



ROYAL HASKONING



On the morphodynamics of Lagos Harbour

An exploratory study of the tidal system



MSc thesis
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Abstract

The city of Lagos, Nigeria is the nation's largest city and acts as an economical hub for the region. Lagos Harbour plays an important role in supplying the region with the logistic needs of the metropolitan area. As the population reaches over 15 million people and economic welfare increases, the need for imported goods is ever growing. The recent past shows a trend in more and increasingly larger vessels calling the port. As the ships become larger, the required navigational depth increases as well.

Currently, two small hopper dredging vessel carry out maintenance dredging operations in the main channels of Lagos Harbour: Commodore channel, Apapa channel and Badagry creek. Especially for Badagry creek holds that the current navigation channel is difficult to maintain at the desired depth. Experiences from the local sailors and port authority shows the problem is that there seems to be a lot of fine material being supplied to Badagry creek and that dredging efforts are ineffective.

A recent study on the bed material at the OKLNG plant site 100 km east of Lagos indicates that a large amount of poorly flocculated montmorillonite clay is present. This material has a very low settling velocity and may be transported as a fluid mud layer. The hypothesis for this thesis is that the same material is present in Lagos Harbour and is causing the navigational issues. The fine material causes the ships to become stuck in a muddy bed after spending time at a quay. As the settling velocity is very low, little dredged material will remain in the hopper's hold and overflow losses are significant.

The main objective of this thesis is to gain more insights into the behaviour of the tidal system. Early on in the study, it has become clear that no definitive conclusion could be drawn due to the lack of sufficient data. Instead, a hypothesis is presented on the mechanisms that cause the observed phenomena. Additionally, recommendations are made for future studies and an alternative dredging strategy.

The 10 day measurement campaign consisted of a bathymetric survey, soil analysis, water level and turbidity measurements and flow velocity, salinity and suspended sediment concentration profiles. The bed was surveyed using a dual frequency echo sounder which also measured the thickness of the top layer.

The original hypothesis stated that there is a large amount of material present in Lagos Harbour with a large content of montmorillonite clay which is the cause of the siltation problem of Lagos Harbour. Based on the soil samples and bathymetric charts, it can be concluded that this is not the case for

Commodore and Apapa channel. A layer of soft mud was encountered in Badagry creek and the Lagoon. Analysis of the material found that it has a low settling velocity and has a low zeta-potential which is not susceptible to changes in acidity. These are properties typical to montmorillonite clay and the hypothesis may therefore be justified. However, as the flow velocities in the main channels of Lagos Harbour are high, the material is easily eroded in the main navigation channels and certainly does not settle in these areas. It is therefore assumed that although fine sediments may cause problem to shipping in Badagry creek, this material does not affect the navigational depth of Commodore and Apapa channel. Here only sand is found on the bed.

A set of 7 OBS sensors was placed in Commodore channel to measure the sediment concentration. The results were not what one would expect for this channel as several sensors close to the bed showed aberrant results. The hypothesis for explaining these results is that the OBS sensors were affected by the local flow regime, distorted by abrupt changes in geometry and obstacles.

By converting the backscatter signal of the ADCP, sediment concentration could be estimated as well. This technique provides sediment concentration data for the entire surveyed cross-sections but has a significant error margin. Regular and extensive calibration of the ADCP results are required to achieve reliable measurements. During the 2010 campaign, neither sufficient time nor the proper equipment was available to do so and the ADCP results are therefore of limited reliability.

Measurements of the salinity and flow direction/velocity profiles in Commodore channel and Badagry creek show stratification of currents which are most noticeable during the turning of the tidal flow towards flood. Stratification of currents or salinity has not been observed in Apapa channel.

The density current has a strong effect on the sediment transport rates near the bed of Commodore channel and Badagry creek. Here, the net transport during an ebb/flood cycle is positive in the flood direction while higher in the water column and in Apapa channel, net ebb directed transport occurs. It is assumed that the discharge of rain water is responsible for the stratification in salinity and therefore the flood directed transport near the bed (except Apapa). The added discharge of rain water also causes the flow velocity during ebb to increase and thus sediment transport, especially higher in the water column.

The conclusions and hypotheses of this thesis are based on the data acquired during a short period in the rainy season. In order to confirm these

findings additional measurements and research is required. Not only in the dry season but during the rainy season as well as the 2010 campaign of 10 survey days was too short to properly survey the large and complex system.

It may be worthwhile to set-up a 3-dimensional morphodynamic model of the system to join the separate data sources and get a better understanding of the processes in the system, for instance, at the junction of the major channels. Haskoning already has 2d model of Lagos Harbour but as the effects of the stratification are neglected in a 2d model, this approach is inadequate to fully model the complex mechanisms.

The current dredging strategy with TSHD dredgers has proven inefficient for maintaining the navigation channel in Badagry creek due to the fine sediments found there. A promising technique for this problem is to use water injection instead. By bringing the sediment in suspension during ebb flow, the tide may carry the sediment out to sea as the fine material will hardly settle in Commodore channel. Water injection dredgers are cheaper to operate and without the need for sailing back and forth to the dumping location, the dredging vessel might even be more productive than a TSHD. The effectiveness should be researched as well as negative side effects to other parts of Lagos Harbour before implementing such a dredging strategy.

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1. INTRODUCTION

1.1 Background & problem definition

Located in the Southwest of Nigeria, Lagos is a metropolis with over 15 million inhabitants. As the economical centre of the country, large quantities of products are shipped in and out of the region via Lagos Harbour. With a fast population growth, the demand for imported goods increases rapidly which results in more and larger ships providing transport.

The Lagos Harbour Area consists of the adjacent Atlantic Ocean, several creeks and channels of various dimensions and the Lagos Lagoon. Figure 1-1 shows an aerial picture of Lagos and the main link between the Lagoon and ocean, Commodore channel. Main harbour activities take place in the region known as Appapa with quays marked as yellow in the figure below and Tin Can Island which is located directly west of this map along Badagry Creek.



Figure 1-1 Lagos tidal system with its main channels, the Lagoon and land masses.

Lagos Harbour experiences heavy siltation of its navigation channels. Currently (September 2010), constant dredging by two small trailing suction hopper dredging vessels (TSHD) of the Lagos Channel Management (LCM) is carried out to keep the port navigable. However, the efforts of the dredgers are not sufficient to maintain the channels at target depths. It is reported that some of the ships with larger draughts found themselves stuck and needed to be pulled free with tugboats. A local tugboat captain suggested that the cause may be found in a mobile mud layer that settled around the ship after it had spent some time (un)loading at the quay.

Large vessels experience difficulties sailing from Commodore channel around the bend into Badagry creek. Strong currents and shallow areas negatively affect navigability in this part of Lagos Harbour and reduce accessibility of the quays along Badagry Creek.

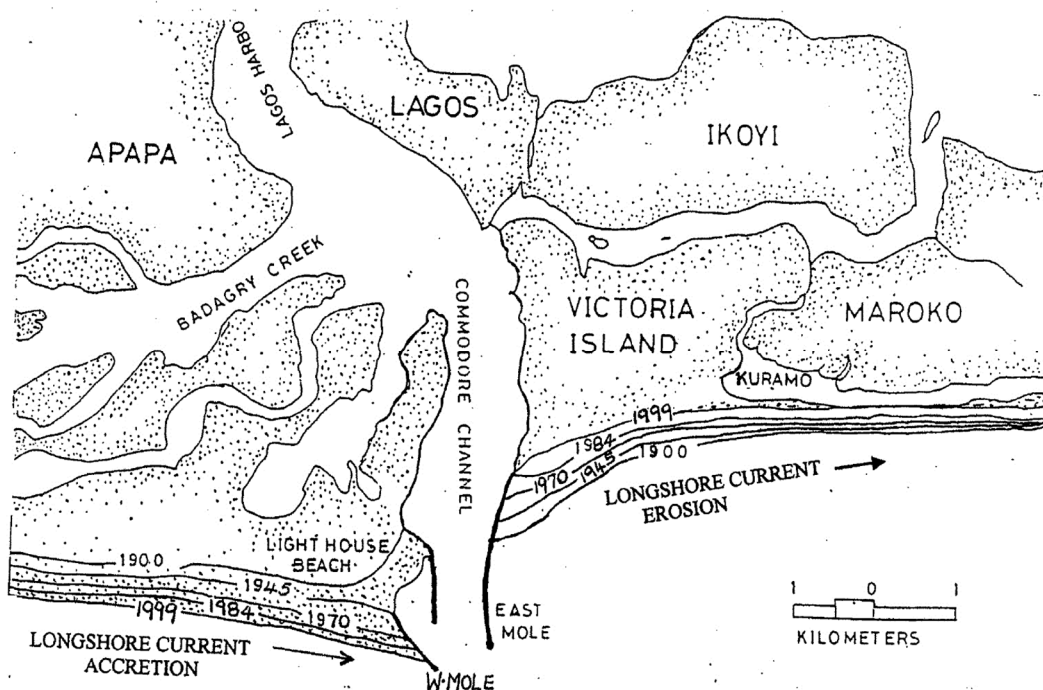


Figure 1-2 Morphology of the coast near Lagos during the 20th century.

In comparison to a recent map as shown in Figure 1-1 some large changes in geometry have occurred since the year of the harbour moles construction in 1912, this is depicted in Figure 1-2. Over the years, the effects of the construction of the harbour moles have caused erosion of Bar beach and accretion of Lighthouse beach. Furthermore, other human interventions like, expansion of Lagos seaport, closing creeks in Badagry, Lagos island and Victoria Island (now a peninsula) have caused the equilibrium (if there was one) of the Lagoon tidal system to be distorted.

The long shore transport of sediment caused by wave action is hindered by the moles, causing not only a change in shoreline but also complex mechanisms of import and export of sediment as the present shoreline of Lighthouse beach nears the tip of the west mole.

Another factor which complicates the morphology problem is the behaviour of the sediment in this region. Sediment types to be found range from very coarse sand to fine clay. A recent study concerning the navigation channel of the OKLNG plant site by Bakker [2009] suggested the mud shows behaviour not previously recorded in literature. Although Bakker states the evidence pointing toward the conclusion is circumstantial, there are strong indications the mud is poorly flocculated. Whether this sediment composition and conditions in Lagos are comparable to OKLNG is not clear. If the hypothesis is valid, it may have serious effects on settling and consolidation behaviour of sediment. Thus, different mechanisms play a stronger role on the sediment balance of the system than would be under 'normal' conditions. Also, the effectiveness of the TSHD dredgers are negatively affected if dredged material does not settle in the hold of the vessel and the dredging strategy should be revised.

1.2 Study objectives

The main objective of this thesis is to gain better insights in the morphodynamics system of Lagos Harbour. This study must be regarded as exploratory and will not provide answers to all the questions applying for the Lagos Harbour system. This thesis will provide first insights to better prepare for future studies and measurement campaigns .

As relatively little is known about the system, a measuring campaign is carried out to provide this study with the necessary data. Based on the analysis of the data and literature study, the following questions are addressed:

- Is there import of sediment to the entire Lagos Harbour system?
 - What is the source of the sediment?
 - Supply of material by rivers discharging in the system?
 - Import of marine sediments during flood, sand/silt/clay?
 - More supply from river than transported out to sea?
 - Does the sediment get deposited in the channels?
 - What role do density currents play in distribution of sediment?
- If not what may otherwise be responsible for channel infill
 - Redistribution of material within the channel(and/or lagoon) system towards the deeper navigation channels

1.3 Limitations

The conclusions of this thesis partly rely on the data acquired during the measurement campaign in September 2010 during the rainy season. From the insights gained during this campaign and from the literature study, it is clear that there is a strong influence of the rain on the behaviour of the hydrodynamic system and supply of sediment. It is assumed that the conclusions of this thesis are probably not valid for the dry season (roughly November to April) and may not even apply for the entire rainy season.

1.4 Reading guide

Section 2 will provide description of the system, the geological background of the area and known data, i.e. metocean data. This section also contains a description of the principles of morphology.

Section 3 describes the measurement campaign. Here, information concerning the used equipment and data acquisition method can be found. The results of the measurement campaign are presented in section 4. Although direct observations on the data are presented, an interpretation of the various measurement results is saved for section 5. Here, the observations made in section 4 are combined and analysed to provide a hypothesis that describes the morphodynamics behaviour of the system.

Lastly section 6 which contains the general conclusions to the research questions stated in section 1.3 as well as recommendations for future projects and studies and a discussion concerning the validity of the conclusions. This report also includes an appendix which show more detailed figures which will be referred to in the report.

2. LITERATURE STUDY

A distinction is made between data available in literature and data specifically collected for this thesis during the September 2010 field campaign (method and results in chapters 3 & 4). During this study, a literature study has been carried out to gain the first ideas. These findings will later be complemented by measurements.

Unless specified otherwise, section 2.1 through 2.4 is derived from the work of Allersma [1993], Allen [1964, 1965a&b], Burke [1972] and Guilcher [1969].

2.1 Description of the topographic features along the West-African coast

2.1.1 West-Africa

Lagos is located in the eastern part of the West African coast between two major rivers: Niger in the east and the Volta River (Ghana) in the west. The sediments carried by these rivers played a major role in the formation of the present coast. Starting from Lagos, the Volta River is located 300 km west and the centre of the Niger delta (most southern point) is 350 km to the south-east.



Figure 2-1 West African Coast [Google maps 2011]

Figure 2-1 also shows the edge of continental shelf which is clearly visible west of Lagos as a sharp line indicating steep slopes. In front of the Niger delta, the transition to the deeper parts is more gradual which is likely to be the result of the deposited sediment transported by the river over time.

Along the coast between the Volta mouth and Lagos, several lagoons and lakes are found. Most of these water bodies are closed off entirely or maintain a small drainage channel to allow discharge of rain water. In front of these lagoons, barrier islands have been formed during a geological period of high sediment supply. As they have been reshaped by the waves, the barrier islands are now part of an almost continuous straight coast. The largest and closest to the ocean of these lagoons/lakes are Keta lagoon, lac Togo and lac Ahémé.

2.1.2 Bight of Benin



Figure 2-2 West African coast Togo-Niger delta [Google maps 2011]

Looking at a smaller scale, the lagoon tidal system becomes visible ranging from Cotonou, Benin in the west to Lekki in the east. West to east, the full length of this system is almost 250 km and the three lagoons; Nakoue, Lagos and Lekki are connected by Badagry creek in the west and a small channel between Lekki and Lagos Lagoon. Southeast of Lagos, the discontinuity in the continental shelf is called Avon canyon.

The West-African coast Togo-Niger is wave dominated with tidal range less than 1m and persistent swell. With the exception of the inlets at Cotonou and Lagos, the coast is smooth and consists of sandy beaches. Swell waves from the South-Southeast induce a longshore current travelling to the East where it meets the Niger Delta.

2.1.3 Lagos area

Zooming in on Lagos, a network of channels, dead branches and the Lagoon, as depicted in Figure 2-3, show the complexity of the system. The channels west of Lagos city (towards the Benin border) are linked together at several locations forming islands and are named Badagry Creek.

After construction of the breakwaters (Lagos Harbour Moles) in the previous century, the beach in front of Victoria Island retreated as a result of the decrease in sediment supply from the West. The longshore transport was interrupted by the West Mole and lead not only to erosion of Bar beach East of the Lagos Harbour entrance but also to accretion of Lighthouse beach West of the Moles. Currently, a massive land reclamation project of 10 km² new land in front of Victoria Island is carried out using dredged material from sandpits south-east of Lagos.



Figure 2-3 Lagos area [Google maps 2011]. The red lined area illustrates the Eko Atlantic reclamation area.

North of Badagry Creek, a network of old mostly dried up channels is visible in a brighter green colour of which the shape suggests it was part of an older estuary system. The light brownish colour suggests higher ground marked with remnants of various drainage channels much larger than could be expected to be the result of just rainwater run-off. It is therefore likely that in a previous period of high sea level, a similar lagoon system existed in this area, bounded by beach ridges which are now the elevated areas on which a large part of mainland Lagos is build.

The southern branch of Badagry creek shows a meandering main channel and several dead end channels. Only relatively small rivers and streams discharge via Badagry creek as the inlet at Cotonou offers a direct link to the ocean for water discharged by the Ouémé River in Benin.

Along the edges of Lagos lagoon, several areas of low lying mud flats are present which may flood regularly. The Lagoon is overall very shallow with an average depth in the order of 1.5-2 m with shoals of sandy material scattered in the Lagoon which are usually exposed during low tides.

A small, secondary channel called Five Cowrie creek connects Lagos Lagoon with Commodore channel and separates Lagos and Victoria islands. Discharge through this channel is considerable with peak discharge in the order of 500 m³/s during spring flood/ebb, present day net sediment transport is more difficult to estimate due a to weir at the Commodore end.

Banana Island located east of Lagos Island and the reclaimed marshland directly east of urban Victoria Island, are examples of human interventions in the region. The material needed for construction was found in the deeper sandy layers of the Lagoon. The sand was dredged close to Lagos Island and the deepened areas are

still visible on bathymetry maps. Land reclamation in the Lagoon area using material from the Lagoon, continues till today on the northern shore of Lagos island.

2.1.4 Human influences to the Lagos lagoon system

Human influences on the Lagos Lagoon tidal system can be categorized into the following:

Since the Harbour Moles were constructed in 1912, the effects of the Moles on the system gradually became visible. Longshore transport from the west was hampered and resulted in accretion at the west side and erosion at the down drift side. Now, as the shore of Lighthouse beach nears the tip of the west Mole, it is expected that the import of sediment into the lagoon system will increase.

Other examples of human interventions are; closing of several creeks and expansion of Lagos seaport into Commodore channel.

The main human factor affecting the system is the dredging work inside the Harbour area carried out by Lagos Channel Management. The LCM is responsible for navigability of the Harbour and uses two small hopper dredgers. Specific information on dredging volumes, ship properties and dredging areas is unknown.

Currently, large scale land reclamation is carried out directly east of the East Mole. Most of the sand filling is done by hopper dredgers operating in the area east of Lagos Harbour. The main longshore current transports sediment in an easterly direction and it is therefore unlikely it will have a large impact on the Lagos tidal system. It is however plausible that dredging operations in the area have a direct effect on the morphology of Lagos Harbour as the dumped material may be transported into the system.

