Terra), and afternoon from Aqua EOS PM (hereinafter denoted as Aqua). However, the numbers of usable MODIS images greatly depends on factors such as cloud coverage; image quality; and most importantly the available operations during the time of satellite overpass.

The MODIS data obtained for this research were processed by DHI-GRAS and are readily used for assessment. The algorithms used to derive the concentration from raw MODIS images were established based on the baseline conditions. Therefore, it should be noted that the MODIS TSS map used in this research has not been calibrated for sediments generated through dredging. Although, it has been reported that the concentration derived from MODIS tends to be a little conservative when compared to the model and in-situ turbidity measurement.

It should also be informed that MODIS represents the TSS at the surface. According to /9/, when MODIS is compared to the secchi depth measured at the upper water column of a lake, at depth above 0.4 meters, it gives RMSE and Mean Absolute Error (MAE) of 0.12 meters and 0.1%. The measurement was taken during rainy season during high stream flow, at which the fluctuation of TSS occur drastically.

Therefore, with these limitations at hand, it is very crucial to determine the reliability of MODIS to be used as standards for measurement of TSS. The methods to conduct such analysis will be explained further in section 3.2.

3.2 Analysis of MODIS to Field Conditions

As mentioned earlier, limitations that exist in MODIS data may produce higher uncertainties which would affect the reliabilities of result. Therefore, it is important to analyse the field conditions with respect to MODIS measurement. Although the method would not be able to reduce significantly the level of uncertainties, it may be possible to determine the effect the uncertainties in the final results obtained.

There are two (2) analyses that need to be conducted to provide a level of confidence in using MODIS for measuring TSS.

1. Correlation assessment between MODIS and in-situ turbidity measurements.
2. Sediment profile assessment.

3.2.1 Correlation Assessment between MODIS and In-Situ Methodology

The assessment will utilizes the TSS (mg/L) data obtained from MODIS and time series of turbidity (NTU) measured at controlled water quality stations. The turbidity loggers were installed at water depths ranging from 5 to 14 meters, while MODIS represents the surface TSS.

Determination of TSS is usually obtained through laboratory analysis after samples are taken from the site either manually or using automated equipment /3/. However, many researches had shown a strong positive correlation between TSS and turbidity (/3/, /4/, /6/). It was reported that the correlation highly dependent on the particle sizes and distribution; whereby the relationship tends to underestimates for coarser sediments (Packman et al, 1999, mentioned in /4/; /6/).

A rough estimation for conversion of turbidity (NTU) to standard concentration unit (mg/L) was given below by /5/.

1 ? ? /? ?? ??? = 1.16 ? ? ? ′? ? ? ? ? ?? ???

The equation above was used for wastewater characteristics. For an open channel (i.e. Lake), a rough estimation was given by /15/ as shown below:

1 ? ? /? ?? ??? = 1.0~1.5 ? ? ? ′? ? ? ? ? ?? ???

However, these estimations are subjected to the particle size which would have affected the scattering of light for turbidity measurement /15/. According to /6/, a one to one relationship could be achieved for sediment mixture of silt and clay, but lower correlation was observed for composition comprising clay-only and mixture of coarse and fine materials. Therefore, to be practical with the site conditions (whereby the suspended material composes of silt and clay and taking into account the bed load component) the following conversion formula will be used for this research to derive the TSS from turbidity measurement:

$$1 ? ? /? ?? ??? = 1.1 ? ? ? '? ?????? ???$$

After the correlation plot between MODIS and TSS derived from the field measured turbidity had been established, statistical analysis by means of Root Mean Squared Error (RMSE) will be conducted to determine how close the MODIS TSS with the field TSS. The following equation will be used:

$$?? ?? = ? \sqrt{? \frac{1}{?} ?? \,{}^{?}_{?=1} (? ? ? - ? ? ?)^2_?}$$

$? h???:$

$?$ = ? ??????? ??? ?? ????

$? ? ?$ = ? ??????? ???? ???? ? ???? ????

$? ? ?$ = ? ? ? ?? ????

3.2.2 Sediment Profile Assessment Methodology

As MODIS represents the surface suspension of material, the sediment profile near the dredger or hopper barge need to be determined. The assessment will uses the ADCP backscatter data obtained during transect survey viewed through Aqua Vision Visea Software.

3.3 Extraction of Data

In order to establish the extraction points, the Dredger Operation Logs need to be referred for the operations that co-exist in the existing MODIS images. After the operation had been determined, the Date and Time references will then be used to determine the accurate coordinates of the respective individual dredger or barge found in the Dredger and Barges Coordinates Logs. The data extraction (TSS and Bed Shear Stress) will commence after the coordinates had been determined.

However, few concerns need to be aware off when establishing the extraction points. The first being is the existence of a river near the study site.

The presence of the river channel itself increases the background suspended sediment concentration at the near-shore zone, in addition to the Longshore Sediment Transport (LST) process. Therefore, in order to create sound results dredging activities operating within the distance of 10KM from the shoreline will be directly neglected from the assessment.

Another concern is the possible effect of the previously generated plume. This happens when a dredger is currently operating i.e. undergoing dumping operation; the old plume generated before from nearby area tends to migrate and affect the concentration level of the existing plume. This provides complexity as to assess the actual spill amount from the current operation. As such, high engineering skills are required to be able to differentiate between the old and the new plume.

3.4 Analysis of Sediment Suspension

The extracted data namely the estimated spill rate (? ? /?), TSS (? ? /?) and BSS (? /? ^{2}) will be processed accordingly using the method explained in this section. Based on the general idea of sediment suspension in relation to the bed shear stress, the following statement can be made. In essence, the amount of spill that will goes to suspension from a given rate is in the relationship shown below:

?′ = ?(?)?

? *h*???,

?′ = ????????? ?????

? = ????????

? = ??????? ?????? ?? ?*h*? ????????? ?? ??? ?*h*??? ?????? (?)

The relationship above shows that higher spill rates, in hypothetical sense, will generate higher suspension compared lower spill rates, given that the scaling factor, S, is constant. Higher bed shear stress will also generate higher suspension for a given rates. This, however, is idealized and simplified to the extreme, without considering the effects from any other parameters such as the effect from the ship's propeller, method of discharging or the homogeneity of the sediments load. For the relationship to valid, a very short time frame of the event is taken into consideration. As some amount fine sediments go into suspension the moment it was released to the water column from a vessel, there will be a significant time lag for the sediment to settle to the bed.

Therefore, the Scale Factor, S, which can also be regarded as the percentage of spill need to be determined by using the available data previously obtained. Normalization by mean method was applied to the estimated spill so to allow the data distributions into a common scale. The equation below was used:

$$?_? = \frac{?_?}{?}$$

? h???,

?? = ? ??? ????? ????? ???? ? ? ?$^{?h}$?????

?? = ? ? ??? ???? ? ? ?$^{?h}$? = ? ?????? ? ? ? ??? ????

The normalized spill rates will then be related to the MODIS TSS concentration as follow:

$$?_? = ?_? \cdot ?_?$$

? h???,

?? = ? ??? ????? ? ? ? ?? ??? ??????????????? ? ? ?$^{?h}$?????

?? = ? ? ? ?? ??? ??????????????? ? ? ?$^{?h}$?????

The normalized concentration, $?_?$, will be plotted against the respective BSS for assessment.

3.5 Key Milestone

The key milestone for this research is shown below.

PLANNING	**BACKGROUND RESEARCH BY CONDUCTING LITERATURE REVIEW** • Define problem statement, objectives and scope of study • Conduct literature review • Understand the available data
PRE-EXECUTION	**PREPARATION OF DATA** • Preparation of BSS data by running the model • Sorting of MODIS data • Preparation of working template to analyse the extracted data
EXECUTION	**CONDUCTING THE RESEARCH** • Conduct analysis of MODIS with field data • Selection of suitable data • Extraction of data • Analysis of data
POST-EXEUCTION	**CONCLUDE RESEARCH** • Interpretation of result • Tabulating and Plotting of results • Conclude research based on the results • Report preparation

Figure 3-1 Key Milestone of Project

3.5.1 Flow Chart during Execution of Project

For the general flow of methodology is given in the following diagram:

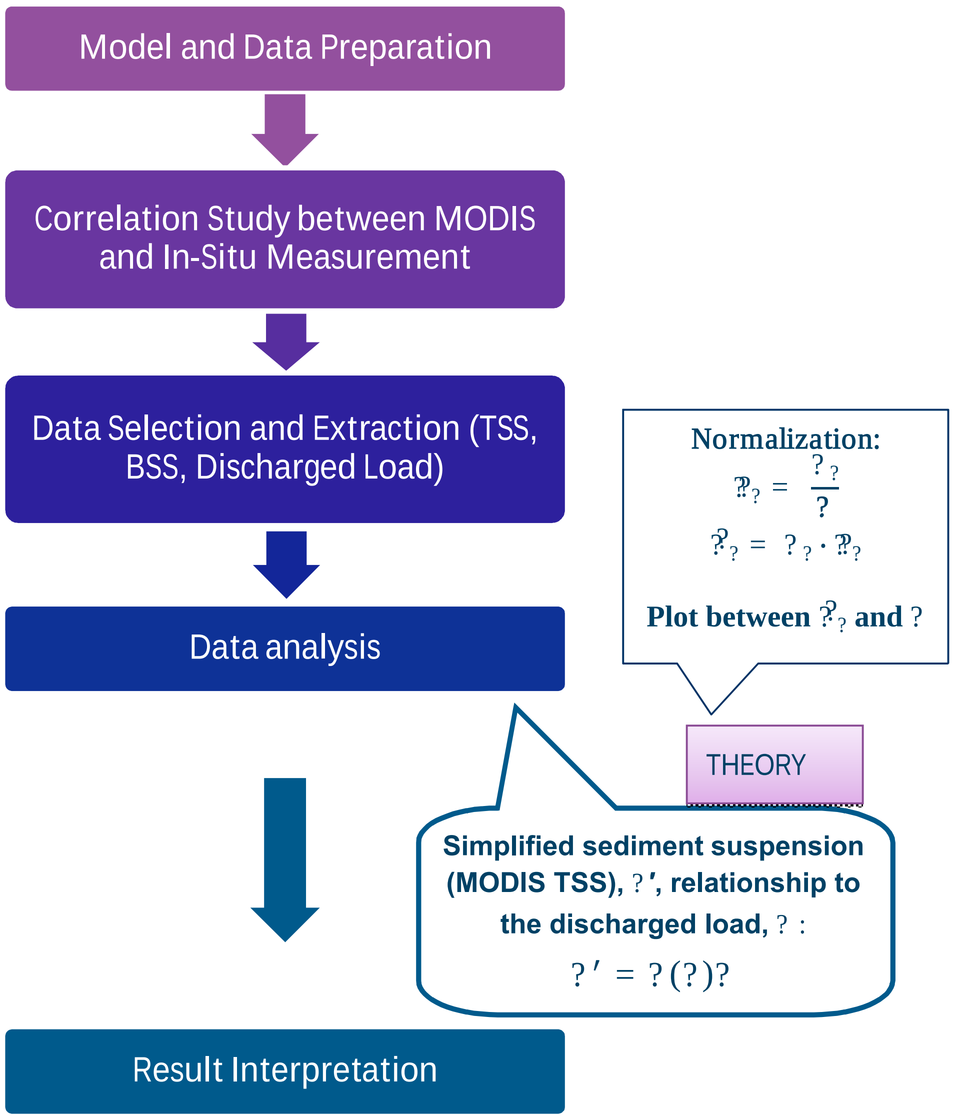


Figure 3-2 Flow chart of project execution

3.6 Gantt chart

The Gantt chart of activities for both first and final semesters are shown below:

Table 3-1 Gant chart showing the project activities during the first semester.

Main Tasks	First Semester (Week)													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Selection of topic														
Preliminary Literature Review														
Submission of Extended Proposal						●								
Detailed Literature Review														
Proposal Defence														
Data Collection														
Data processing and Analysis														
Interim Report Draft													●	
Interim Report														●

● Suggested milestone

Table 3-2 Gant chart showing the project activities during the final semester.

Main Tasks	Final Semester (Week)														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Data collection															
Data processing and analysis															
Detailed Literature Review															
Submission of Progress Report							●								
Pre-SEDEX										●					
SEDEX											●				
Submission of Draft of Final Report												●			
Submission of Dissertation (softcopy)												●			
Submission of Technical Paper													●		
Viva														●	
Submission of Dissertation (Hard Bound)															●

● Suggested milestone

3.7 Tools

The overall tools and software used to conduct the assessment were described in the table below.

Table 3-3 List of software and tools used to conduct the assessment

No.	Name	Function
1	MIKE by DHI	• Use to run the Sediment Plume Model to obtain the BSS. • Use to assist in the data analysis and interpretation by creating time series plot etc.
2	ArcGIS	• Use to create shapefiles for data extraction. • Use to run the MODIS data extraction toolbox developed by DHI.
3	Microsoft Excel	• Use for data analysis
4	Aqua Vision Visea Program	• Use for viewing of sediment profile from ADCP backscatter data.

CHAPTER 4 RESULT AND DISCUSSION

This section discuss on the result obtained based on the propose methodology.

4.1 Analysis of MODIS to the Field Observation

The analysis was conducted using field data namely the ADCP backscatter data and turbidity log as mentioned in Chapter 3. One of the reasons why the field TSS measurement (which could be derived from the backscatter and turbidity data) was not used as the main data for assessment is because the data were measured far from any source term. Within that distance, the plume may have been entrained with local current, reduces the concentration and dispersed to another area. As such, the data could not give the 'real' initial suspension concentration as compare to MODIS.

4.1.1 MODIS and In-situ TSS Correlations

The assessment uses the turbidity measured at two (2) water quality stations namely at Seagrass and Paroo. The TSS derived from turbidity was based on the rough estimation stated in section 3.2.1. The coordinates of the stations were used to extract a time series of TSS data from MODIS. The time series of TSS distribution comparing both MODIS and measured TSS at the two stations are shown in Figure 4-1.

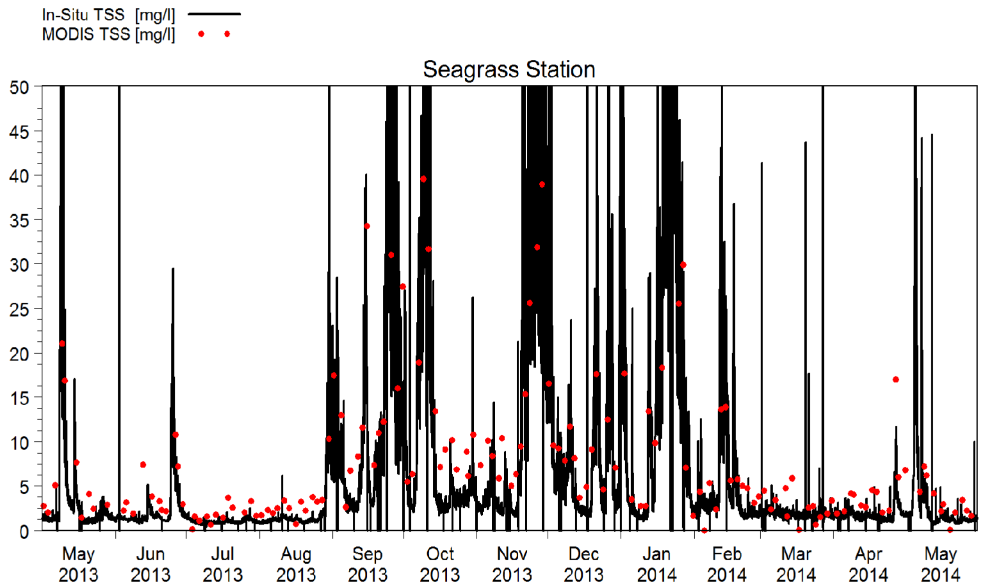
Figure 4-2 and Figure 4-3 show the correlation plots between MODIS and the estimated field TSS derived from turbidity at Seagrass and Paroo stations. A total of 407 points were used to plot the correlation at Seagrass and 391 points for Paroo. Table 4-1 shows the summary of the analysis.