Lagos is an enormous city with over 15 million inhabitants using the channels and Lagoon as an open sewage. A significant quantity of human produced waste enters the system of which a part is transported out to open sea. Human and animal excrement is likely to have an effect on the amounts of organic content in the top layer of the bed. Bulk soil properties may also be affected by the large quantities of other material (e.g. plastic) dumped in the Lagoon and channels.

2.2 Geology

2.2.1 Geological time scale

In the geology section of this report, references are made to the geological periods that distinguish the phases of coastal evolution of the West-African coast. Figure 2-4 schematizes the geological timeline in eras, periods and epochs providing a frame of reference for the following section.

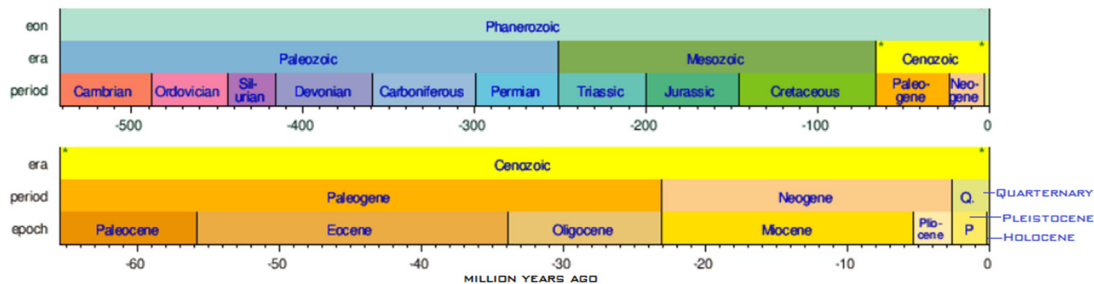


Figure 2-4 Geographical timeline [Wikipedia, {geology}]

An important factor in coastal evolution is the mean sea level, varying strongly throughout history. Figure 2-5 depicts the sea level changes during Holocene epoch (Quaternary period) for the West-African coast. It shows that the sea level rose rapidly up to 8000 years ago and a recent maximum may have occurred 2000 years B.P.

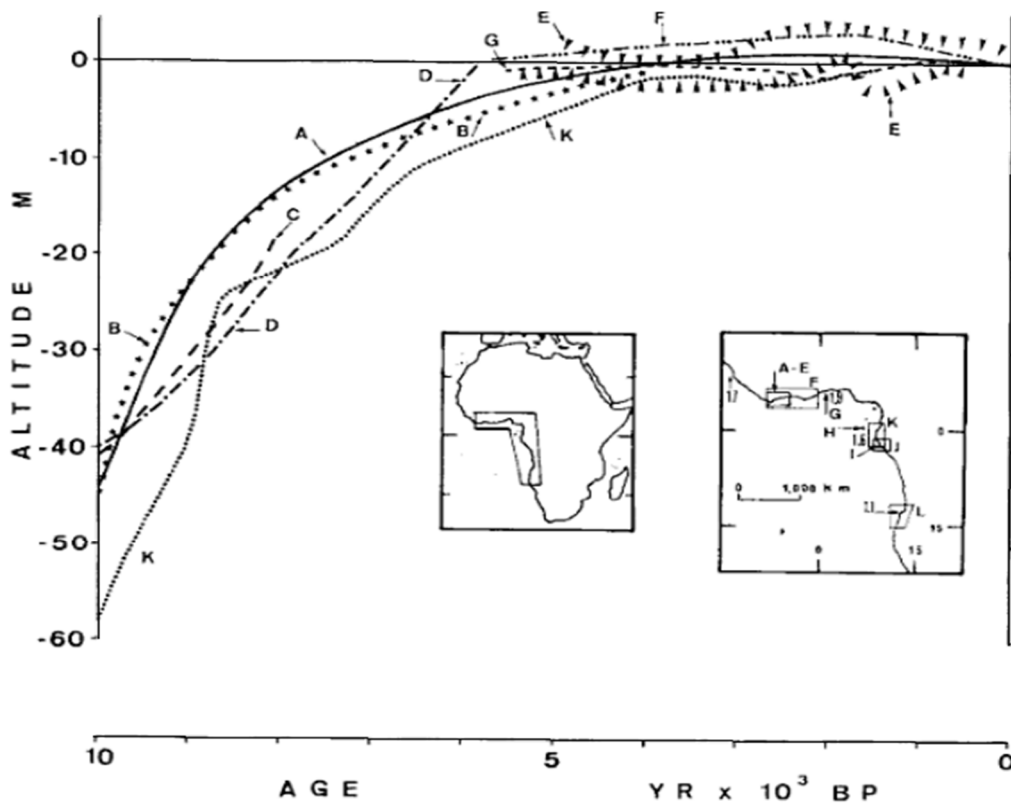


Figure 2-5 Sea level variation during the Pleistocene and Holocene epochs [Pirazzoli, 1991]. Plotted lines relate to locations depicted in inserts.

2.2.2 Geologic history of the West-African coast

The West-African coast started to develop about 135 million years ago in the beginning of the Cretaceous period when South-America and Africa drifted apart. The most important geological feature along the Nigerian and perhaps the West-African coast is the Niger delta. Figure 2-6 depicts the geological changes since the Cambrian period (Palaeozoic era). The Niger, Benue and Volta river basins as well the Togo- Nigerian coast, instantly stand out as areas which have evolved heavily since the beginning of the Cambrian period about 540 million years before present.

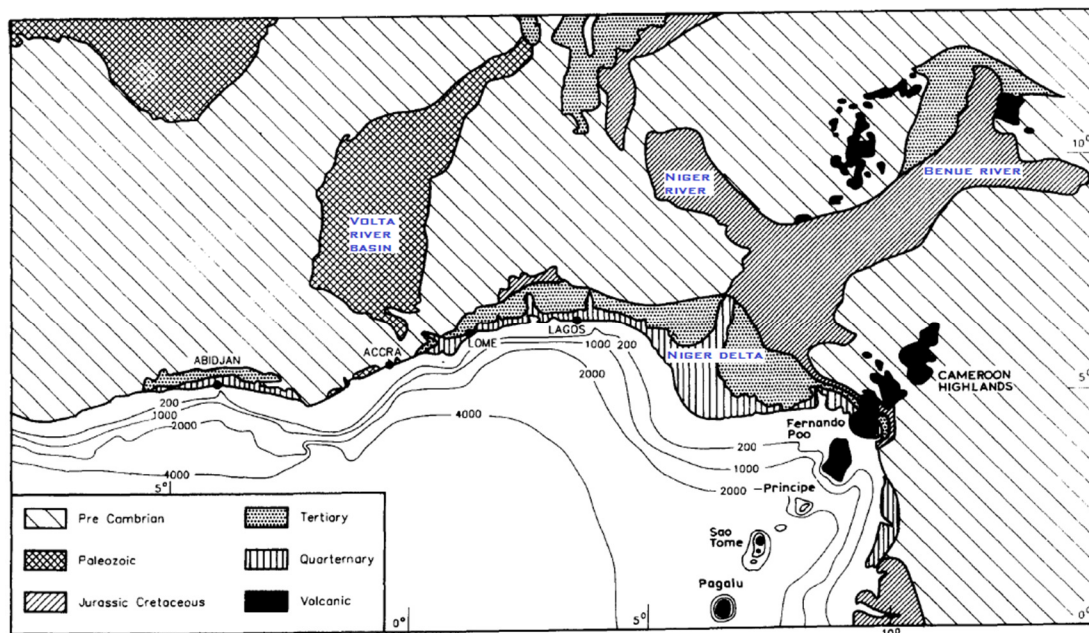


Figure 2-6 Geologic changes in the Phanerozoic eon (Cambrian period - present day)

For the current Nigerian coastline, the quaternary period (dating back up to 2.5 million years B.P.) is most important. The two most important formations related to the last two phases in coastline evolution are: the Older Sands from the Pleistocene period and the Younger Suite since the Holocene. The Older Sands and Younger Suite lie upon the sandy Benin formation, which is up to 2000 m thick.

The evolution of the Niger Delta and the Bight of Benin coast during the quaternary can be divided in three phases [Bakker, 2009 after Allen, 1964; 1965]:

- Late Pleistocene: sea levels dropped to 120 m below present mean sea level. In this period, rivers cut through the shelf resulting in gullies and shelf edge canyons
- Transgressive deposition during sea level rise
- Regressive deposition when a balance between sea level rise, sediment supply and subsidence was reached.

2.2.2.1 Older Sands

The Older Sands layer dates from the Late Pleistocene to Early Holocene period when the sea transgressed [Allen, 1964]. The sea level during this period some 16,000 years ago was nearly 120 m below its present level [Wikipedia, {sea level}]. Sand from the river mouths spread across the shelf to form beaches and offshore bars. The bottom rose in terraced stages due to the combined tectonic and compaction subsidence of the continental margin. The Older Sands consist of well-rounded and sorted quartzose sands with shell debris and glauconite [Allen, 1964].

2.2.1.2 Younger Suite

The Younger Suite comprises sand near the shore, silts in moderate depths and clays in deep water and was subsequently deposited on the Older Sands. The Younger Suite was deposited during the most recent post-glacial sea level rise [Allen, 1964; Allen, 1965b]. These Holocene sediments are thus less than 10,000 years old. The Younger Suite sediment entails sands, silts and clays in the modern delta and estuary and barrier-lagoon systems [Allen, 1964]. Transgression was converted into seawards regression due to a new balance between subsidence, sediment supply and sea level change. The delta propagated seawards when sediment supply was so abundant that subsidence and sea level rise could not keep up. These sediments were subsequently deposited on the Older Sands.

2.2.3 Development of Lagos lagoon

The present coastline near Lagos is relatively young and is still changing. The features of the lagoon tidal system i.e. the Lagoon, the various channels and creeks, older beach ridges, etc. were formed during the Holocene period when sea level progressively rose to its current level. In the pre-Holocene period when sea level was low, the rivers now discharging in the Lagoon, continued their paths to Avon canyon [Burke 1972] leaving gullies in their wake. The inset of Figure 2-7 shows the approximate shoreline with numerous estuaries at 7000 years B.P.

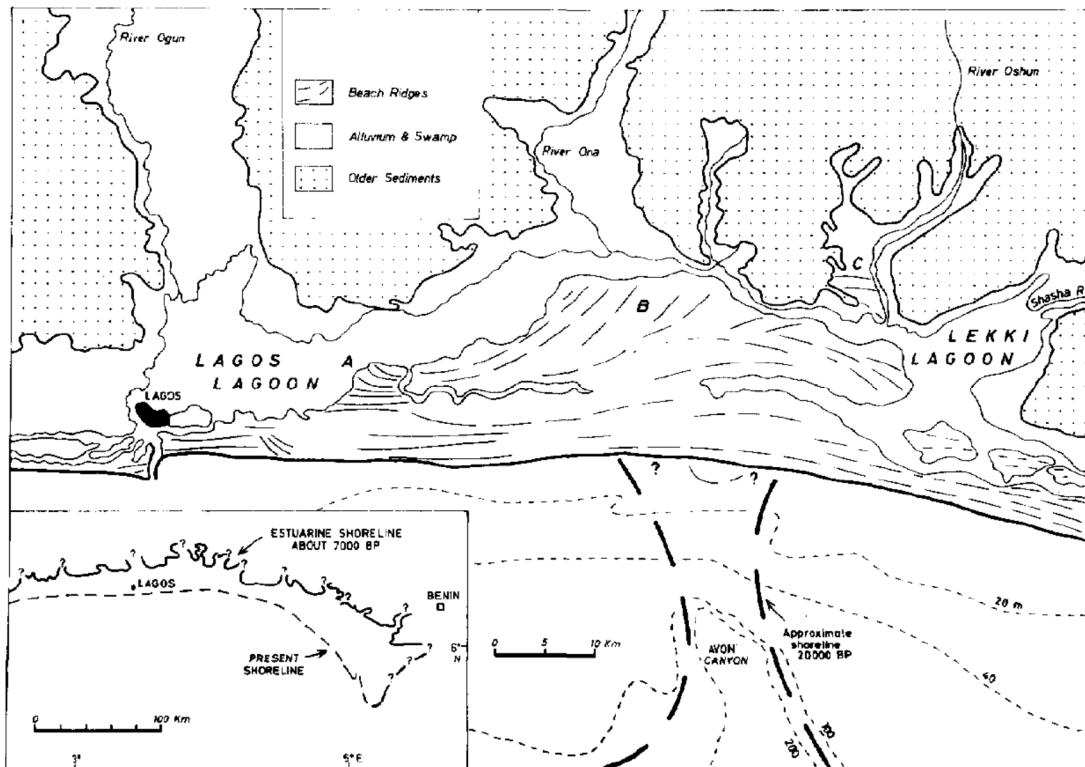


Figure 2-7 Beach ridges east of Lagos [Burke 1972]

The shape and alignment of the oldest beach ridges east of Lagos at A, B and C indicate that after maximum extent of last transgression (about 7000 years B.P.) longshore drift constructed beaches which first filled irregularities in coastline: major estuaries at Ogun mouth (A), Ona mouth (B) and Oshun mouth (C). Later beach ridges have a smooth outline because, when they formed, estuaries had been largely filled. [Burke 1972]. The construction of the beach ridges must have occurred in relative short time as the waves did not have sufficient time to rework the deposited material and straighten out the coastline.

2.3 Sediment

This section provides a description of the sediment types that can be found along the coast of West-Africa, especially near Lagos, based on literature studies. A more detailed description based on recent measurements in Lagos Harbour and at the OKLNG site is given in chapter 4. There is little information available on the characteristics of the sediment near Lagos, especially about the behaviour of the finer bed material, i.e. clays, silt and organic material.

2.3.1 General composition of the Nigerian continental shelf

Sediment types of which the seabed offshore of Lagos is composed, vary from very coarse sand to silty clay and show large spatial variety. West of Lagos on the continental shelf, muddy material is found mainly consisting of silt, the deeper parts are mainly composed of clay.

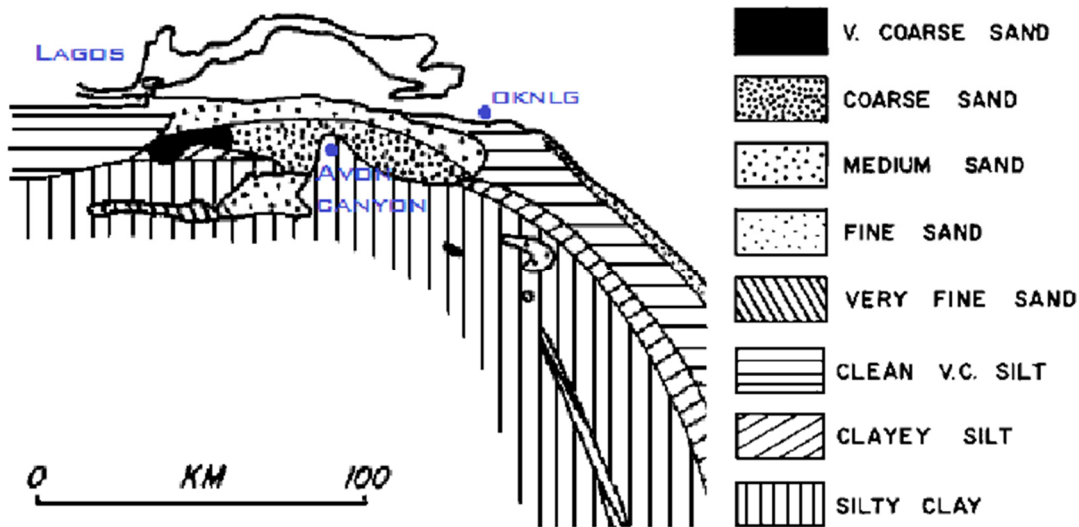


Figure 2-8 Composition of the seabed material in the bight of Benin [after Allen 1965]

The area south-east of Lagos near Avon canyon, shows large variations in material composition ranging very coarse sand to silty clay in Avon canyon itself. The silt and clay material illustrated by line shadings in Figure 2-8 were deposited during the Holocene. The absence of these materials in the shallows near Avon canyon suggests sediments are lost via transport to the deeper areas where silty clay is abundant. Figure 2-9 shows a more or less similar map with distinct areas of sandy material and a muddy seabed. The maps are contradicting each other in some areas, clearly visible in the Avon canyon region. The publication data of both sources differ 33 years, which means that, if both sources are accurate, significant sedimentation of clayey material occurs off the Lagos coast (deeper areas).

The stretch of sandy seabed roughly 100 km long by 10 km wide, starts at the entrance to Lagos Harbour and ends at the OKLNG site. West of Lagos the sandy bed is quite thin (about 500m) and width seems to start increasing at the entrance.

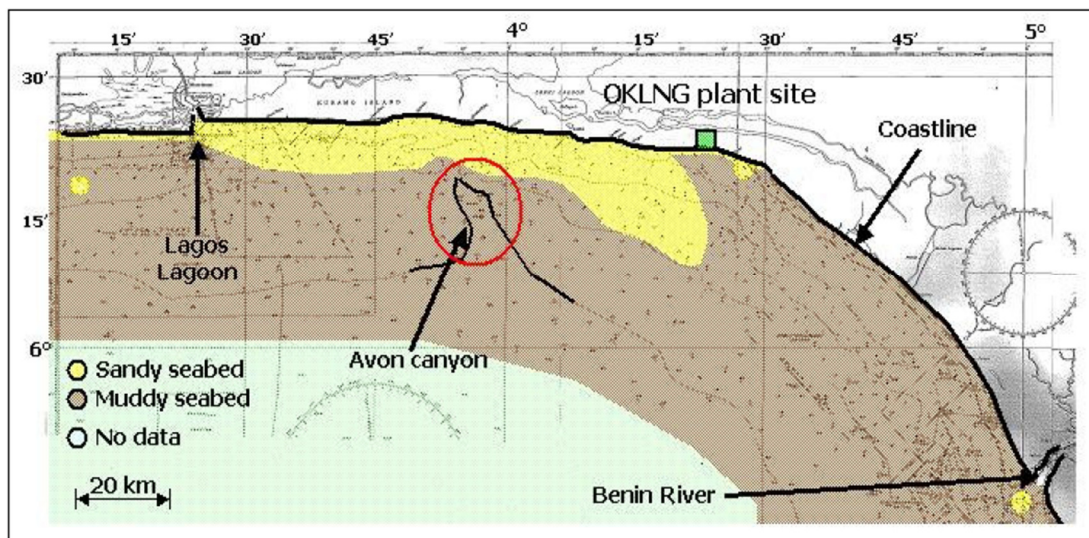


Figure 2-9 Seabed soil types [Bakker 2009 (based on Admiralty Chart, 1998)]

Close to the shore, little mud is found which can be explained as the wave stir up the sediment in the breaker zone. The smaller particles have no chance to settle under these conditions and remain in suspension. The muddy sediments are transported towards Lagos and enter the tidal basin during flood, where it either remains and settles or flows out again during ebb. Although wave conditions west of Lagos are similar to that east of the harbour entrance, the suspended mud does not settle. Whether the strong flow conditions during ebb in Commodore channel is responsible for this phenomena or the less saline environment of the Lagoon plays a role is not clear. Either way, for a stretch of 100 km east of Lagos, no mud is found on the bed. The mud near OKLNG may originate from the Benin and Niger River and be transported west.

2.3.2 Supply by rivers

Relatively little is known about sediment discharges from rivers feeding the West African Coast. An estimation of sediment load is made based on information sources containing data of catchment area and sediment yield estimations depending on topography, geology and climatologically situation [Allersma, 1993].

Figure 2-10 shows the catchment areas of the West-African coastal and major river. Relevant for this study are the river Volta, Niger and all local river located in between. A summary of their characteristics are given in Table 2-1 including an approximation for sediment load carried by these rivers. The catchment area of local rivers and streams near Lagos is 6000 km², relatively small compared to the major rivers or even smaller contributories like the Ouémé and Ogun rivers. Ouémé ends near Cotonou, Benin which is linked directly to the ocean. Although some of the (sediment) discharge may enter Lagos via Badagry creek, it is likely that most sediment and water will not be discharged through Commodore channel.

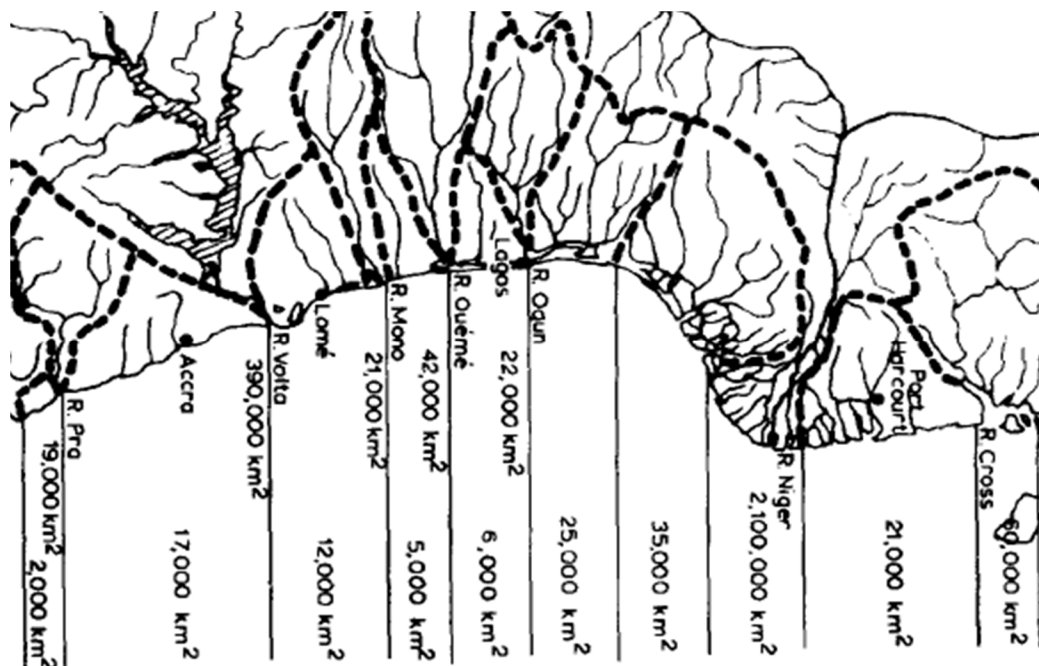


Figure 2-10 Catchment areas of major rivers and coastal creeks [Allersma, 1993]

Two rivers discharge directly in Lagos Lagoon, Ogun and Ona River, which are relatively small respectively 60 and 20 meters wide. No data for Ona River is known, but according to the characteristics shown in Table 2-1, Ogun River may carry considerable volumes of sediment to the Lagoon.

River Oshun discharges at Lekki lagoon and will contribute to the discharge at Commodore channel as there is no other link from Lekki lagoon to the ocean. Which portion of the Oshun River will be discharged after evaporation and groundwater transport is unknown as well as the sediment transport towards Lagos lagoon.

Catchments	Catchment area (1000 km ²)	Length of coast (km)	Load (1000 tons per year)
River Volta	390	-	15000
Volta-West Nigeria	495	325	4200
Lagos lagoon	6	90	300
Ogun river	22	-	1100
Niger Delta	2156	550	40000

Table 2-1 Holocene sediment supply by rivers and fluvial erosion of hinterland (extract) [Allersma, 1993]

The sediment load figures in Table 2-1 are based on the assumption that the catchment area yields 30-80 metric tons/km² per year of which 10-15 % is sand. This is a very unreliable method for determining sediment transport volumes and the calculations by Allersma are likely to be even less accurate due to human adaptations to the rivers in the past decades. Unfortunately, no other data sources are available concerning sediment load.

2.3.3 External sources

The main sources of sediment out of the Lagos system are, sediments carried to the coast by the Volta, Benin and Niger River and erosion of the west-African coast by waves and ocean currents. Longshore transport caused by waves may transport sediments to Lagos.



Figure 2-11 Longshore transport as a result of the almost unidirectional wave forcing.

The longshore transport is related to the angle between the waves and the coast. The general wave direction in this region is north-northeast and causes eastward transport up to the point where the coastline is perpendicular to the wave direction which is close to the OKNLG site. Sediments from the Niger River are partly transported in westward direction and partly towards the east.

A build-up of sediment is expected near the OKNLG site where material from both the Niger in the east and long shore transport from the west is deposited. It is unlikely that coarse sediments from the Niger reaches Lagos via wave generated longshore transport as the transport direction near Lagos is to the east. Fine, cohesive sediments from the Niger river may remain suspended

Estimates of the littoral transport near Lagos Harbour range from 0.5 to 1.0 million m³ of sediment per year [Allersma & Tilmans, 1993]. It must be noted that these estimates are based on studies carried in the late 70's and 80's so it may have become less accurate. Especially since the construction of major dams in both the Volta and Niger in the mid 60's had a strong effect of the sediment supply by these rivers.

2.4 Overview of the Lagos lagoon system

The Lagos lagoon system came to being after a rapid increase in sea level rise starting 7000 years ago and has been fairly constant with an increased rate in the last century. Up to the end of the last ice age, the West-Nigerian coast was irregular and contained numerous estuaries at locations where now a smooth coast is found.

With high sea level and large sediment supply from the major rivers, wave-driven longshore sediment transport resulted in rapid reconstruction of the coastline filling the irregularities (estuaries) first. At locations where the infill of sediment did not meet

up with the relative sea level rise, lagoons separated from the ocean by barrier islands, emerged.

According to the Admiralty Charts on which Figure 2-9 is based, the seabed near Lagos is predominantly muddy with exception the section between Lagos Lagoon and the OKLNG site, which is mainly sandy and is about 10 km in width. From Figure 2-11 it is clear that fine sediments must arrive in this section via eastward longshore transport. The reason that only small quantities of mud are present must be caused by net import of mud into the Lagos Lagoon system and/or channelled by the Avon canyon towards the deeper parts.

As the seabed west of Lagos is muddy and (under wave action common in this region and suspended sediment concentrations may be high) significant amounts of sediment may be imported into the tidal system by flood currents. In this scenario, the Lagos Lagoon system acts a sediment trap accumulating marine sediments from the west.

Whether the material found at OKLNG has the same origin as the sediments in Lagos is unclear as OKLNG seems to receive material via longshore transport from both the Niger delta and from the west. Coarse sediments will not be transported towards Lagos by longshore transport as the direction of the current near Lagos is eastwards. Fine sediments discharged by the Niger river may however remain in suspension for very long periods and distributed along the entire West-African coast by large ocean currents (see section 2.6.3).

2.5 Climate

Temperatures in Lagos are high to very high throughout the year. At latitude of 6 degrees north, seasonal variations in temperature due to solar radiation are very limited. Instead of summer and winter Lagos experiences a dry season and periods of heavy rainfall.

2.5.1 Air/Sea surface temperature

During the wet season, when the Lagos area is under the influence of the maritime air mass, mean daily maximum temperatures are usually between 28°C and 30°C, whereas the mean daily temperature is about 24°C. During the dry season, when Lagos is mostly dominated by the dry north-east trade winds (Harmattan), days are hot and dry with mean daily temperatures rising as high as 34°C. At night, temperature hardly drops and may still be 30°C at daily minimum.

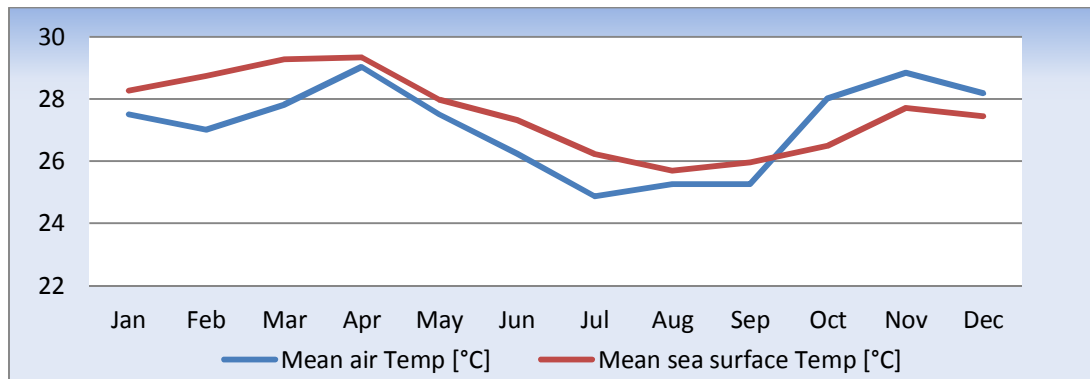


Figure 2-12 Monthly mean sea surface and air temperature for Lagos [N.I.O.M.R. 1982]

2.5.2 Rainfall

Due to its location in the equatorial zone, the climate in Lagos is mostly under the influence of the warm wet tropical maritime air mass. The city experiences two periods of rainfall with about six to eight months of rain a year. The first season begins between April and May and ends in July, while the second starts late August and ends in early October. Total annual rainfall in Lagos exceeds 1,750 mm [N.I.O.M.R. 1982].

Figure 2-13 shows the seasonal variation in salinity of Lagos Harbour and monthly precipitation (based on measurements of 1978-1981). The peak of the rainy season is in July with over 350 mm rain and a drop in salinity to below 11.5 parts per thousands. It is not known at which depth the salinity measurements were taken but it assumed to be close to the surface. In case of stratification fresh rain run-off floating on a layer of salt sea water, the salinity given in Figure 2-13 may not be representative for the whole depth.

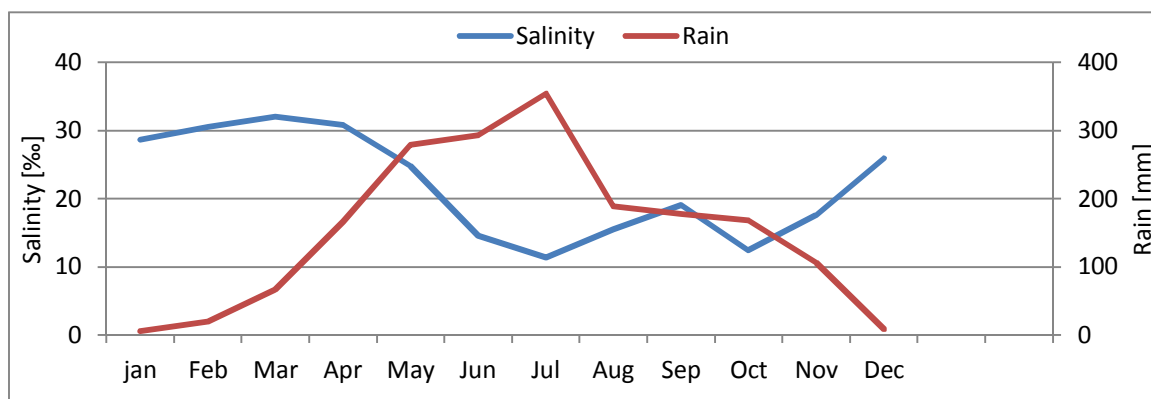


Figure 2-13 Seasonal variation in salinity and rainfall [N.I.O.M.R. 1982]

2.5.3 Wind

The wind climate for this part of Nigeria is quite mild with wind speeds rarely exceeding 10 m/s. The general direction is southwest and is fairly constant during the year. Above average wind speeds are observed during the wet season from June to September. Lower wind speeds are observed in the dry season from November to

March. Figure 2-14 shows the wind rose based on NOAA hindcast data. The rose is comprised of 32,152 records of wind speed and direction at 3 hour intervals from January 1997 until February 2008. The wind rose is based on offshore location 3°45'00"E ; 6°00'00"N (50 km southeast of Lagos).

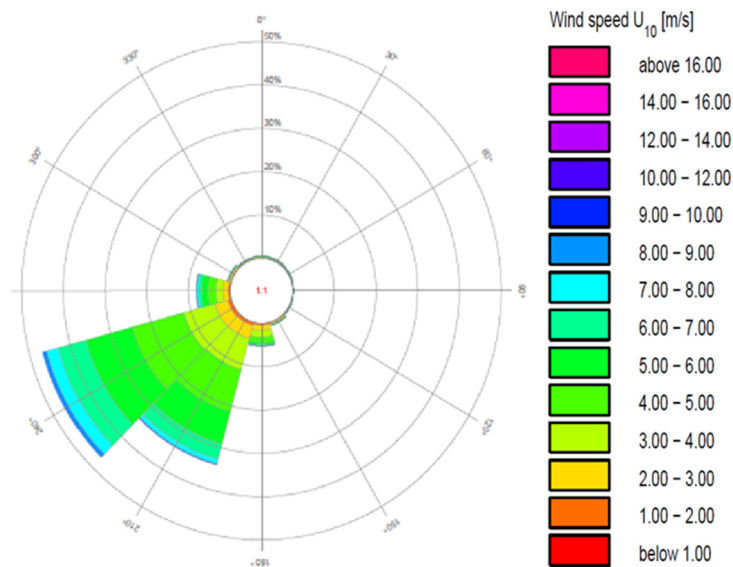


Figure 2-14 – All year wind climate based on NOAA hindcast data

Figure 2-14 shows that the wind climate for the West-Nigerian coastal zone is near unidirectional where 90% blows from the Southwest by South-Southwest. Extreme wind velocities are rare while wind speed is below 7 m/s for 70% of the time.

2.5.4 Offshore wave climate

The available offshore wave data consist of data from NOAA hindcast model at 3 hourly intervals from January 1997 until February 2008 for offshore location 3°45'00"E ; 6 °00'00"N. In total 32,152 records of wave height, -period and -direction were available. The annual dominant wave directional sector is very narrow, highly dominated by waves from 195°-225° N. Significant wave heights are typically between 1 and 2 m with typical wave periods of 10-12 s.

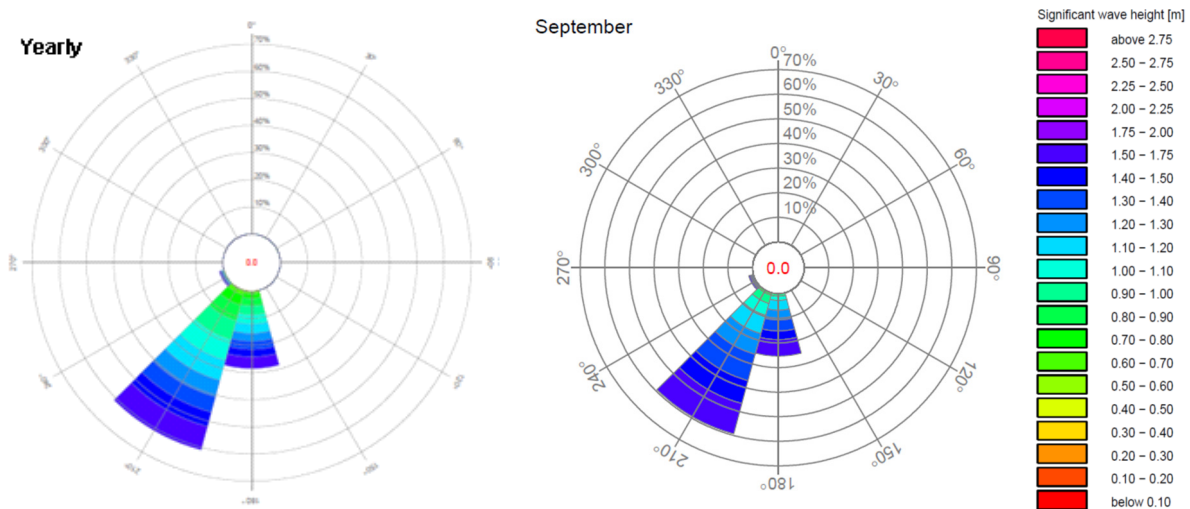


Figure 2-15 11-year average wave height/direction: All year and September

As stated in section 2.5.3, the wind climate is considered quite mild. This means that the local wave climate is mainly determined by swells generated further offshore on the Atlantic Ocean. A fair 10% of the time, a significant wave height of 1.50-1.75 m swell is recorded.