Table 4-1 Summary of results for the MODIS-in-situ TSS correlation analysis.

Site	Correlation, r^2	RMSE (mg/L)
Seagrass	0.5258	5.729
Paroo	0.2256	2.168

Correlation at Seagrass shows an acceptable value with $?^2 = 0.5258$, while Paroo shows relatively lower correlation at $?^2 = 0.2256$. However, Paroo has lower RMSE value at 2.168 mg/L, which is 60% less than that from the Seagrass's RMSE. By relating to Figure 4-1, the reason is because the scattering of MODIS data at Paroo is seen more uneven as compared to Seagrass despite MODIS concentration able to capture the trend of the actual concentration. For Seagrass, it can be clearly observed that MODIS overestimate the suspension at lower concentration although with consistent distribution as the actual suspension. Both time series plots show that at higher concentration, MODIS tends to be underestimated, but it is able to capture the trend.

One of the reasons for the lower in correlation coefficient is due to the resolution of MODIS data. Coarse MODIS image resolution was used for this project, at 250m grid size. Therefore, MODIS represents the average concentration over a wide area instead of a point series. Other than that, it should be reminded again that the TSS derived from turbidity is just a rough estimation based on previous researches. The actual TSS concentration may slightly varies since turbidity measurement greatly affected by the particle composition and sizes within the water column. Nevertheless, the first analysis of MODIS to field data concludes that MODIS can be used as standard for TSS measurement for the sake of this project but it is subjected to uncertainties that could not be isolated from the data.



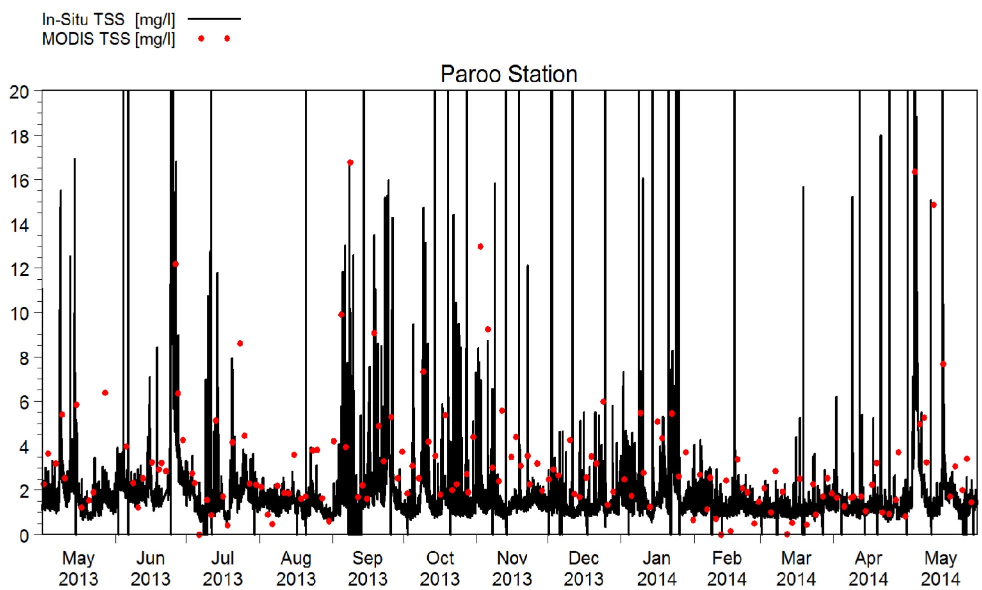


Figure 4-1 Comparison between TSS derived from MODIS and in-situ turbidity measurement at (above) Seagrass and (below) Paroo stations.

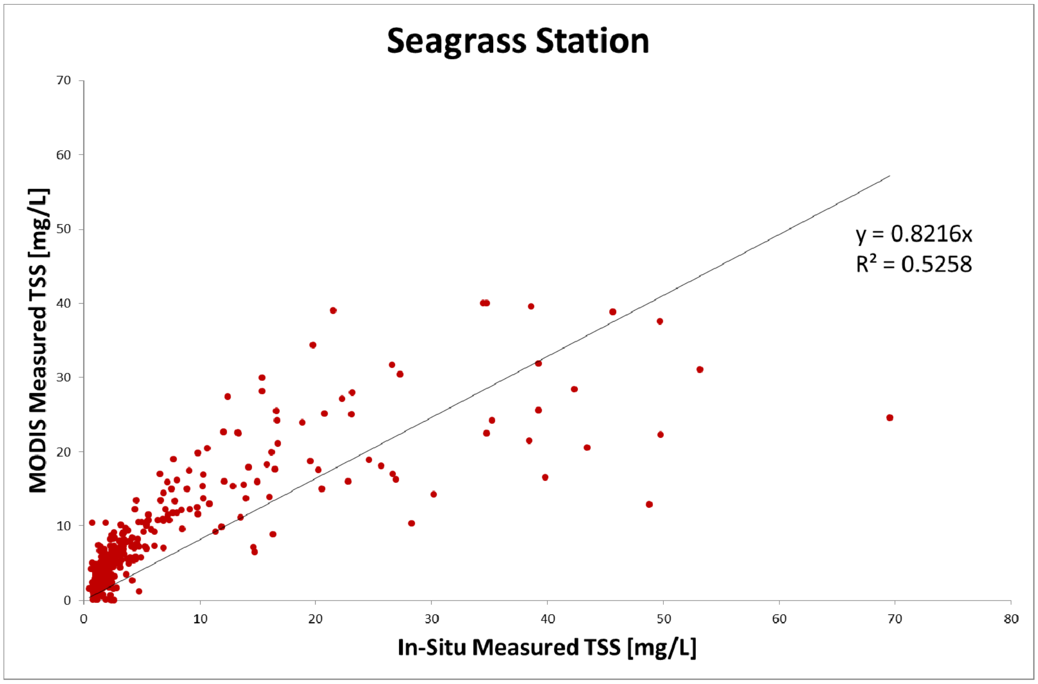


Figure 4-2 Correlation plot between MODIS and in-situ turbidity measured at Seagrass station.