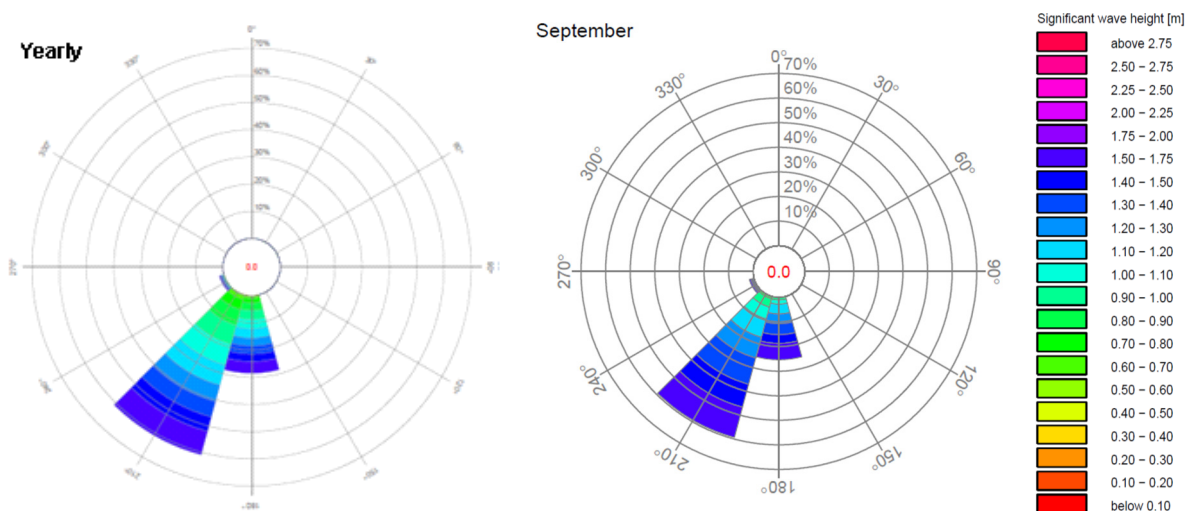


Figure 2-15 11-year average wave height/direction: All year and September

Figure 2-15 shows that most waves approach Lagos from a south-southwest direction. As these waves approach the coast from an oblique angle, a wave induced longshore current is created. This current causes sediment to be transported along the coast in an easterly direction.

The waves during the wet season (September figure) are slightly stronger than the year-round average. Although waves during this period are not much higher, high waves are more common. Stronger waves were experienced during the last days of the measuring campaign although there are no specific wave records available for the first two weeks of September 2010 to support the visual observations.

2.5.5 Sea level rise

Global sea level rise is an extensively studied phenomenon and can be a strong factor in the development of the Lagos Lagoon tidal system. Although the predictions of the future increase in mean sea level vary strongly in literature, the general consensus is that the sea level will continue to rise and at a stronger rate than it does present day. For the last century, sea level has risen by approximately 25 cm. The International Panel on Climate Change estimates sea level rise for the 21st century to be in the order of 40 cm.

The expected morphological response to sea level rise of tidal inlet systems in general is, if sediment supply is sufficient, net import of material into the system to maintain the equilibrium channel depth. As the water level rises and thus the flow velocity in the channel decreases, sedimentation increases. Considering the longshore sediment transport passing the Lagos tidal inlet, it is conceivable that as the sea level rises, net import of sediment will start/further increase.

2.6 Hydrodynamic processes

2.6.1 Water level variations

Water level variations can be the result of earth-moon and earth-sun interaction (vertical tide), wind set-up and other meteorological phenomena such as seiches. Since the wind climate in this part of Africa is quite mild, wind set-up may be neglected for this study. Also, other meteorological phenomena are beyond the scope of this thesis.

In general, along the Nigerian Coast, tides are semi-diurnal with significant diurnal inequalities and a periodicity of about 12h 25min. The mean tidal range is about 0.8 m, increasing to 1.3 m during extreme spring tides. A monthly variation in the mean sea level was reported to be 0.2m. More information is provided from the Admiralty Tide Tables (ATT, 2008) that give tidal constituents as well as high and low water times and heights for stations Lagos Bar and further along the coast. Similar information is available from the Nigerian Navy Tables (2000) and is presented in Table 2-2.

Water level		Level [m, + CD]
MHWS	Mean High Water Spring	0.945
MHWN	Mean High Water Neap	0.701
MSL	Mean Sea Level	0.457
MLWN	Mean Low Water Neap	0.213
MLWS	Mean Low Water Spring	0.091
LAT	Lowest Astronomical Tide	0

Table 2-2 Characteristic tidal water levels at Lagos (entrance) [Nigerian Navy Tide Tables]

2.6.2 Tidal asymmetry

2.6.2.1 General

The term, tidal asymmetry, can have four different but related meanings, asymmetry of: duration of water level rise and fall (vertical tide), high and low water slack

duration, absolute flow velocities and sediment transport. The latter is a complex function of the flow velocity, duration of these conditions, slack water period and the sediment properties.

In this study the tidal asymmetry related to sediment transport is important, therefore the horizontal tide will be considered flood dominant if it generates residual sediment transport into the system and ebb dominant if net export of sediment is caused.

Morphology and tidal asymmetry are closely interrelated where tidal asymmetry induces a morphological response, which in turn, affects the tidal asymmetry. Under varying conditions such as sea level rise and human interventions (e.g. dam construction), equilibrium between tidal asymmetry and morphology may never be achieved.

2.6.2.2 Origin of tidal asymmetry

As tidal waves propagate in, relative to the tidal wavelength, shallow water, they induce other, higher frequency harmonics due to non-linear effects such as bottom friction, depth variations and tide-tide interaction [Holthuijsen, 2007]. Considering only the influence of the moon (M2) and the sun (S2), tides are sinusoidal waves that show a 2-weekly variation due the relative positions of the sun and the moon to the earth.

An explanation for the higher frequency M4 tide component can be found when examining the wave propagation under shallow water conditions. When a tidal wave travels in shallow water, the wave celerity is determined by the local depth:

$$c = \sqrt{g(d \pm a)}$$

Where c is the wave celerity [m/s], g =gravitational acceleration, d is the still water depth [m] and a = amplitude of the wave. In the deeper ocean waters, the amplitude is small compared to the depth but as the wave propagates into shallower water, the crest will travel faster than the trough where the local depth is slightly smaller.

The result is a deformation of the wave where the surface elevation h as a function of time t is described by:

$$h(t) = h_0 + \sum_n a_n \cos(\omega_n t - \alpha_n)$$

Where:

h_0 = still water level

a_n = amplitude of component n

ω_n = frequency of component n

α_n = relative phase difference of component n

The parameters of each wave component are not known for Lagos Harbour but qualitative conclusions can be drawn based on this general theory. Figure 2-16

shows the M2 tidal component (middle), the effect of different celerity's (top) and the M4 component (bottom) which is the difference between the top 2 plots. It can be observed from the dotted line shows a steeper, shorter flood period while the decrease in water level during ebb takes more time. A steeper water level rise indicates a stronger flood current, leading to more sediment being stirred up, more sediment transport and thus flood dominance.

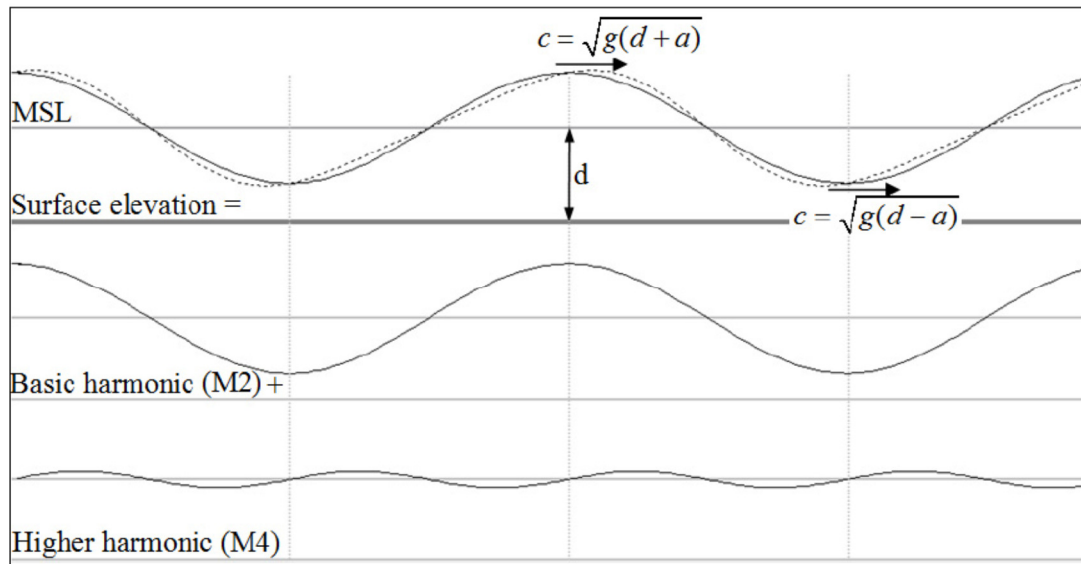


Figure 2-16 Deformation of the tidal wave as it propagates in shallow water [after Holthuijsen].

2.6.2.3 Residual sediment transport

As mentioned, the effect on tidal asymmetry on the net sediment transport is considered important for this thesis. Figure 2-17 shows an example of a flood dominant system (not related to Lagos) that illustrates the effects of tidal asymmetry on residual transport. In this scenario, higher flow velocities are present during flood but the ebb period duration is longer. Considering a sediment type with a specific threshold for motion, two slack periods are created during the turning of the tide when flow velocities are lower than the threshold value for that particular sediment fraction. The lime-coloured triangles represent the slack water periods and are shorter for low water slack than high water slack periods. Also, during flood, current speeds are higher thus mobilizing more sediment. The result is that more sediment is transported and has more time to settle causing net transport in the flood direction.

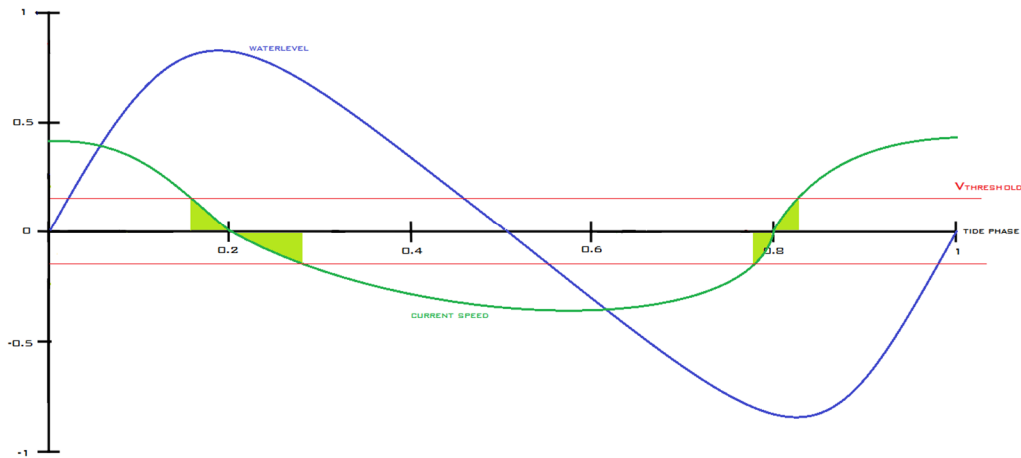


Figure 2-17 Example of the effect of tidal asymmetry on residual sediment transport.

If settling velocities are very low, the disturbed bed may not have sufficient time to settle during the turning of the tide and flow back in the other direction. This may be the case for very fine particles like silt and clay. Also, other properties may change due to the difference in salty flood water (ocean) and less saline water from, for instance, a lagoon.

In this example the flood and ebb tidal prism are equal while river discharge may cause ebb dominance of the system and net sediment export.

2.6.2.4 Lagos situation

The approach of section 2.6.2.2 is generally valid for Type 1 estuaries [Dronkers, 1986] which are characterised as a wide deep, rectangular shaped channel cross section of which the mean depth increases with flood. Commodore channel qualifies for this type as it has steep banks and thus friction reduces with increased depths stronger than the added resistance of the increase surface area. This assigns flood dominance for these Type 1 systems resulting in net accumulation of sediment. It is not clear if the same holds for Badagry Creek and the Lagoon where low areas prone to flooding are found that may lead to more friction and lower propagation velocities. These parts of the system may classify as Type 2 which are ebb dominant. Whether Badagry and the Lagoon are Type 1 or 2 depends on the exact bathymetry and altimetry. Also, the influence of fresh water discharge through Commodore channel on flood/ebb dominance should be taken into account.

2.6.3 Currents

Not only can currents be created by tide and river discharge as mentioned above, waves, wind and density gradients may also cause water flow in the system. At a larger scale, ocean current may have an effect on the system.

2.6.3.1 Ocean Currents

The coastal waters of Nigeria are located directly at the Atlantic Ocean, within the Gulf of Guinea, which starts at Cape Palmas, near Harper. The temperature of this current is warm (ca. 25 degrees) all year, salinity is however strongly affected by the wet and dry season. These surface waters circulate in a clockwise direction along the West African coasts from Senegal to Nigeria. Two currents create the Guinea Current: the deeper South Equatorial Current moving north-eastward, and the Canary Current (Figure 2-18). The Ocean system does not cause any coastal upwelling in the Nigerian region, which results in very low productivity. The Guinea Current creates a dominant offshore flow in clockwise direction.

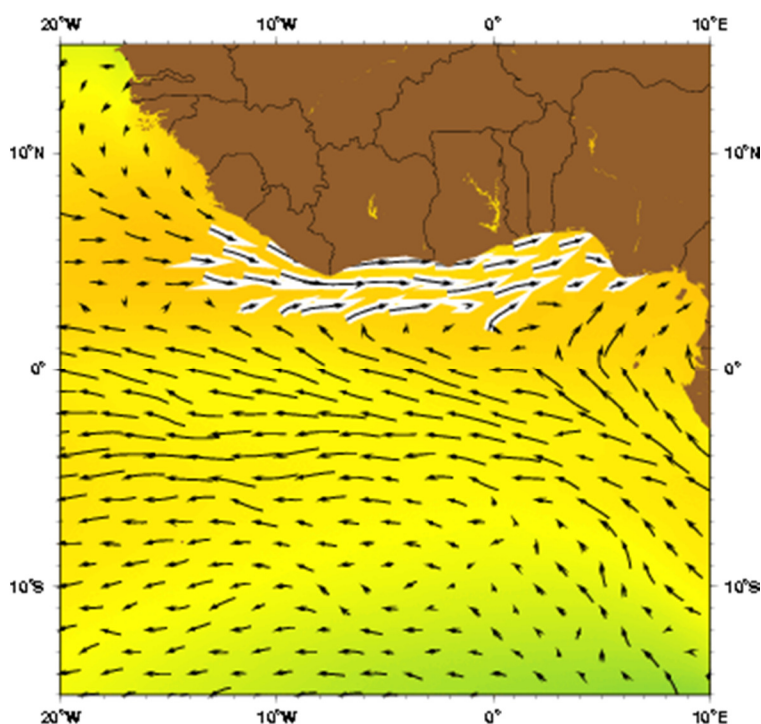


Figure 2-18 Ocean currents off the coast of West-Africa [Gyory et al, 2005]

The west – east directed Guinea current is the dominant ocean current affecting the Nigerian continental margin. The Guinea current, which is an extension of the north Equatorial Counter current, attains speed of 0.3 m/sec with some reversals. This current reversal seems to occur most frequently at the beginning and end of the rainy season (Longhurst, 1964). The Guinea current runs above an undercurrent which is thought to be a westward flowing extension of the northern branch of the Equatorial Undercurrent which splits into two branches after impinging upon the African continent at Sao Tome Island. The other important surface current in the Gulf of Guinea is the South Equatorial current (SEC).

2.6.3.2 Wind driven currents

Because the wind climate near Lagos is very mild during all seasons, the wind driven currents are insignificant compared to the other mechanisms mentioned. For simplicity sake, the wind generated currents (ocean and inside the Lagoon tidal system) are neglected.

2.6.3.3 Wave driven currents

Wave driven currents have a significant effect in shallow waters like beaches where wave breaking processes are dominant. A predominant wind blowing to the northeast and swell waves from the Atlantic Ocean, result in a dominant wave direction of south by southwest. Due to the orientation of the coast, waves arrive on the coast at oblique angles of between 10 to 15 degrees. As a result of waves breaking at oblique angles to the coast, longshore currents are generated which flows in a predominantly easterly direction. Longshore currents attain speed averaging 0.2 to 0.4 m/s along the coastline.

Little wave energy enters the Harbour basin from the Ocean as most waves will break on the Harbour Moles. Furthermore, a slight bend in Commodore channel hampers wave intrusion deep into the system. Locally generated waves (wind, ships) are regarded insignificant to the morphology of the system.

2.6.4 River discharge

The combined river runoff through the port entrance is small compared to the tidal storage capacity of the connecting lagoons (such as Lagos Lagoon of 700 km²). The tidal prism of the estuary is estimated to be in the order of 300-500 10⁶ m³. Maximum flow rate in the entrance (Commodore Channel) is in the order of 10⁴ m³/s during spring ebb and flood. There is no data from discharge measurements on the average yearly run-off of the rivers running of via the port channel. Furthermore, the distribution of the river run-off over the various branches is yet unknown.

An estimation of the daily discharge of fresh water via Commodore channel is made [Isebor et al], based on meteorological data from the N.O.I.M.R. using the method described by Gordon et al, 1996. A rough estimation states there is a daily discharge in the order of 10 10⁶ m³/day during the wet season, the dry season seems to be only slightly less with 9 million m³ per day. This volume results in an average discharge of about 100 m³ of fresh water per second to be discharged via Commodore channel. As the fresh water mixes with saline water it will form brackish water, with a volume several times that of the fresh water volume. During spring ebb, discharge of water in Commodore channel is in the order of 10.000 m³/s. This results in a few % of the total flow being fresh/brackish water. It must however be noted that Isebor does not specify which rivers contribute to the Lagoon system or which precipitation data is used.

While the combined catchment areas of Ogun River, local rivers near Lagos and (partly) Oshun River, considering the yearly precipitation of 1500-2000 mm, one might expect a larger discharge. Also, the difference in river discharge during a day in the rainy season compared to one in the dry season is only 10% while the precipitation at the height of the rainy season in July is 10 times that of an average month in the dry season.

A simplified calculation of the discharge through Commodore channel based on rain data and catchment area might provide a different estimation. Assuming a

catchment area of 22000 km² (Figure 2-8) for Ogun river with estimated average depth 2.5m and width 60m, a yearly precipitation of 1750 mm and maximum average flow velocity 1 m/s. With assumed river dimensions, the maximum volume of water the Ogun could discharge yearly, corresponds with 170 mm of rain. The remaining 90% must have been used for irrigation or drink water purposes, evaporated or drained via groundwater transport. Assuming the same percentages for Oshun River and local run-off for discharge via surface water, the average volume fresh water through Commodore channel is in the order of 300 m³/s. This value is fairly close to the result by Isebor and shows that the percentage of fresh water discharge compared to the total flow in Commodore channel is in the order of a few per cent. The effect of fresh water on sediment transport is expected to be modest compared to the tidal forcing on the system.

2.6.5 Stratification

Salinity of the Ocean and the Lagoon vary strongly over the year as a consequence of the dry and rainy season. The Lagoon shows strong variations in its salinity, ranging from 14 to 21 ‰. The Ocean near the entrance of Lagos Harbour shows less extreme seasonal influences with mean salinity of 33 ppt. during the dry season and 29 ppt. in the rainy season. Differences in salinity between the two water masses mean there will probably stratification of currents in the Lagoon tidal system where fresh water may float on salty sea water. This will seriously affect hydrodynamics and sediment transport. This could result in two separate layers that may flow in opposite directions as their turning points in the tidal phase may not occur simultaneously. The behaviour of sediments in a saline environment may also differ to that in fresh water.

2.7 Sedimentation processes

In this report, a distinction will be made in cohesive and non-cohesive sedimentation processes. Both types of sediment are found in Lagos Harbour and each shows different behaviour.

2.7.1 Definition of mud / silt / sand

Sediment mixtures may consist of clay, silt, sand gravel, organic and carbonate (shells) material. Figure 2-19 shows the classification of particles based on their sizes for several widely used standards. For this thesis, the internationally used ASTM D422 standard will be used to classify the types of sediment. A distinction is made between clay, silt, sand and gravel based on their particle sizes rather than mineral composition.

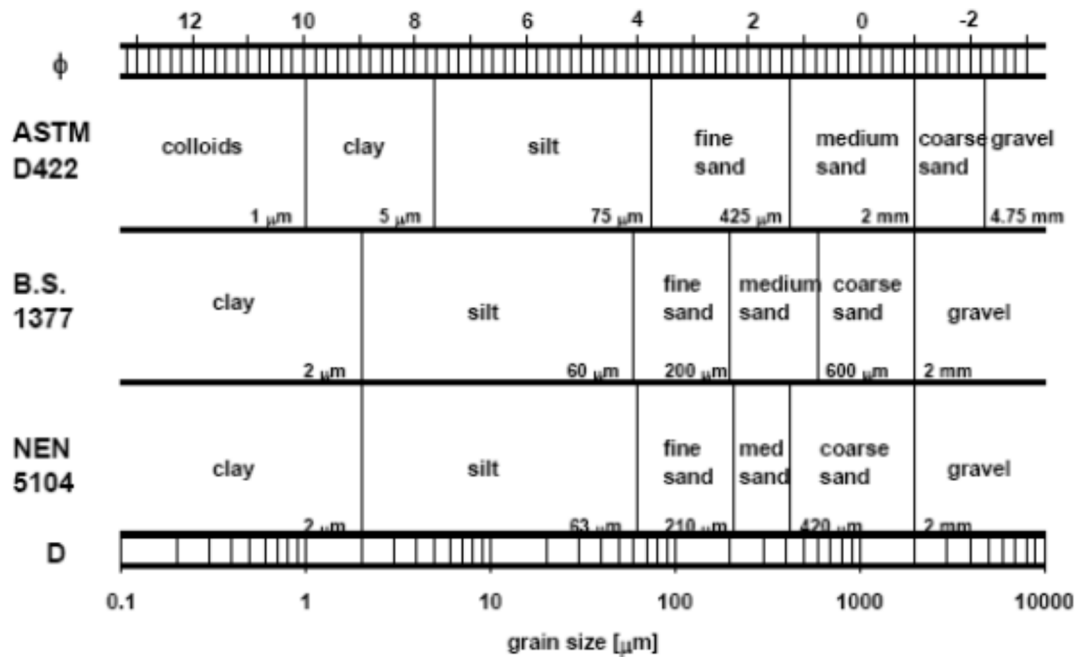


Figure 2-19 Soil classification according to international, British and European standards

Cohesive sediment (fine sediments) mixtures, or mud, can be defined as a fluid – sediment mixture consisting of water, clay, silt, organic material and sand. The mineral composition of the sediments is often composed of silicates; quartz, feldspar and clay minerals. The most important clay minerals are: kaolinite, illite, montmorillonite and chlorite. Three of these types are shown in the electron micrograph in Figure 2-20. Due to the flat shape of the particles, clay is to a large extent responsible for the cohesive nature of mud as they have an electric charge.

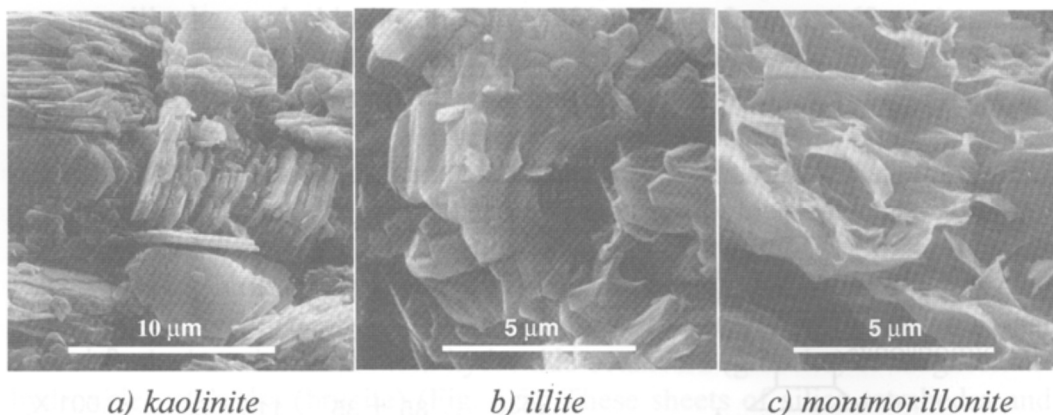


Figure 2-20 Different types of clay mineral, electron micrograph [Tovey, 1971]

Kaolinite is coarse clay with particle sizes between 1 and 5 μm , while montmorillonite is fine clay with particles smaller than 0.2 μm [Delgado, 1985]. Porrenga [1966] identified that recent Niger Delta sediments consist mainly of these two minerals and some illite.

2.7.2 Non-cohesive sediment processes

2.7.2.1 Transport mechanisms

The following classification and definitions in accordance with the ISO-standards (ISO 4363) concerning sediment transport mechanisms are given:

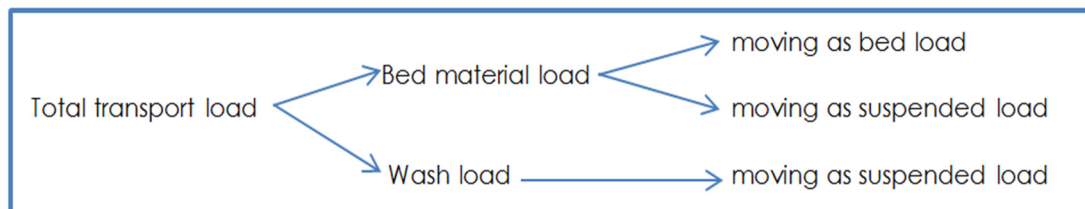


Figure 2-21 transport mechanisms [van Rijn, 2007].

Bed material: The material, the particle sizes of which are found in appreciable quantities in that part of the bed that is affected by transport.

Bed material load: The part of the total sediment transport which consists of the material which can be found on the bed at still water. The transport rate is governed by the transport capacity (is a function of material properties and flow velocities) of the channel. Bed material load can be transported via suspended sediment load or bed load:

- Suspended load: That part of the total sediment transport which is maintained in suspension by turbulence in the flowing water for considerable periods of time without contact with the stream bed. It moves with practically the same velocity as that of the flowing water.
- Bed load: The sediment in almost continuous contact with the bed, carried forward by rolling, sliding or hopping.
- Wash load: The part of the total suspended sediment load which is composed of particle sizes small enough to be nearly permanent in suspension. In contrast to the other transport mechanisms mentioned, wash load is generally composed of cohesive sediments.

2.7.2.2 Settling velocity

The settling velocity of non-cohesive particles (sand) is given by:

$$w_s = \sqrt{\frac{4(s-1)gd}{3C_d}}$$

In which: w_s = terminal fall velocity of a sphere in still fluid, d =sphere diameter, s =specific gravity (=2.65), C_d =drag coefficient and g =gravitational acceleration. The drag coefficient C_d is a function of the Reynolds number $Re=w_s d/\nu$ and shape factor. In the Stokes region ($Re < 1$) the drag coefficient is given by: $C_d=24/Re$, yielding:

$$w_s = \frac{(s-1)gd^2}{18\nu}$$

Outside the Stokes region there is no simple expression for the drag coefficient. The C_D -value decreases rapidly outside the Stokes region ($Re < 1$) and becomes nearly constant for $10^3 < Re < 10^5$, yielding w_s proportional to $d^{0.5}$ [van Rijn, 1993].

2.7.2.3 Critical bed-shear stress and initiation of movement

Particle movement will occur when the instantaneous fluid forces caused by currents and/or waves on a particle is just larger than the instantaneous resisting force related to the submerged particle weight and the friction coefficient. Initiation of motion in steady flow is defined to occur when the dimensionless bed-shear stress (θ) is larger than a threshold value (θ_{cr}).

Thus: $\theta > \theta_{cr}$

$$\text{Where } \theta_{cr} = \frac{\tau_{cr,0}}{((\rho_s - \rho_w) * g * d_{50})} \approx 0.04$$

$\tau_{cr,0}$ = critical bed-shear stress of cohesionless particles on a horizontal bed, ρ_s = sediment density, ρ_w = fluid density, $s = \rho_s / \rho_w$ = relative density, d_{50} = median sediment diameter [van Rijn, 1993].

2.7.2.4 Non-cohesive sediment transport in tidal flow

Under tidal flow conditions, the actual sediment transport rate may be smaller or larger than the transport capacity of the channel resulting in net erosion or sedimentation. Bed-load transport is directly related to the sediment concentration and flow velocity near the bed as this type of transports quickly adapts to the hydraulic conditions. This is not true for suspended sediment transport, as it takes time (lag effects) to transport particles up and down in the water column and it is therefore necessary to model the vertical-convection process.

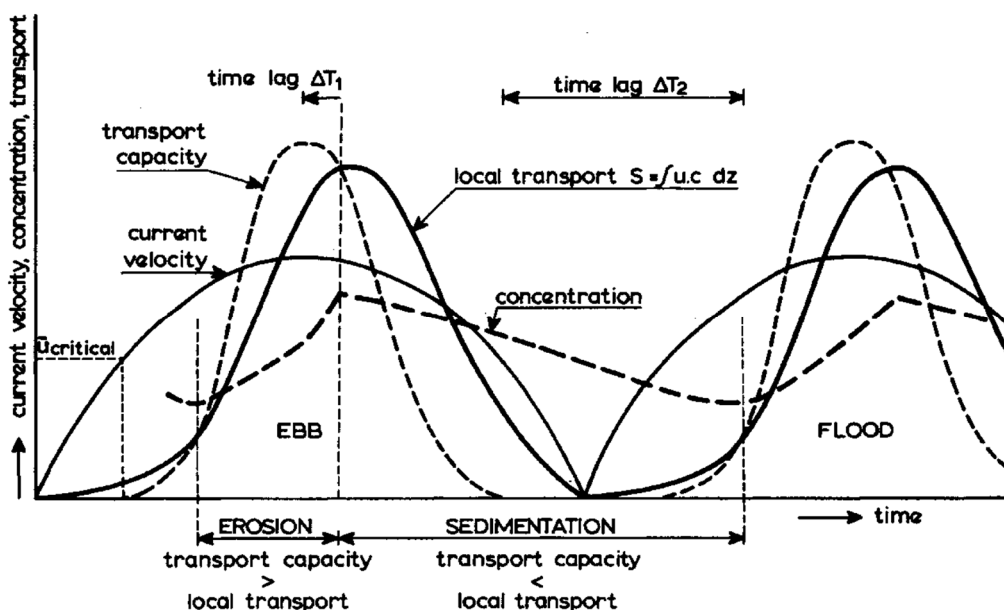


Figure 2-22 Time lag of suspended sediment concentrations in tidal flow [van Rijn, 2007].

Figure 2-22 shows the transport capacity for a given current velocity, the actual transport rate and the concentration of suspended material. As it takes time to transport bed material upwards during stronger current velocities, the average concentration and actual transport increases as long as the transport capacity is larger than the actual transport rate. As the current velocity starts to decrease, the actual transport is still less than the transport capacity and concentration and actual transport continue to increase until it is equal to the capacity.

2.7.3 Cohesive sediments

Cohesive sediments show, compared to non-cohesive sediments, different behaviour in the water column as they interact with other particles. These fine particles may stick together and their behaviour is controlled by complicated processes of which an overview is shown in Figure 2-23. The most important properties and processes for cohesive sediments are:

- Cohesion
- Flocculation
- Settling
- Deposition
- Saturation
- Consolidation
- Erosion
- Transport

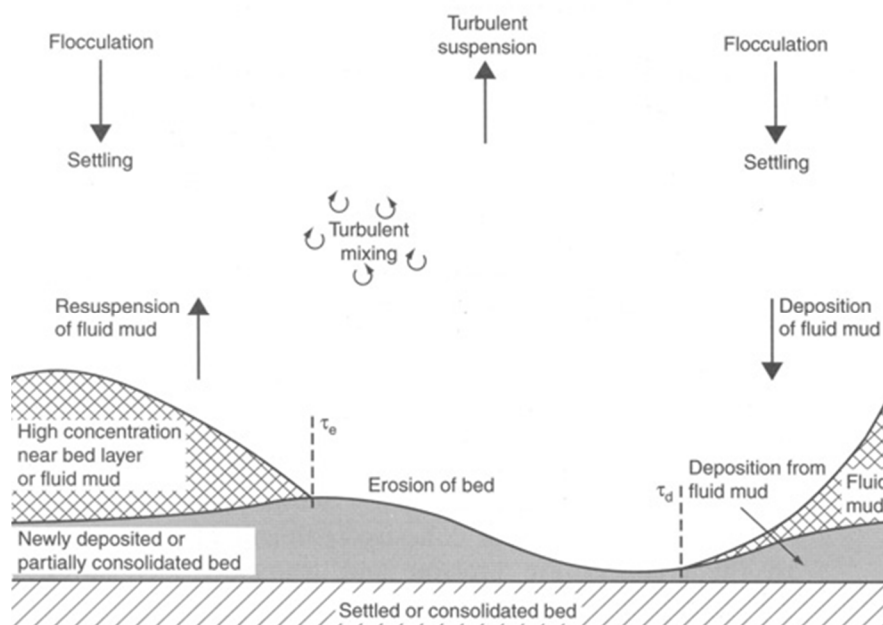


Figure 2-23 Processes of cohesive sediments (Whitehouse, 2000)

The state and position of sediments over the vertical is not only determined by the processes and properties mentioned above, local environmental circumstances (waves, flow, salinity, etc.) are also of importance. Mud occurrence can generally be categorized in three states:

- In suspension, with concentrations up to 10 grams of dry material per litre.
- Mobile fluid mud, near the bed with concentration in the range 10 to 300 gr/l. This layer consists of newly deposited material, often found in navigation channels where it is stirred up regularly by high velocities.
- Consolidated bed. These are older deposits and have consolidated for years and gained in concentration, up to 650 gr/l for stiff mud.

2.7.3.1 Flocculation

Flocculation is the process typical to cohesive sediments, which causes clay particles to aggregate with silt and organic material to form flocs. As flocs contain a large amount of water, even low concentrations of clay, silt and organics may result in high volumetric concentrations of mud flocs. Flocs may break-up by, i.e. critical turbulence. Aggregation of particles occurs when particles collide and bind together. According to Winterwerp [2002], flocculation effects are governed by three agents:

- Brownian motions cause the particles to collide where the chance of collision is linear proportional to the sediment concentration;
- Differential settling velocity: particles with higher settling velocity fall on particles with lower settling velocity. Collisions between these particles may result in aggregation;
- Turbulent motions will cause particles, carried by eddies, to collide and form flocs. Turbulent shear may, on the other hand, cause the flocs to break-up.

In dynamic environments such as estuaries and coastal water, the turbulent motion is considered most important. The rate of flocculation is also affected by:

- Particle size and concentration. Smaller particles and higher concentrations increase the chance of collision and increases aggregation rate;
- Salinity. The presence of ions in the water (salt) negates the repulsive forces between particles leading to more intensive flocculation. However, Van Leussen [1994] concluded that salt decreases floc sizes due to increased shear caused by fresh and salt water bodies' interference.
- Organic material has binding properties, increasing flocculation
- Higher temperatures increase collision chance due to Brownian motions

Large flocs can have volumetric densities up to 10 gr/l in excess of the fluid density while the specific density of the particles relative to the fluid is 1600 gr/l. So, flocs mainly consist of water.

2.7.3.2 Settling

The settling velocity of a single particle in still water is given by $w_{s,0}$. Stokes found for spherical, solid particles (sand) in the Stokes' regime (particle Reynolds number $Re_p = \frac{w_{s,0}D}{\nu} < 1$ (Eq. 2.1)

$$w_{s,0} = \frac{(\rho_s - \rho_w)gD^2}{18\mu} \quad (\text{Eq. 2.2})$$

In which ρ_s is the density of the primary sediment particles, ρ_w the water density, g the acceleration of gravity, D the particle size, μ the dynamic viscosity and ν is the kinematic viscosity. Equation 2.2 is however not valid for mud flocs as they are not spherical and solid.