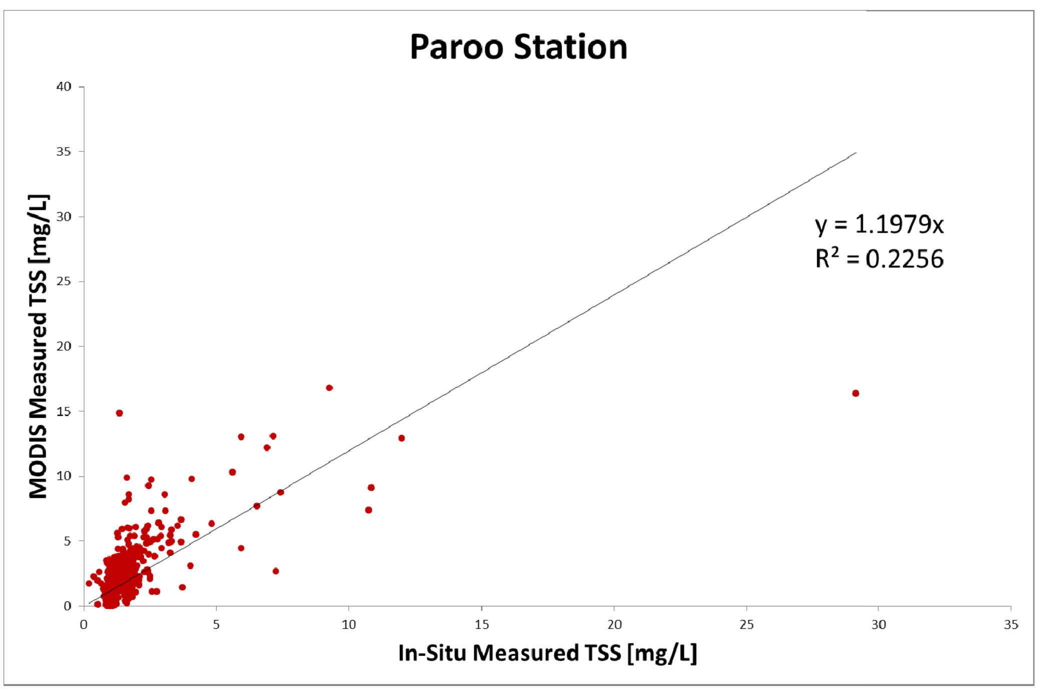


Figure 4-3 Correlation plot between MODIS and in-situ turbidity measured at Paroo station.

4.1.2 Sediment Profile Assessment

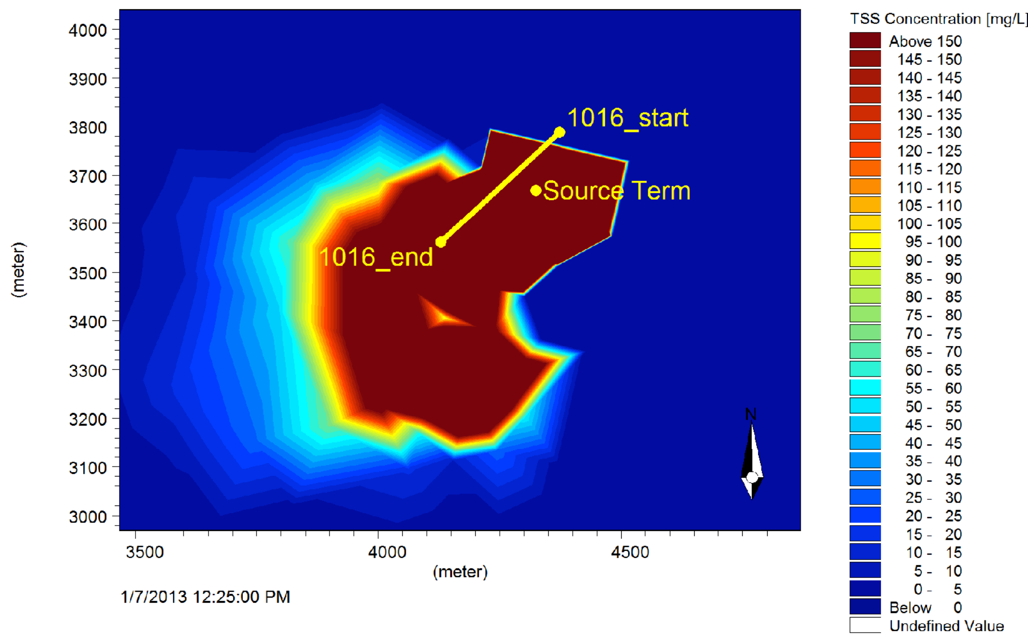
Two (2) sediment profiles closest to the working dredger were obtained from the ADCP backscatter data received during the field transect campaign. Both the chosen transects were having the same source term which was during CSD loading to TSHD with overflow reported. Table 4-2 shows the details of the transects.

Table 4-2 Transects details during CSD loading to TSHD with overflow on 1-Jul-2013.

No	Transect Name	Time of Survey	Distance from Source	Average Current Velocity
1	1016	1223 - 1227	72 m	0.31 m/s
2	1018	1240-1243	75 m	0.31 m/s

Figure 4-4 and Figure 4-5 show the transect location on the plume and the respective profiles obtained. The plume used in the plots was generated from the Sediment Plume Model and only to serve as indication for the location of the transect and source term over the spill area. It should also be informed that the sediment profiles shown were in terms of scattering magnitude, decibel (dB). The SSC derivation from the backscatter data was not performed since it was not within the main scope of the research. However, the sediment profile still could be determined based on the acoustic magnitude. In general, higher scattering level is required in highly turbid water and vice versa. This is because higher acoustic frequency is needed to be able to pass through a thicker layer of sediment that tends to block its path.

Based on the profiles, it can be seen that dispersion of plume from the source term follows the direction of current. Lower scattering level (green) was observed at one side of the transect path, while higher dB (orange - red) was observed at the other side. During the overflow period, it can be seen that higher scattering level (at 225 dB) is observed at the upper water column soon as the sediment is discharged from the dredger, and immediately disperse following the direction of current. At the same time, medium scattering (at 150 dB) was observed at the benthic region near the sediment source. Therefore, conclusion can be made that MODIS TSS may represent the passive plume concentration since the surface suspension shown by the backscatter data confirms with MODIS suspension properties.



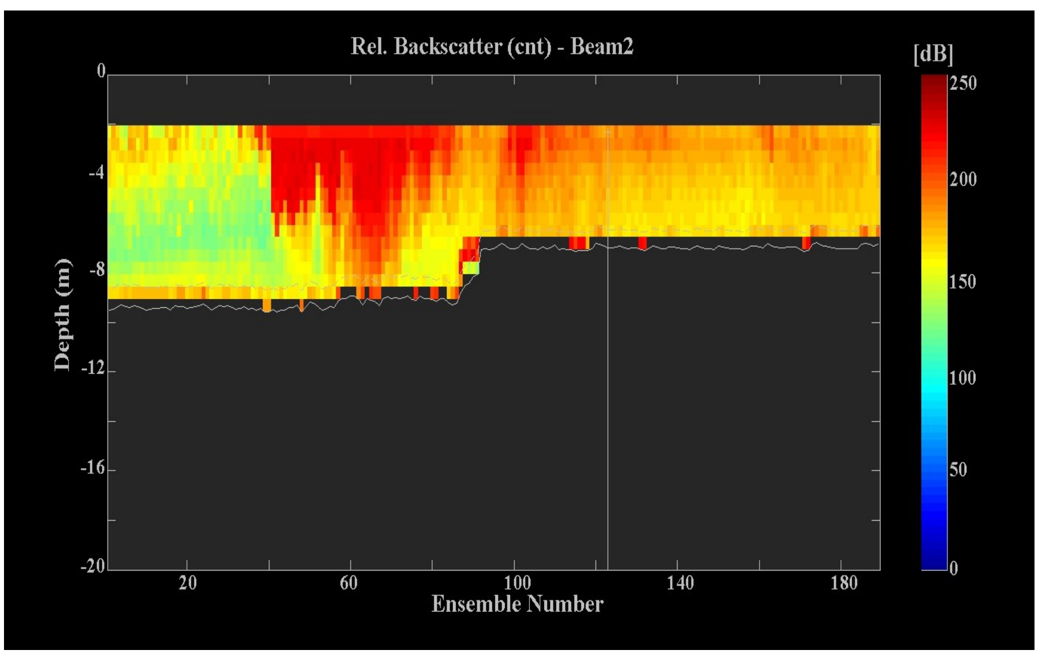


Figure 4-4 (Above) Transect 1016 overlaid on model generated plume. (Below) Sediment profile derived from transect 1016.

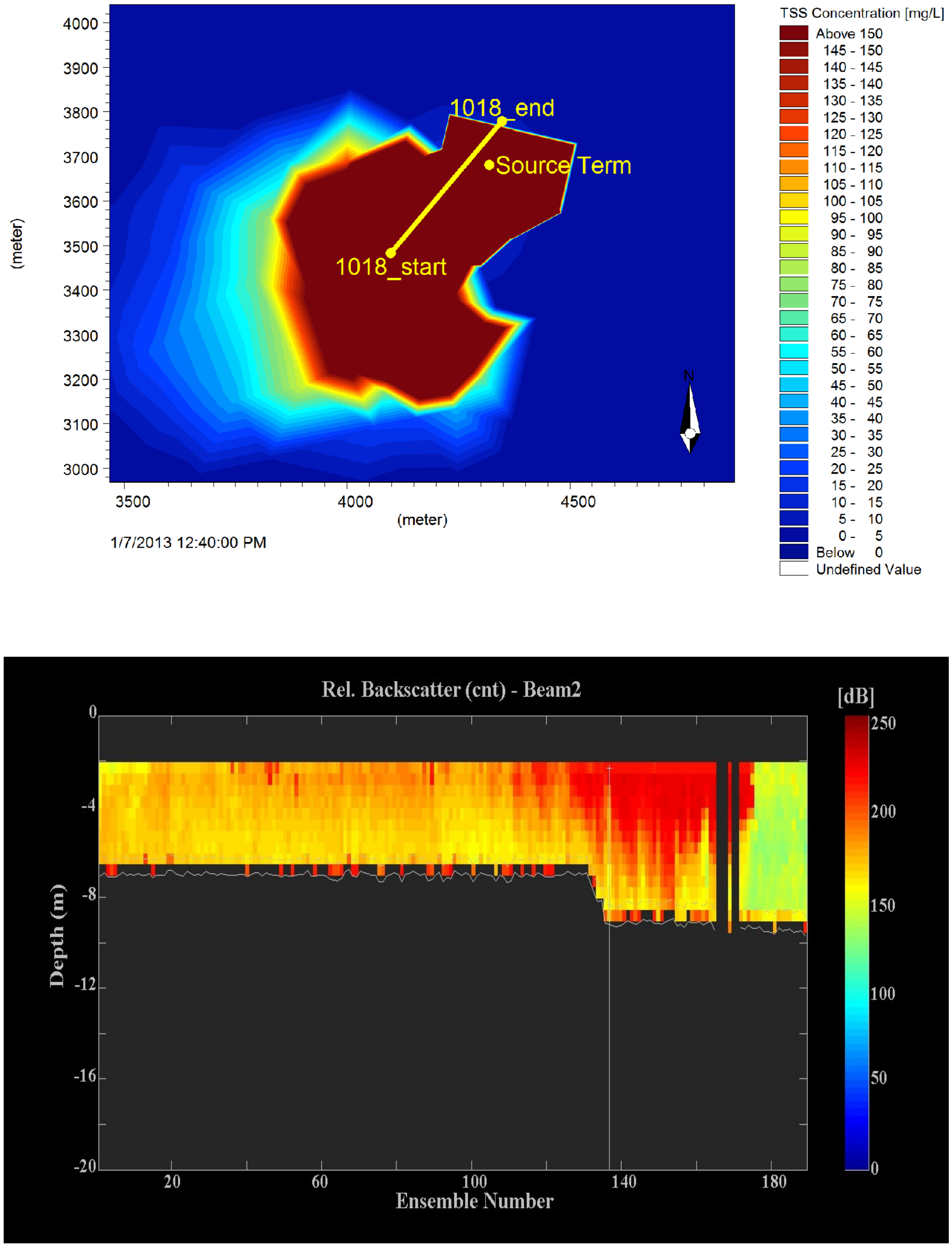


Figure 4-5 (Above) Transect 1018 overlaid on model generated. (Below) Sediment profile derived from transect 1018.

4.2 Sediment Suspension and Bed Shear Stress Correlation

A total of 60 points obtained from assessing 240 MODIS images were used to describe the relationship between the immediate suspensions of dredge material and the respective bed shear stress. The reason for the few numbers of data used for this correlation study was due to the unavailability of clear MODIS daily (due to the cloud coverage); and the absence of dredger or hopper barges that operates during the time of MODIS.

Apart from that, the major factor that contributes to the lower number data used was due to the elimination of points that did not meet the requirement to be considered as 'suitable' data – see section 3.3. It was observed that highest occurrence of operating dredger during most of the clear MODIS images were by CSD operation when it loads to its hopper barges (inclusive of TSHD) with and without overflow. However, since the effects from background turbidity were very high, the points were not considered in the assessment. Figure 4-6 shows the locations of the overall extracted points across the study area.

Figure 4-7, Figure 4-8 and Figure 4-9 show the correlation plots grouped according to the dredger types. The plot for BHD operation (Figure 4-7) shows relatively lower correlation at $?^2$ = 0.2519. Yet, this seems to be the best correlation coefficient achieved for wider BSS range compared to others. It can be seen that the plot vaguely agree that with increase in bed shear stress magnitude, the concentration also increases.

For operations by CSD barges (hopper barge and TSHD), very low (almost negligible) correlations was observed for hopper barges. The correlation for TSHD as barge to the CSD shows a negative gradient correlation between the two parameters. However, this is most unlikely since there are very few points to describe the overall correlation for the operation. At lowest bed shear stress, it was observed the suspension of material defies the hypothesis proposed. It was found that high suspension can still occur even during lower bed shear stress. This may have been caused by the current instead of the bed shear stress since the parabolic current velocity profile suggested that higher magnitude can be observed at upper water column and decreases exponentially to the bed. Therefore, since both hopper barge and TSHD dispose the material using open-door system, the sediment may have interacted with current first instead of the bed shear, causing suspension to occur even at lower bed shear stress. Other than that, as mentioned by /13/, the particle sizes play an important role in the generation of passive plume. Very fine sediment i.e. clay colloids are easily entrained to the ambient current due to its flakiness and self-weight.

For TSDH operating as dredger during loading only; loading with overflow; and disposal operation (see Figure 4-9), it was observed that there were not enough data that can be used to create the trendlines for disposal and loading with overflow operations. For loading only operation, there seems to have a positive correlation at the lower bed shear stress region. The single point at the upper bed shear stress magnitude found to be at lower concentration. However, since there is only one point that exists at the upper region of bed shear stress, it promotes ambiguity of the actual suspension at the respective shear stress. Re-plot of Figure 4-9 is shown in Figure 4-10 after omitting few of the data that is not sufficient to establish the correlation of interest. It was found that at lower bed shear stress region (range from 0 N/m^2 to 0.08 N/m^2), the concentration of passive plume generated from TSHD loading increase with increase in bed shear stress (correlation coefficient $?^2 = 0.9194$).

As seen to all of the correlation plots between sediment suspension and bed shear stress, the trendlines were not intersected to the origin (zero). This is because it was assumed that at zero bed shear stress, suspension may still be generated. However, the amount may not be significant as compared to when the hydrodynamic force is present.