The settling velocity of mud flocs is a function of their size D and their differential density $\Delta\rho_f$ (the excess density relative to water ($\rho_s - \rho_w$)). Flocs have a relatively small $\Delta\rho_f$ due to flocculation and their high water and organic material content. Values for $\Delta\rho_f$ can amount up to a few tens of kg/m^3 (Winterwerp, 1998). Winterwerp (1998) found for mud flocs with a fractal structure an implicit formula for the settling velocity of single mud flocs in still water ($w_{s,0}$):

$$w_{s,0} = \frac{\alpha}{18\beta} \frac{(\rho_s - \rho_w)g}{\mu} D_p^{3-n_f} \frac{D^{n_f-1}}{1 + 0.15Re_p^{0.687}} \quad (\text{Eq. 2.3})$$

Where α and β are shape factors of the flocs, D_p is the diameter of primary mud particles, n_f is the fractal dimension of mud flocs, which is based on $\Delta\rho_f$, and Re_p is the particle Reynolds number. $1 \leq n_f \leq 3$, but in general $n_f \approx 2$, which shows that the settling velocity is proportional with the floc diameter (D) and not with D^2 as in Stokes' formula.

Mud flocs rarely settle as individual particles. With increased concentrations, the settling flocs start to hinder each other's movement, a process generally known as hindered settlement [Winterwerp, 2002]. Hindered settling in mud suspensions normally occurs when concentrations reach over a few kg/m^3 . At lower concentrations particles settle with a settling velocity defined by Stokes, as described in Equation 2.2 for sand or Equation 2.3 for flocs. Seven processes can be identified that affect the settling velocity of individual particles in a suspension of [Dankers, 2006, after Winterwerp 2002] of which the major three are:

- Return flow and wake formation. Falling particles create an upward directed return flow and a wake. The fall velocity of other particles in the near vicinity will be affected, decreasing the overall effective settling velocity of the suspension.
- Viscosity. The effective viscosity increases with particle concentration. Each individual particle falls in the remainder of the suspension with increased viscosity, thus decreasing the effective settling velocity of all particles.
- Buoyancy or reduced gravity. Individual particles settle in the remainder of the suspension with an increased bulk density, decreasing the effective settling velocity.

These three effects combined yield in a formula for the effective settling w_s in suspensions of cohesive sediment affected by hindered settling:

$$w_s = w_{s,0} \frac{(1-\phi)(1-\phi_p)}{1+2.5\phi} \quad (\text{Eq. 2.4}) \quad \text{where:} \quad \phi = \frac{c}{c_{gel}} \quad \text{and} \quad \phi_p = \frac{c}{\rho_s}$$

In which the factor $(1 - \phi)$ account for the return-flow effect, $(1 - \phi_p)$ for the buoyancy, ϕ is the volumetric concentration, c is the mass concentration of sediment particles and c_{gel} is the gelling concentration, i.e. the concentration at which flocs become space filling and form a network structure, called a gel, and a measurable shear strength builds up.

2.7.3.3 Deposition

The result of settling is deposition of sediment on the bed where deposition is defined as the gross flux of cohesive sediment flocs on the bed. Sedimentation is defined by Winterwerp [2004] as the net increase in bed level equal to deposition rate minus erosion rate. Deposition occurs when bed shear stress is lower than a critical value, τ_d , determined by properties of the sediments.

2.7.3.4 Consolidation

Consolidation is defined as: a process of floc compaction under the influence of gravity forces with an accompanied expulsion of pore water. A gain in strength of the bed material is the result [van Rijn, 2005]. Three consolidation stages are distinguished:

- Initial stage (days): Hindered settling and consolidation occur at the same time. Freshly deposited flocs are grouped in an open structure with large pore volumes. Bed surface level is linear related to time t .
- Intermediate stages (weeks-months): Pore volume is further reduced while pore water is drained through small openings. Bed level drops with $t^{0.5}$ or $\log(t)$.
- Final stage (years): flocs are broken down, pore volume further reduced and bed level sinks with $\log(t)$.

Consolidation will increase the density and strength of the bed, so consolidated mud will therefore erode less easily. Typical density ranges for consolidating mud in several consolidation stages are given in Table 2-3. Mud with wet density lower than 1200 kg/m³ is still sailable for ships. The transition from the fluid to solid phase occurs at a wet density of about 1300 kg/m³.

Consolidation Stage	Rheological behaviour	Wet sediment density (kg/m ³)	Dry sediment density (kg/m ³)
Freshly consolidated (1 day)	Dilute fluid mud	1000 - 1050	0 - 100
Weakly consolidated (1 week)	Fluid mud (Bingham)	1050 - 1150	100 - 250
Medium consolidated (1 month)	Dense fluid mud (Bingham)	1150 - 1250	250 - 400
Highly consolidated (1 year)	Fluid - solid	1250 - 1350	400 - 550
Stiff mud (10 years)	Solid	1350 - 1400	550 - 650
Hard mud (100 years)	Solid	> 1400	> 650

Table 2-3 Typical density ranges of consolidating mud [van Rijn, 2005]

2.7.3.5 Erosion

Sediment particles, flocs or lumps of the bed surface (incl. fluid mud layer) will erode when current and/or wave induced bed-shear stress (τ_b) exceeds a critical value for erosion (τ_e), which depends on the bed material characteristics (mineral composition, organic materials, salinity, density, etc.) and bed structure. Experimental research shows that critical bed-shear stress for erosion is strongly dependant on the deposition and consolidation history.

3. MEASUREMENT CAMPAIGN

3.1 Overview campaign

In September 2010, Haskoning Nigeria Ltd., carried out a measuring campaign to provide specific data of the hydrodynamic conditions and sediment characteristics of the Lagos Harbour area. It has been tried to take as many measurements throughout the area as possible within a period of ten days as the survey vessel was a limiting factor. In March 2011, a measuring campaign was carried out for a Haskoning project in Apapa channel. This campaign provided some additional turbidity data for this thesis.

Figure 3-1 shows the locations where measurements and samples (numbered purple circles) were taken. A more specified description can be found in the following sections. The results of the measured data are presented in Chapter 4.



Figure 3-1 Navigation chart with sample locations, ADCP cross sections and tide/OBS sensor locations

3.2 Tide

At each location marked with a black diamond in Figure 3-1, a tide sensor was installed. Time series for the Badagry location range from 7/9/10 12:00 until 11/9/10 14:00. The Appapa location provided time series from 8/9/10 14:30 until 11/9/10 13:45.

Due to an error in the data logging system the first day of measurements were lost for this location.

The third sensor was placed along a mooring jetty in Commodore channel. The strong currents in this area must have ripped the sensor from its support allowing it to sway with the current. Therefore, this pressure sensor was not in the same vertical position thus the measurements indicate very little variation in water level.

Tide data for this location is therefore unavailable. We do have offshore water level data at the entrance of Lagos Harbour based on the worldwide tide predictions by mobilegeographics.com. Detailed plots of all tide data can be found in Appendix A.

3.3 OBS sensors

Suspended sediment concentrations were monitored by 7 Optical Backscatter Sensors (OBS), measuring turbidity of the water at depths ranging from -3 m CD to -15 m CD. These sensors were attached to a weighted line and placed next to a mooring platform (indicated with a blue triangle in Figure 3-1. This structure consists of a concrete platform on several steel tubes with diameter of roughly 60 cm. The platform was chosen to provide a dry location where the data loggers could be stored without getting wet or stolen. The flow near the structure will be affected by the structure itself and may also have an influence on the measured concentrations. This location was however the best location available by lack of a dry and secure location elsewhere.

The OBS's were installed at 0.25, 0.5, 1.0, 2.0, 4.0, 8.0 and 12.0 meters above the bottom near the West edge of the navigable part of Commodore channel. The configuration was chosen such that it would record data for the whole depth and provide sufficient detail of the (expected) concentration gradient to be found near the bed.

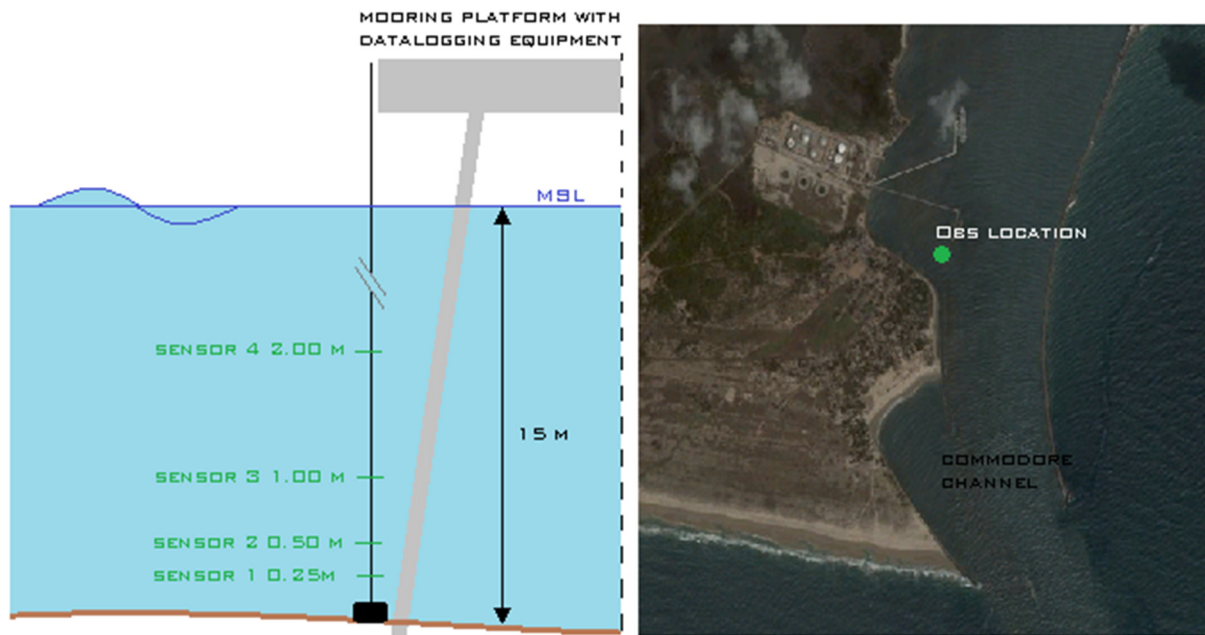


Figure 3-2 Schematic overview of OBS sensors location.

Turbidity is linear related to sediment concentration once calibrated to local conditions and material. The OBS sensors measure turbidity in formazin turbidity units (ftu) on a scale of 0-500 ftu and was logged every minute. The OBS sends out an infra-red pulse and measures the reflection of the particles in front of the sensor. It is very likely that a fish passing by or piece of plastic may be recorded as very turbid water while a moment later a very low value is recorded. This seems to be the case as the results show several peaks of high concentrations over a very short period of time which drops to a low turbidity in 1 minute time. These measurements are considered as errors. The logged values are sampled at 1 minute intervals from 07/09/10 15:20 until 11/09/10 14:20.

Calibration is done by adding small amounts of sediment taken from the muddy layer found near the bed at various locations throughout Lagos Harbour to a large beaker of filtered sea water. The sediment was stirred to bring it in suspension and the turbidity as well as the total amount of sediment added was recorded before adding more material. This was continued until the maximum of 500 ftu was reached which corresponded to a total of 3.5 grams of dry material being added. The relation between turbidity and suspended sediment concentration turned out to be 141 ftu=1 gram dry sediment per litre (see section 4.5.3.2). The material used was a mixture of clay, silt and fine sand to represent the material, which is likely to have passed the sensors while in suspension.

3.4 Salinity/PH/temperature measurements

Several salinity profiles have been measured at each of the three main locations: Badagry, Appapa and Commodore channel. These locations are similar to those of the ADCP current velocity/direction and backscatter measurement cross sections indicated in red lines [Figure 3-1]. The instrument used was an YSI CTD-PH probe. The

device measured salinity (conductivity), temperature, depth and acidity. Results are presented in Chapter 4.

3.5 DFES/bathymetry measurements

The campaign also included a bathymetric survey of the area roughly indicated by the parts where depth data is showed in Figure 3-1. These numbers represent a bathymetric survey carried out by LCM, probably in 2007. Although no digital information of that survey is available, comparisons can be made to the measured bathymetry of September 2010 to provide basic insights in recent morphologic changes.

The instrument used for the bathymetric survey was a Odom single beam, dual frequency echo sounder (DFES) that was simultaneously used to measure the thickness of any soft unconsolidated mud layers on the bed. This is done by sending out pulses at 33 and 210 kHz which reflect on respectively the transition zone between the soft and stiff layer and the transition zone of water to soft mud.

The survey was carried out by sailing cross-sections 100 meter apart throughout Lagos Harbour and part of the Lagoon. The data density along the sailed lines is much higher with depth/layer thickness measurement every 25 cm. The results are interpolated on a 5x5 m grid. Detailed maps of the water depth and soft mud layer from the measured data is presented in Chapter 4.7

3.6 Sample collection

3.6.1 Soil samples

Over the years, several studies on the Lagos Harbour bed material have been carried out. The objectives of the majority of those studies seem to be different to this one. Many samples have been taken in order to find sand to use as landfill or construction material. Therefore, very little is known about the properties and occurrence of finer sediments like silt and clay.

This study's measurement campaign included soil investigation by laboratory analysis. It was however not possible to analyse the samples locally due to the lack of required equipment at the local laboratories. A total of 16 soil samples were taken with a van Veen-grab sampler. Due to logistical limitations several samples were described visually and discarded. The remaining 11 were transported to the Netherlands for analysis at Deltares laboratory. In the lab, sediment composition (% gravel, sand, silt, clay, organic and carbonate content) was determined for all the samples. The results of the analysis can be found in chapter 4.5

3.6.2 Water samples

For calibration purposes of the OBS sensors and ADCP backscatter data, various water samples had to be taken and analysed for suspended sediment concentration (SSC). These samples could also be used to determine sediment

characteristics of the usually finer material to be found higher in the water column responsible for fine sediment and wash load.

For the collection of water samples, a water pump was used to fill containers for later analysis. This pump was connected to a hose which could be lowered to the desired (approximated) depth while a CTD-depth sensor registered the actual position on the vertical. The CTD-sensor was accompanied by an OBS in order to instantly compare results of the other OBS sensors and ADCP measurements.

This way, a few water samples were pumped up and transported to The Netherlands for lab analysis. Despite a cable/hose length of 25m and depths up to 15 m, it was often not possible to reach greater depths where larger concentrations of suspended sediments could be expected. The reason was that strong currents dragged the frame on which the hose and sensors were attached so far away from the survey vessel that soon the cables proved to be too short. It was found that under these conditions ($>1\text{m/s}$ flow velocity) depths over 7 meters were unreachable. The bottom could be reached during calm conditions but because the layer of high sediment concentration under these circumstances is quite thin and close to the bottom, it was still very difficult to take a good sample as the hose clogged up very easily with lumps of sediment from the bed.

Water samples with concentration of up to 50 ftu ($\approx 0.35\text{ gr/l}$) were taken. The amount of material taken this way was not nearly enough to perform tests on in a laboratory. Instead, the van Veen-grab was used to take a sample just above the bed. To remove the sand particles scraped from the bed, this sample was mixed and the sediment containing turbid water was decanted after some time.

The material gathered this was used to perform settling velocity tests and the zeta-potential was determined.

3.7 ADCP

3.7.1 Instrument

An Acoustic Doppler Current Profiler (ADCP) is a sonar-device that measures water current velocities over a range of depths. This ADCP emits a wave of sonic energy at a specific frequency to the water below the transducer. Some of the acoustic energy returns to the transducer as it bounces on water and other particles. As the sound energy returns at the transducer face it is shifted in frequency, known as the Doppler Effect, caused by the relative velocity of the water. As the emitted signal returns at different times at the transducer (depending of distance/depth to the target cell and sound velocity) a velocity profile can be calculated.

The instrument used for this measuring campaign is a RDI Workhorse Monitor operation at 1228.8 kHz.

3.7.2 Current velocity/direction and backscatter measurements

The ADCP can simultaneously measure current velocity, current direction and backscatter strength for each depth cell. These values were logged in text files also containing data of date, time, horizontal and vertical position of the vessel by differential-GPS, temperature and water attenuation. The latter two are used to calculate suspended sediment concentrations from backscatter data.

The ADCP was mounted on a frame on the side of the survey vessel 1 meter below the water line to keep the device submerged under strong wave conditions. The first meter of water just below the ADCP is too close to the transducer to provide accurate measurements and is discarded. Cell height was set at 0.25m and 80 depth cells per location were logged. Measurement density was set at 0.5 Hz while sailing at ca. 2.5 m/s, resulting in direction/velocity/backscatter profiles at 5 meter intervals.

For 6 days the above mentioned parameters were measured at four locations in Badagry Creek, Commodore channel and 2 cross sections in Appapa channel (Figure 3-1, red lines). Time series at the following dates/locations are recorded (Table 3-1).

Location	date	Time series length
Badagry Creek	05/09/10	4 hours
	10/09/10	8 hours
Commodore channel	06/09/10	11 hours
	09/09/10	8.5 hours
Appapa channel North & South cross sections	07/09/10	7.5 hours
	11/09/10	6 hours

Table 3-1 Collected ADCP time series

During these surveys it became clear that the flow direction measurements relative to the heading of the ADCP were affected by the GPS compass. This means that a single survey line sailed from bank 1 to bank 2 resulted in an opposite flow direction to what was measured a moment later when sailing back to bank 1. The error with the GPS compass could however not be fixed so the bottom tracking option of the ADCP was used for reference. Bottom tracking is based on the assumption the bed is stationary so the accuracy is affected when the bed is mobile. Additionally, it was no longer possible to estimate bed transport load by analysing the bottom tracking data from the ADCP compared to the 'real' position and direction calculated by the GPS systems.

3.7.3 Discharge measurements

One of the applications of the ADCP is discharge measurements. This is an automated function of the QINSY software used to operate the ADCP and is used for this campaign to measure discharges of the four main channels in the Lagos Harbour area: Commodore channel, Badagry Creek, Appapa channel and Five Cowrie Creek. The measurements were carried out at the intersection of these channels on

10/09/10 at 7:30, 12:30 and 17:00. An advantage of this type of measuring is that now also the top 2 meters (above and just below the transducer) are taken into account as well as the parts near the banks unreachable due to the depth of the vessel. It is however not possible to record discharge and backscatter at measurements at the same time, therefore for the majority of the survey time this function was disabled and the other parameters mentioned were logged. Although less accurate, velocity in combination with direction measurements can be integrated to estimate discharges.

4. MEASUREMENT RESULTS

4.1 Bathymetry

The dual frequency echo sounder (DFES) used for bathymetric survey produced to measured depths at each location surveyed. Paragraph 4.7.1 shows the result by the 210 kHz signal and will be representative for the level where sediment concentrations are high enough to classify it as soil instead of the sediment containing water above.

The second frequency used, 33 kHz, penetrated further into the bed and reflects were a strong gradient in density is present. It is assumed that the top layer consists of soft mud as has been found at several locations and sampled with a grab sampler (samples 11&12). Characteristics of the denser under layer are not known and because no calibration with coring has been done, the error margin is unknown. The results will therefore not be used to quantify volumes of soft material. Spatial variation of layer thickness can however be analysed qualitatively.

4.1.1 Bathymetry: 210 kHz reflection

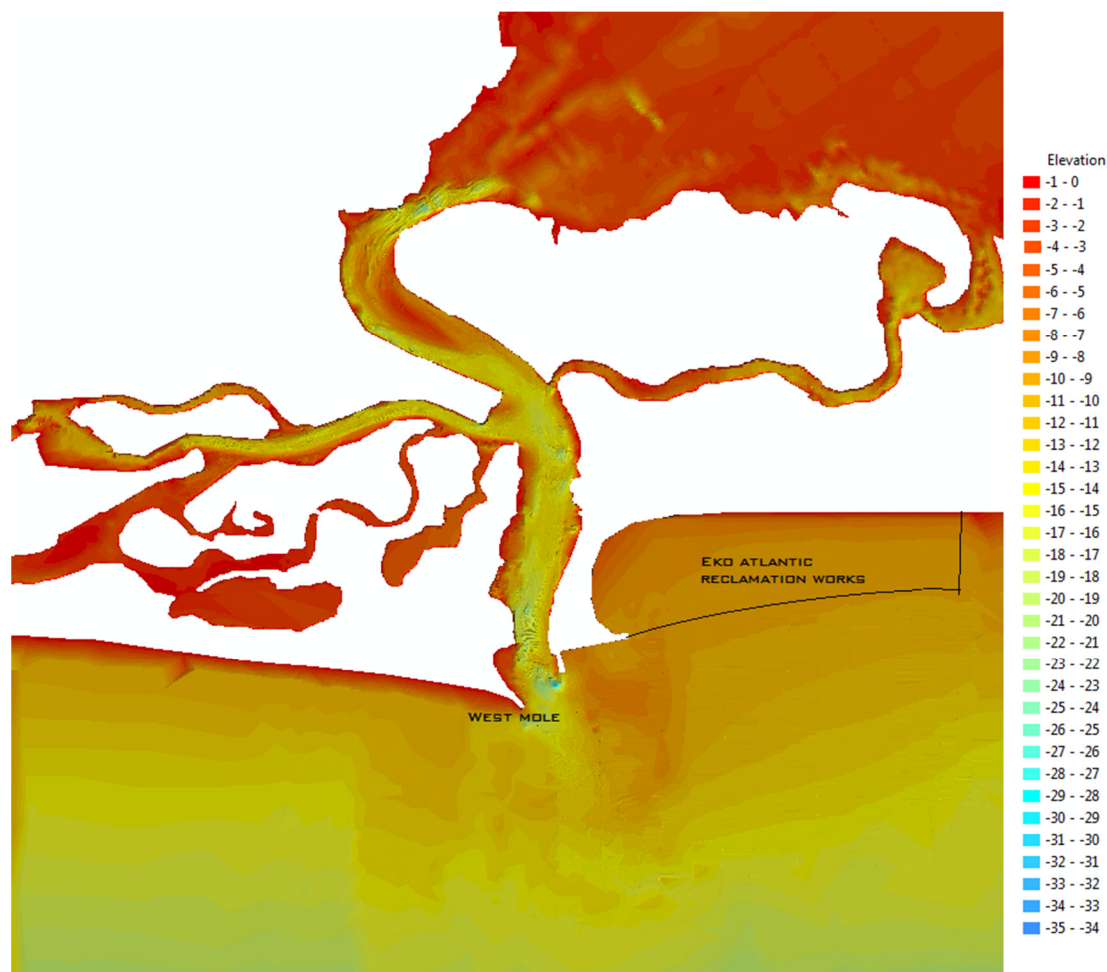


Figure 4-1 Bathymetry of Lagos Harbour (210 kHz reflection) in m +Chart Datum (= LAT/MSL-0.457 m)

Figure 4-1 displays all available bathymetry data from the measuring campaign carried out by DEEP bv (hydro graphic contractor) for Royal Haskoning in [2008] and [09/2010]. Where no surveyed data was available, older surveys and satellite data were used (Mainly the ocean and shallow parts: creeks south/west of Badagry creek and most of the Lagoon). A clear map of the surveyed area in the 2010 campaign is shown in Figure 4-5, which depicts the 33 kHz reflection. The 2008 campaign supplied data for the area beginning at ca. 1 km west of the west Mole, is roughly 0.5 -1 km wide and ends at 7 km to the east of the Harbour entrance. The satellite data is very inaccurate (the error ranged up to 6 meters in comparison to other sources) and was only used where no other data is available. As a result of the use of different data sources, each modified to their original purposes, the accuracy of bordering parts is unreliable.

Bathymetry east of the East Mole will change drastically in the near future due to the land reclamation works for the Eko Atlantic City project. Several hundreds of meters southeast of the East mole, the bathymetry map in Figure 4-2 shows a shallower area where it is believed (based on observations by local people) most of the material dredged inside the Harbour is dumped. Whether the shallow part is (partly) the result of dumping dredged material is not clear as no official statistics are available for this study.

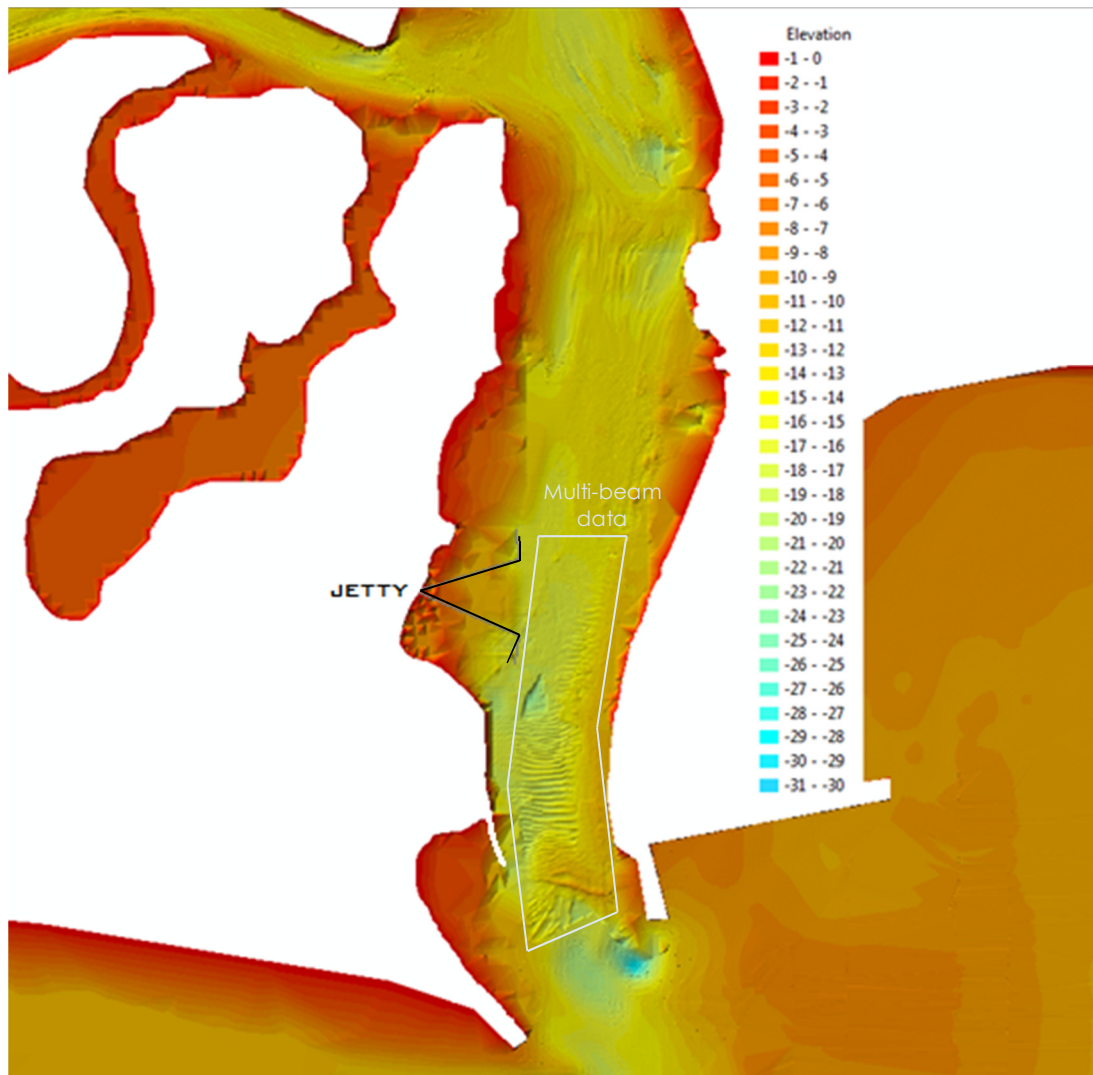


Figure 4-2 Bathymetry of Commodore channel (210 kHz reflection)

Near the mouth of Commodore channel, dunes in the bed are shown. Typical lengths of these ripples (crest to crest) are 15 to 20 meters and up to 0.5 m in height. This section relies on bathymetric data of another (recent) survey by a multi-beam instrument (outlined area), providing much more detail of the bed. Near the tip of the East-mole, a deep scour hole is present of over 25 m deep. Commodore channel contains several small deeper areas, one near the jetty where the OBS sensors were placed.

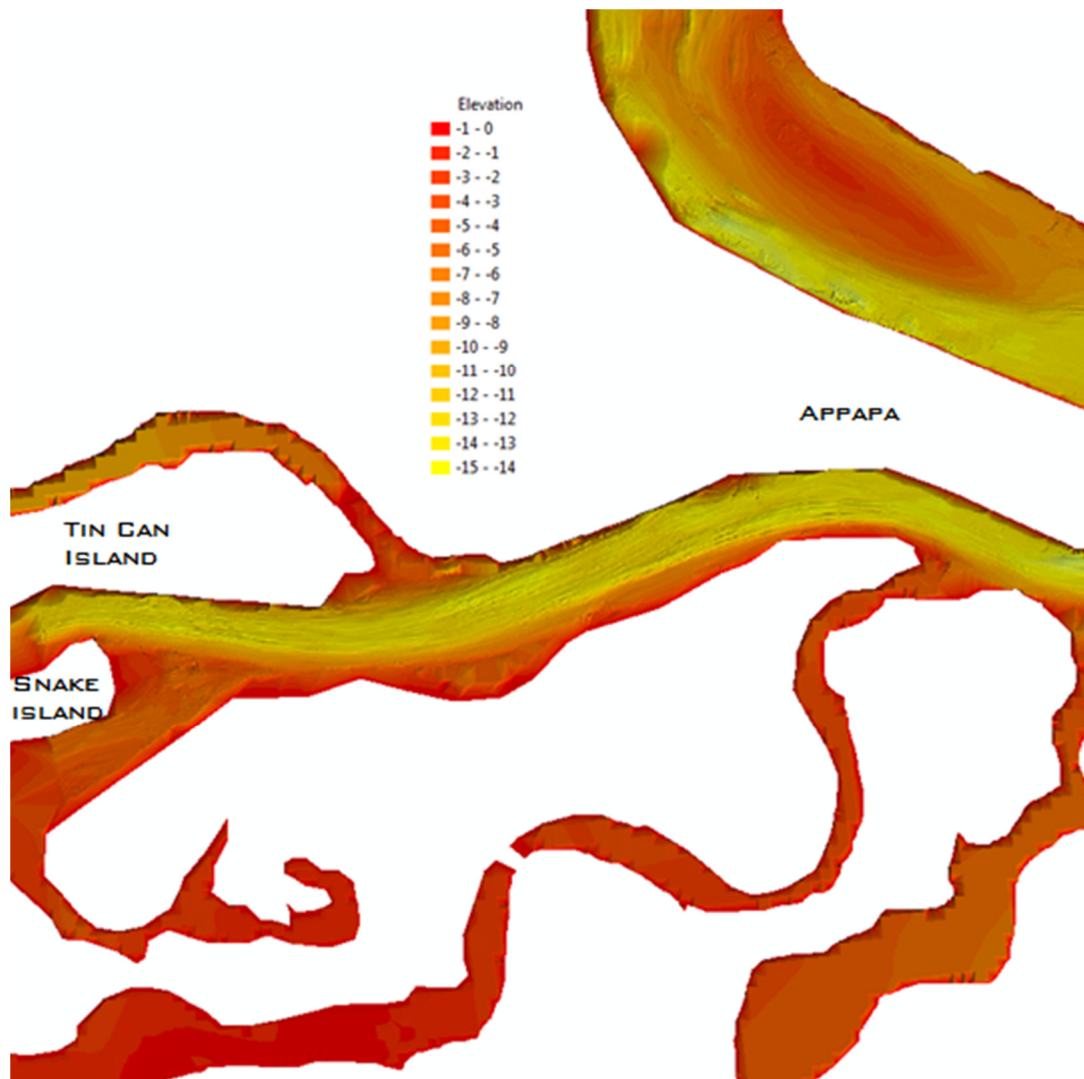


Figure 4-3 Bathymetry of Badagry creek (210 kHz reflection)

The main channel of Badagry creek is maintained by dredgers to navigable depths. Clear gulleys are present in Badagry creek along the Apapa and Tin Can Island quays. The channel south of Snake Island is considerable shallower than the northern branch of Badagry creek where dredging activities do take place. For the smaller, dead end channels, no vessel based bathymetry data is available. Satellite data indicate these channels are very shallow and are likely areas of sedimentation as current velocity is relatively low. Along the main branch of Badagry creeks, parallel lines are visible indicating dredging activities which leave trenches in the bed.

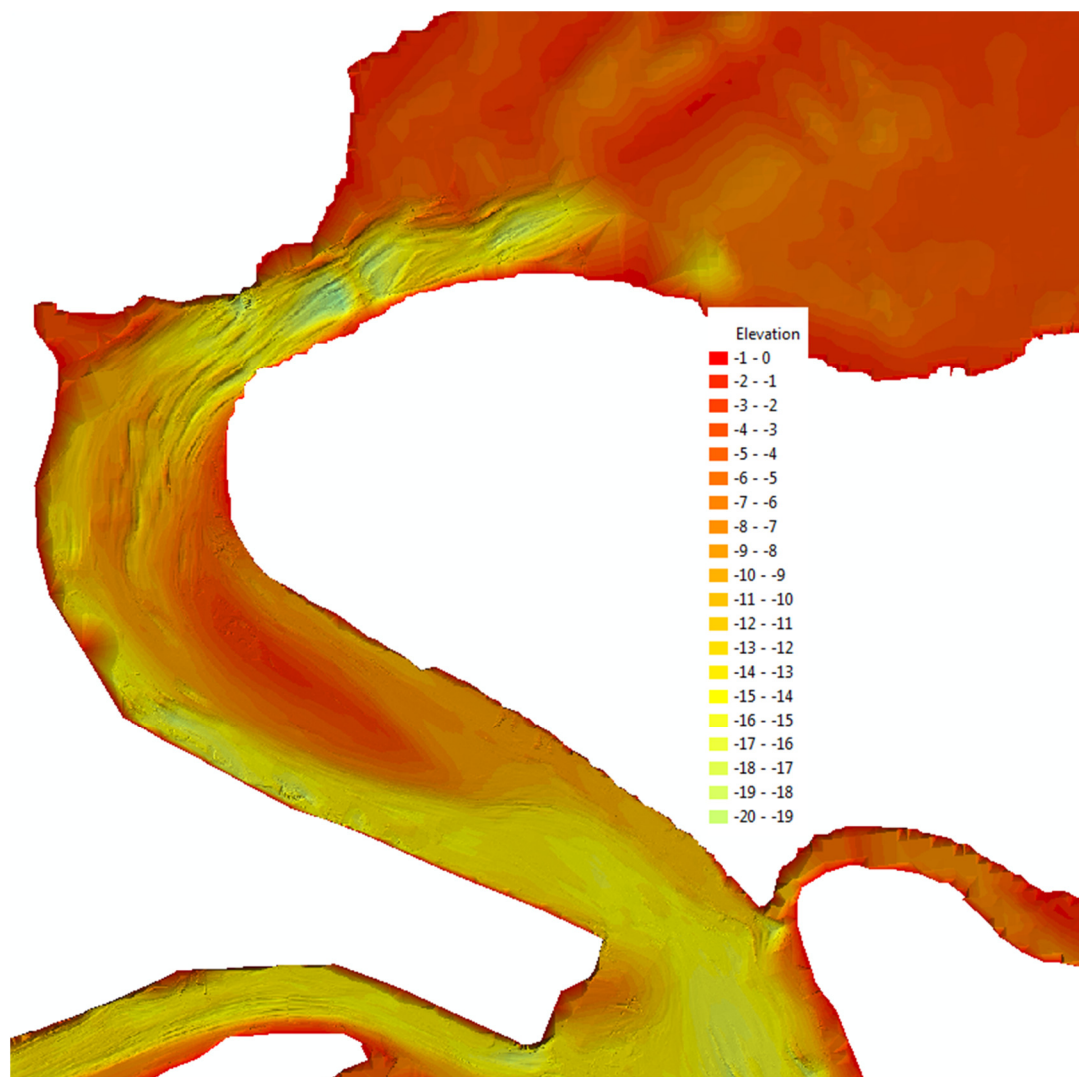


Figure 4-4 Bathymetry of Apapa channel (210 kHz reflection)

Apapa channel consists of two channels near the banks, separated by a shoal with minimum depth of about 2 m. The outer bend is significantly deeper than the inner bend along Lagos Island. A shallow ridge between two deeper areas near the entrance of the Lagoon marks the bridge connecting Lagos Island to the mainland. In the bend around Lagos Island, strong currents were experienced during surveying. The measured bathymetry shows the results of those currents as gulleys following the curvature of the channel flow.