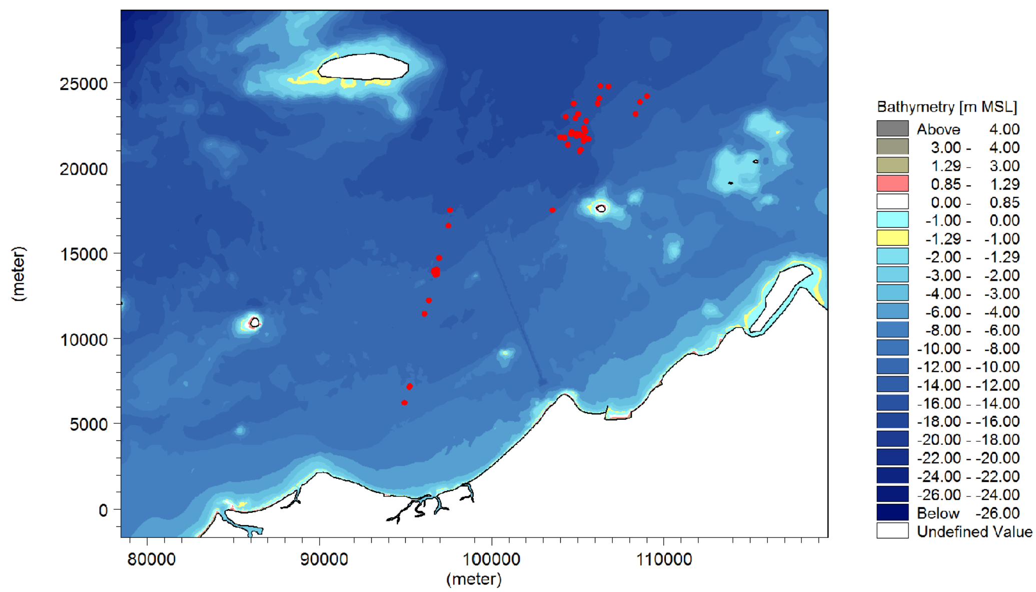


Figure 4-6 Location of extracted points across the study site.

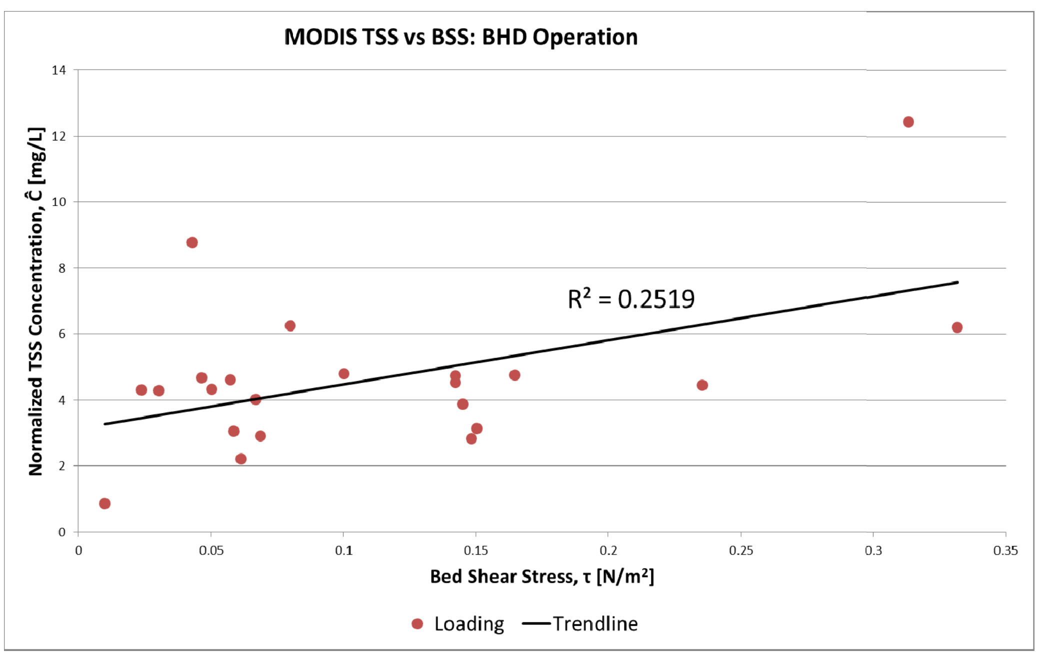


Figure 4-7 Correlation plot between normalized concentration and bed shear stress during BHD loading operation.

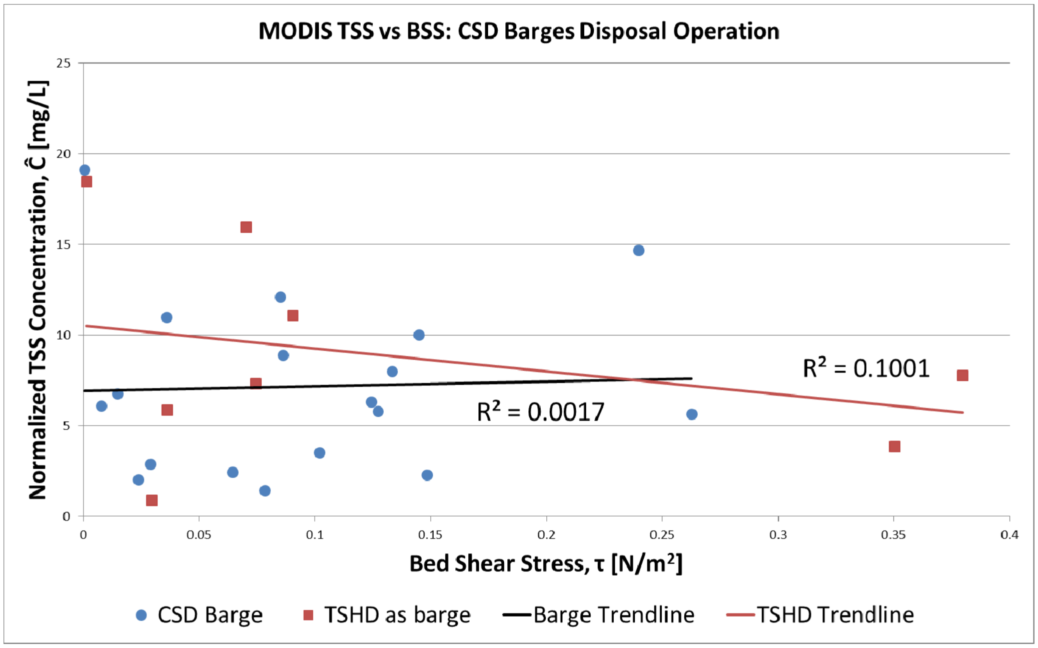


Figure 4-8 Correlation plot between normalized concentration and bed shear stress during CSD barges (hopper barge and TSHD) operation.

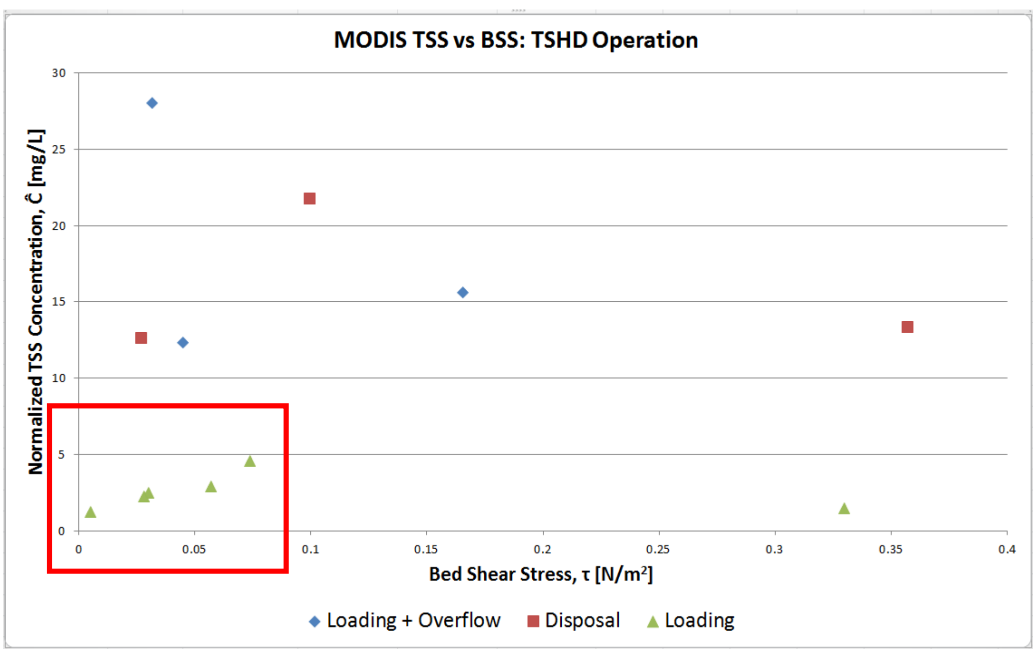


Figure 4-9 Correlation plot between normalized concentration and bed shear stress during TSHD working as dredger operation. The points enclosed in the red box are re-plotted in Figure 4-10.

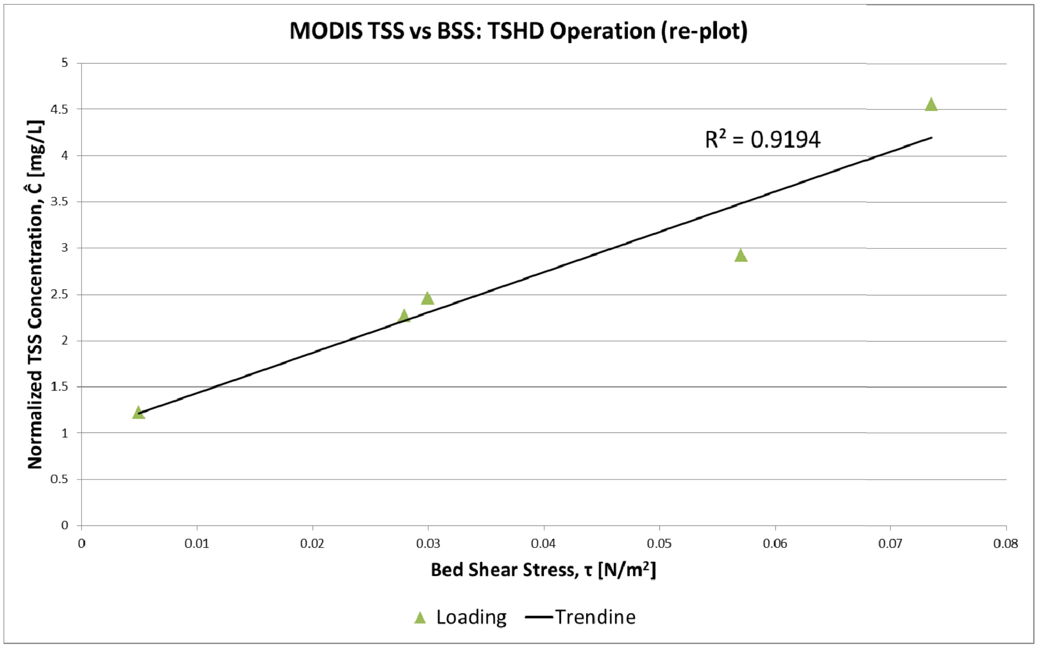


Figure 4-10 Re-plotted correlation between normalized concentration and bed shear stress during TSHD working as dredger operation.

4.3 Reliabilities of Result

There are various uncertain parameters that affect the results of the research. Although it had been discussed on the criteria to determine the suitable data for assessment, the uncertainties still have greater effect to the result obtained. These uncertainties, to a higher degree, reduce the reliability of the result, as well as creating a challenging situation for interpretation of data. The uncertain variable includes:

1. **MODIS Resolution**

   The use of coarser MODIS had brought to a degree of errors in measurement. Since this research uses MODIS images with 250m resolutions, the interpolations between points that are at 250 meters apart had cause the loss in the "actual" TSS at the immediate point of reference between the interpolation points. This is to say that MODIS represents the average surface TSS over a wide area, instead of point series. Because of this, there are possibilities that most of the concentrations derived from MODIS to be higher than expected.

2. **Dredging frequency, duration and load**

   A stationary dredger that frequently operates over a longer period of time generates higher sediment suspension concentration at the vicinity of the dredge. Thus, the immediate actual suspension amount for a given rate could not be determined due to the 'masking' effect of the on-going dredging. It had been discussed also that different operations contributes different source strength. The higher load tends to generate higher suspension as compared to the lower loads. Therefore, the significant increase in concentration has a tendency to contribute to the background suspension at nearby source (depending on the current magnitude and direction) as well as the source terms in the near future.

3. **Limitations in separating long-term, short-term suspension and resuspension of bed material.**

   One other critical element that needs to be discussed is the ability to separate the long term plume with short term suspended concentration, and the possible effect from bed material resuspension. Most of TSS measurements, either obtained using MODIS, ADCP or turbidity measurement, are the combinations of old and new plume and possible sources from bed material resuspension.

   For this research, it is very important that the immediate dredge spill to be isolated from any other source of sediments. This is because, through the effect of the tide current only (without considering the net currents), the plume tends to be brought from dredging back and forth over the dredge location, and the turbidity at any given time will be the resultant of the residuals from various loads. However, separating the plume cannot be achieved since the data used for this study were taken from uncontrolled conditions of the ocean, and there are limitations to determine the MODIS concentration level before any source terms were generated.

4. **Assessment method**

   The current assessment applies measurement of TSS based on point series. One of the limitations to the use of point measurement is the inability to describe the overall suspension across the individual plume from a single source terms.

5. **Lack of result data**

   As seen through most of the results obtained, the correlations for some of the operations could not be determined due to the lack of data.

CHAPTER 5 CONCLUSION AND RECOMMENDATION

The correlation between modelled bed shear stress and sediment suspension derived from MODIS had been obtained. However, the results could not support fully the hypothesis of this research whereby higher bed shear stress will produce higher suspension concentration. The main reason to this is because of the various factors that contribute to the uncertainties of the raw data. Nevertheless, some plots vaguely agree with the hypothesis proposed such as the BHD. A strong correlation was achieved at $?^2 = 0.9194$ for TSHD operation. However, it was only valid for bed shear stress between 0 N/m^2 to 0.08 N/m^2. At higher concentration however, the effect of increasing bed shear was unknown.

The use point measurement or ‘hard’ measurement to assess the suspension from coarse MODIS seems to be not the appropriate method in order to establish the correlation of interest. Visual assessment approach may seem to be more applicable since it may help in reducing the error due to the MODIS resolution. The approach may require assessing the plume concentration and size and then determines the appropriate percentage of spill. Afterwards, the percentage of spill will be used in the model to see for the effect.

It is suggested that the physical modelling of the dredging operation at controlled condition is highly recommended as it would reduce significantly the uncertainties involved. Other type of data such as series of ADCP backscatter data obtained during different water condition (i.e. higher and lower current season); installed very close to the source; and are free from the effect of background suspension and long-term spill are highly recommended.

It is important to note that this research is not entirely a new area that was just discovered, but more to improving the current knowledge of fine sediment characteristics and behaviours in the field of dredging. The theories i.e. deposition, resuspension, and any others relevant to this project were developed by past researches, and these ideas were put to use in the context of dredging process.

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APPENDIX

Appendix 1

Data for CSD operation

No	MODIS Date&Time	Dredger Type	Dredger Operation	Estimated Spill Rate[Kg/s]	Normalized Spill Rate (by mean)	MODIS Concentration [mg/L]	Normalized Concentration	Modelled Bed Shear Stress [N/m²]
1	28/07/2013 10:05:00 AM	CSD Barge	Disposal	97.9	1	7.99840498	7.99840498	0.133328
2	01/08/2013 02:05:00 PM	CSD Barge	Disposal	97.9	1	6.10256624	6.10256624	0.00772756
3	03/08/2013 11:05:00 AM	CSD Barge	Disposal	97.9	1	1.42271996	1.42271996	0.078312
4	07/08/2013 10:40:00 AM	CSD Barge	Disposal	97.9	1	2.02743006	2.02743006	0.0238704
5	08/08/2013 02:10:00 PM	CSD Barge	Disposal	97.9	1	5.80975008	5.80975008	0.127397
6	12/08/2013 01:45:00 PM	CSD Barge	Disposal	97.9	1	19.09664154	19.09664154	0.00052012
7	14/08/2013 10:50:00 AM	CSD Barge	Disposal	97.9	1	10.96238613	10.96238613	0.0359095
8	19/08/2013 11:05:00 AM	CSD Barge	Disposal	97.9	1	2.44845653	2.44845653	0.0643176
9	20/08/2013 02:35:00 PM	CSD Barge	Disposal	97.9	1	6.33401203	6.33401203	0.124281
10	29/08/2013 10:05:00 AM	CSD Barge	Disposal	97.9	1	2.87744427	2.87744427	0.0289845
11	07/09/2013 10:00:00 AM	CSD Barge	Disposal	97.9	1	14.67325592	14.67325592	0.239853
12	07/09/2013 02:20:00 PM	CSD Barge	Disposal	97.9	1	3.51688933	3.51688933	0.10208
13	23/09/2013 02:20:00 PM	CSD Barge	Disposal	97.9	1	8.90511131	8.90511131	0.0860439
14	25/09/2013 02:10:00 PM	CSD Barge	Disposal	97.9	1	6.75460911	6.75460911	0.0146897
15	26/09/2013 10:30:00 AM	CSD Barge	Disposal	97.9	1	5.65515232	5.65515232	0.262641

16	06/10/2013 11:05:00 AM	CSD Barge	Disposal	97.9	1	2.27669334	2.27669334	0.148402
17	18/10/2013 02:15:00 PM	CSD Barge	Disposal	97.9	1	12.10539722	12.10539722	0.0848952
18	23/10/2013 10:10:00 AM	CSD Barge	Disposal	97.9	1	10.00762749	10.00762749	0.14486
19	11/07/2013 01:45:00 PM	TSHD as barge	Disposal	97.9	1	15.93054962	15.93054962	0.0702722
20	12/07/2013 02:30:00 PM	TSHD as barge	Disposal	97.9	1	11.11032391	11.11032391	0.0903864
21	19/07/2013 02:35:00 PM	TSHD as barge	Disposal	97.9	1	5.86482143	5.86482143	0.0363449
22	25/07/2013 02:00:00 PM	TSHD as barge	Disposal	97.9	1	7.78171682	7.78171682	0.379704
23	05/08/2013 10:55:00 AM	TSHD as barge	Disposal	97.9	1	0.92491364	0.92491364	0.0296924
24	20/08/2013 10:10:00 AM	TSHD as Barge	Disposal	97.9	1	18.48509216	18.48509216	0.00136207
25	22/08/2013 02:20:00 PM	TSHD as barge	Disposal	97.9	1	3.86549807	3.86549807	0.350589
26	04/09/2013 01:50:00 PM	TSHD as barge	Disposal	97.9	1	7.34042215	7.34042215	0.0741924

Appendix 2

Data for BHD operations

No	MODIS Date&Time	Dredger Type	Dredger Operation	Estimated Spill Rate[Kg/s]	Normalized Spill Rate (by mean)	MODIS Concentration [mg/L]	Normalized Concentration	Modelled Bed Shear Stress [N/m²]
1	05/07/2013 02:20:00 PM	BHD	Loading	6.32	1	4.30175304	4.30175304	0.023813
2	10/07/2013 10:20:00 AM	BHD	Loading	6.32	1	4.79631948	4.79631948	0.100315
3	10/07/2013 02:40:00 PM	BHD	Loading	6.32	1	3.87215662	3.87215662	0.145088
4	12/07/2013 02:30:00 PM	BHD	Loading	6.32	1	4.60698795	4.60698795	0.0572409
5	15/07/2013 10:35:00 AM	BHD	Loading	6.32	1	2.21514249	2.21514249	0.0611755
6	25/07/2013 02:00:00 PM	BHD	Loading	6.32	1	6.21594954	6.21594954	0.331802
7	28/08/2013 11:00:00 AM	BHD	Loading	6.32	1	3.14614439	3.14614439	0.150426
8	30/08/2013 10:50:00 AM	BHD	Loading	6.32	1	0.85904342	0.85904342	0.0100738
9	30/08/2013 01:35:00 PM	BHD	Loading	6.32	1	4.68275642	4.68275642	0.0465585
10	31/08/2013 02:15:00 PM	BHD	Loading	6.32	1	2.90588021	2.90588021	0.0685972
11	01/09/2013 10:35:00 AM	BHD	Loading	6.32	1	4.27542496	4.27542496	0.030319
12	03/09/2013 10:25:00 AM	BHD	Loading	6.32	1	4.32065058	4.32065058	0.0502495
13	04/09/2013 01:50:00 PM	BHD	Loading	6.32	1	3.04805875	3.04805875	0.0584676
14	07/09/2013 10:00:00 AM	BHD	Loading	6.32	1	4.44951153	4.44951153	0.235438
15	07/09/2013 02:20:00 PM	BHD	Loading	6.32	1	4.52240086	4.52240086	0.142184
16	09/09/2013 02:10:00 PM	BHD	Loading	6.32	1	6.25752306	6.25752306	0.079851
17	10/09/2013 10:30:00 AM	BHD	Loading	6.32	1	4.7592454	4.7592454	0.164675
18	12/09/2013 10:20:00 AM	BHD	Loading	6.32	1	2.83137107	2.83137107	0.148226
19	12/09/2013 02:40:00 PM	BHD	Loading	6.32	1	4.02189493	4.02189493	0.0668196
20	23/09/2013 10:00:00 AM	BHD	Loading	6.32	1	12.45418453	12.45418453	0.313225

21	23/09/2013 02:20:00 PM	BHD	Loading	6.32	1	8.78380871	8.78380871	0.0428198
22	23/10/2013 10:10:00 AM	BHD	Loading	6.32	1	4.72990942	4.72990942	0.142336

Appendix 3

Data for TSHD operations

No	MODIS Date&Time	Dredger Type	Dredger Operation	Estimated Spill Rate[Kg/s]	Normalized Spill Rate (by mean)	MODIS Concentration [mg/L]	Normalized Concentration	Modelled Bed Shear Stress [N/m²]
1	10/09/2013 10:30:00 AM	TSHD	Loading + Overflow	750	2.120141343	7.36543894	15.6157716	0.165272
2	11/09/2013 02:00:00 PM	TSHD	Loading + Overflow	750	2.120141343	13.23562908	28.06140441	0.0317261
3	28/09/2013 02:40:00 PM	TSHD	Loading + Overflow	750	2.120141343	5.80759001	12.31291168	0.0448316
4	17/09/2013 10:35:00 AM	TSHD	Disposal	465	1.314487633	9.61822033	12.64303167	0.0268417
5	07/10/2013 10:10:00 AM	TSHD	Disposal	465	1.314487633	10.16024494	13.35551632	0.356967
6	12/10/2013 10:30:00 AM	TSHD	Disposal	465	1.314487633	16.54173851	21.74391069	0.0994605
7	13/09/2013 11:00:00 AM	TSHD	Loading	100	0.282685512	16.14363861	4.563572752	0.0735203
8	15/09/2013 10:50:00 AM	TSHD	Loading	100	0.282685512	8.70873833	2.461834157	0.0299685
9	16/09/2013 02:15:00 PM	TSHD	Loading	100	0.282685512	4.31831121	1.220724017	0.00492348
10	08/10/2013 10:55:00 AM	TSHD	Loading	100	0.282685512	5.30549908	1.499787726	0.32988
11	08/10/2013 01:40:00 PM	TSHD	Loading	100	0.282685512	8.04058266	2.272956229	0.0278975
12	23/10/2013 02:35:00 PM	TSHD	Loading	100	0.282685512	10.32402039	2.918450994	0.0570478