The bend in Apapa towards the Lagoon is re-surveyed in 2011, again by DEEP by commissioned by Royal Haskoning, but for this section a multi-beam echo sounder was used which provides a very detailed bathymetry. The survey results are presented in appendix B and shows a detailed map with features like wrecks, scour holes and sand dunes.

4.1.2 Soft layer thickness

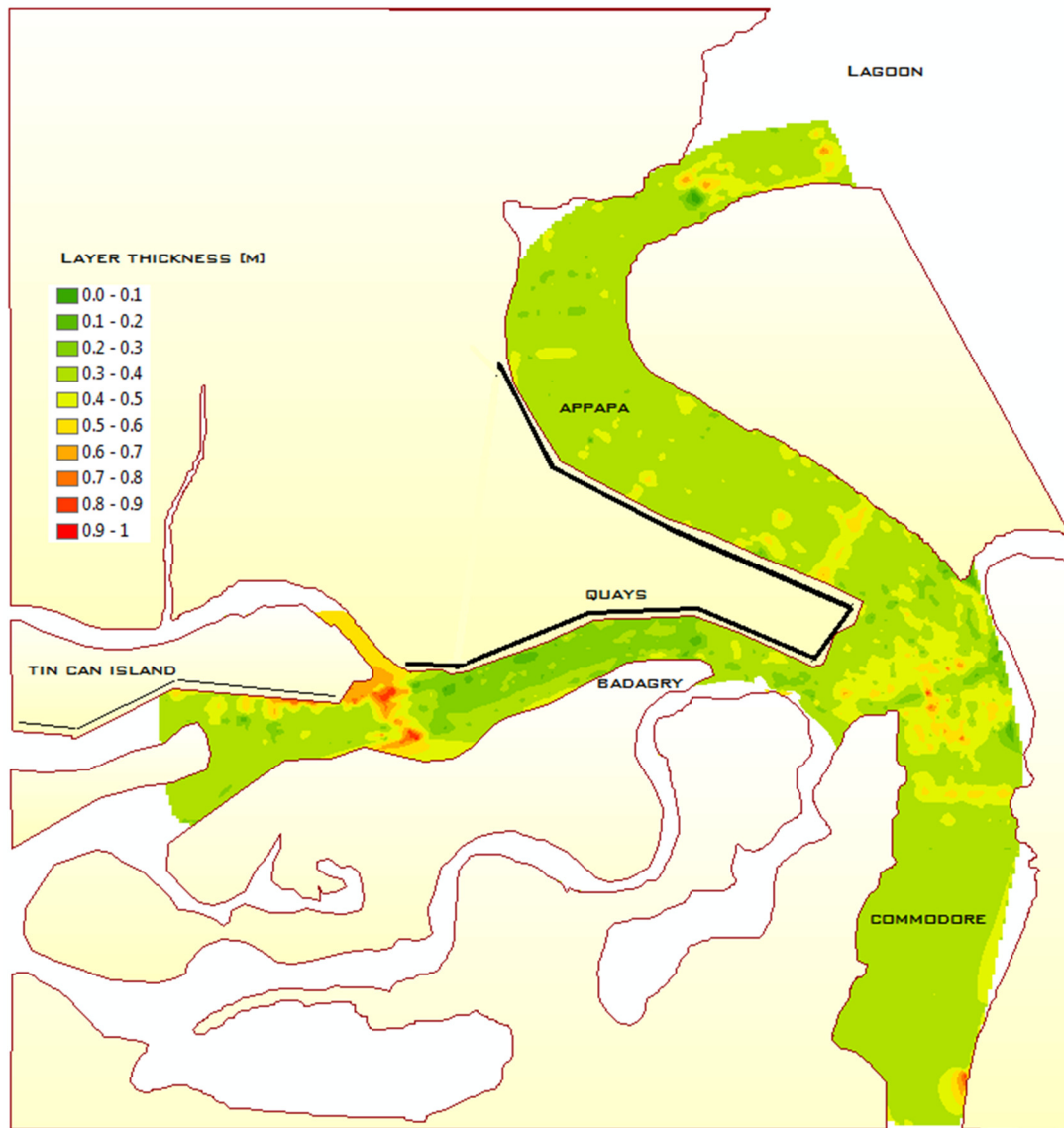


Figure 4-5 Spatial variations of soft layer thickness

The low frequency signal emitted by the echo sounder penetrates deeper in the bed and reflects where there is a strong difference in the bed composition (e.g. different material or more compact). The difference between the 210 kHz and 33 kHz reflection provides information of this layer, presumably consisting of softer, poorly compacted material e.g. mud. The instrument provides no additional data concerning the nature of this layer besides thickness, nor is it certain that the layer thickness measured in one area of the system represents the same type of material as measured in other regions. It does however indicate where soft material may be expected and may show smaller scale patterns. The reliability of this method will be discussed later.

Figure 4-5 displays the measured thickness of the soft top layer of the bed in the surveyed area. This layer typically ranges 0.3-0.4 m for large parts of Commodore and Apapa channels with local extremes near the bridge pillars at the entrance to the Lagoon and some of the deeper parts at the intersection with Badagry, Commodore, Five Cowries Creek and Apapa. Badagry Creek itself show more variation, especially near the junction of 'main' Badagry creek and one of its side channels at the east end of Tin Can Island. East of this point, the effects of the dredging activities in the area are visible. Along the north bank of this part of Badagry Creek, the quays for some of the largest ships mooring at Lagos Port are kept at depth as well as possible. Here, soft layer thickness is only 0-0.2 m. A closer look at this part is presented in the figure below.

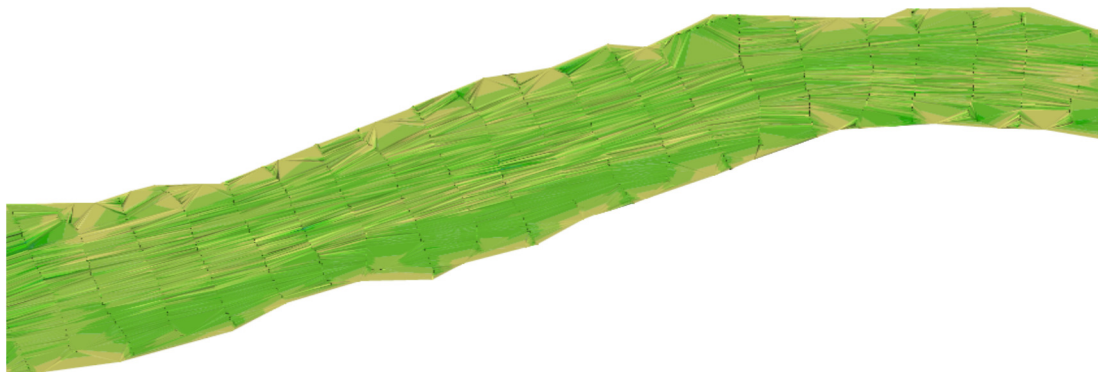


Figure 4-6 Badagry creek soft layer thickness data interpolated by ArcGIS TIN-creator

The vague dark lines, perpendicular to the channels flow direction, are remnants of the interpolation technique used by ArcGIS Tin and coincide with the cross-sections sailed 100 m apart. The different interpolation technique shows more detail along the channel. Here, clear lines can be observed which are probably the paths sailed by the dredgers leaving trenches with little soft material. This suggests the dredgers are effective although not efficient enough considering these dredgers are neglecting other parts of the Harbour channels as they seem to focus on this section. In other parts of the system, lines like in this section of Badagry creek are not found as clear as here. An example of the soft layer thickness measurements is depicted in the figure below. Here, one of the sailed cross-sections is plotted. The steep variation in soft layer thickness may be caused by dredging operations.

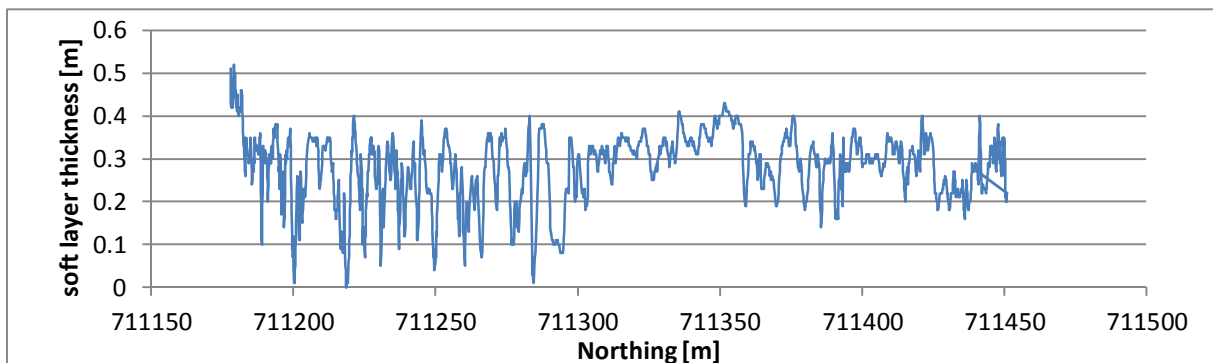


Figure 4-7 The soft layer thickness of the cross-section in Badagry creek surveyed with ADCP for two days. This cross-section was surveyed on 05/09/10 at 8:00 during ebb flow conditions.

The measured layer thickness is derived of the 33 and 210 kHz signal echoes and is interpreted visually. An example (not related to this thesis) of the conversion of the analog signal to a layer thickness is illustrated in the figure below.



Figure 4-8 Example of analog echo sounder signal interpretation [interpretation software manual]

The colored lines are added manually and should represent the interfaces between different materials/water. The dual frequency echo sounder data was analysed by DEEP BV using a method similar to this example provided by the manufacturer of echo sounder. The difference between the red and blue line is recorded as the top layer thickness. The blue line represents the 210 kHz signal and the top of the top layer of the bed and is generally very easy to observe. The interface between the top and under layer is marked by the red line and is more difficult to identify. This example shows a clear interface in the left part of Figure 4-8 but the top layer thickness is hard to measure for the right part. Errors in the interpretation of the top layer thickness are easily made, especially when the surveyed bed has steep slopes (e.g. dunes).

The available multi-beam bathymetry data shows two sections, in Commodore channel (outlined area in Figure 4-2) and Apapa channel (appendix B), show bedforms which contradict with the implied existence of a soft layer in these areas. Sediment samples taken from the bed show very little fine sediments (see section 4.2) in the multi-beam surveyed areas in Commodore and Apapa channel. It is assumed that the measured soft layer thickness is incorrect in these sections of Lagos harbour.

Other sections, e.g. Badagry creek and at the junction between these main channels were surveyed with single beam sensor only and therefore cannot show detailed bedforms. Whether the soft layer thickness measurements in these areas are correct cannot be checked with the single beam bathymetry data but sediment samples taken from the bed confirm the presence of cohesive sediments. Also, the layer thickness was easier to measure as the interfaces were much clearer. The data from these areas is believed to be correct.

4.2 Soil characteristics

4.2.1 Soil composition

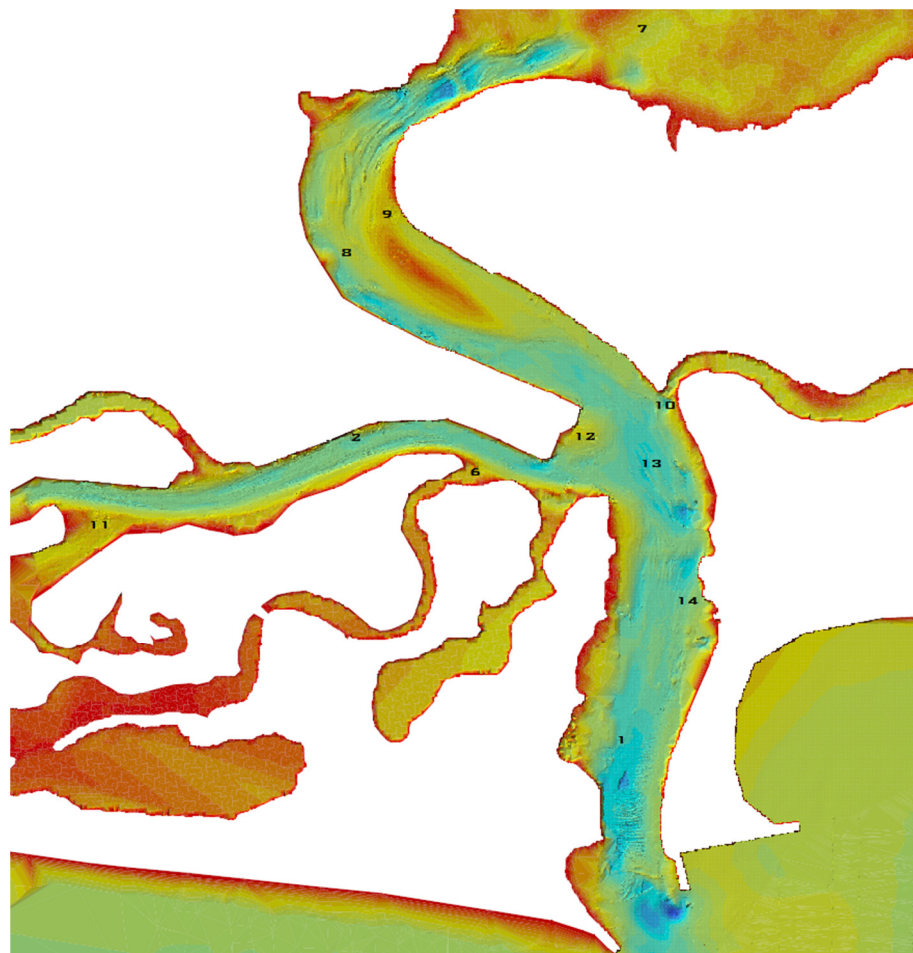


Figure 4-9 Sample locations taken in areas of various depths within Lagos harbour

Of 14 collected samples, 11 were analysed for material composition making distinction between gravel, sand, silt & clay and organic material (including carbonate, i.e. shells). The samples were dried and weighed before removing any organic substances via acidic and base solutions. The residue was dried and weighed to determine the mass lost due to oxidation of organic material and wet-sieved to distinct three classes [in μm] : >1400 , $53 -1400$ and smaller than $53 \mu\text{m}$. The results are listed in Table 4-1.

Sample no.	1	2	6	7	8	9	10	11	12	13	14
% Gravel	4.97	10.90	0.11	0.00	2.75	26.17	0.00	0. 0	0.00	20.03	2.31
% Sand	89.03	79.54	94.53	16.56	91.33	68.85	97.69	65.98	52.19	69.97	80.47
% Silt & clay	1.04	2.11	1.46	73.78	2.33	1.22	0.90	23.53	32.17	5.88	1.79
% org+carb.	4.95	7.45	3.91	9.67	3.60	3.77	1.41	10.49	15.64	4.11	15.43

Table 4-1 Sediment composition of analysed samples.

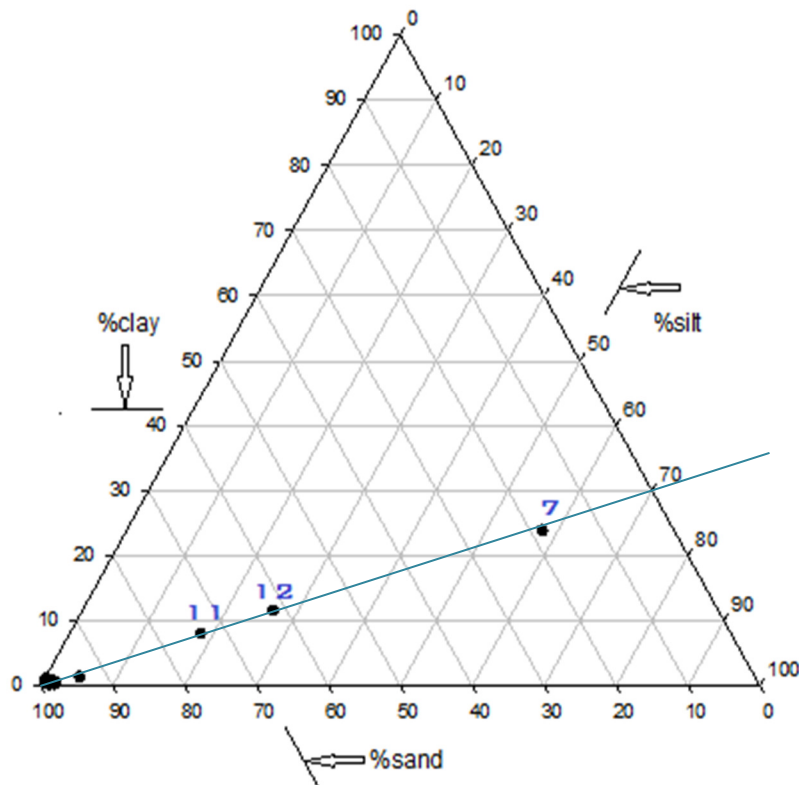


Figure 4-10 Sand, silt, clay diagram of the analysed samples.

Samples: 7, 11 and 12 consist of finer material and were found in areas of low flow velocities. Note that the diagram in Figure 4-10 only shows sand, silt and clay (=100%) and does not include the organic material. When plotted on a diagram as in Figure 4-10, the samples align. Even though there is spatial variation in the sediment composition, this is a strong indication that the material found on the bed in the entire surveyed area has a common origin.

4.2.2 Size distribution

A sediment size distribution analysis has been carried out at the Deltares laboratory using the guidelines described in [Van Rijn, 1986; 2007]. This document describes the method for wet sieving of the sample over a stack of pre-weighed sieves. A sample is placed on the top sieve (with mesh size of 2 mm) and is flushed through to the next sieve with a finer mesh. During this process, the stack was vibrated to speed up separation. The sieves were dried, cooled and weighed. The smallest of the total of 8 sieves used was 53 μm . Any particles passing through all sieves were collected and further analysed using a Malvern mastersizer 2000 capable of measuring particle sizes in the range of 20 nm to 2000 μm . This device could measure the full size range of the analysed samples but provides more accurate sediment size distributions for samples that are easily maintained in suspension. Most of the sieved samples contained little material smaller than 53 μm (up to 5% of total mass). These samples were not analysed with the mastersizer and the size distribution is obtained by sieving only.

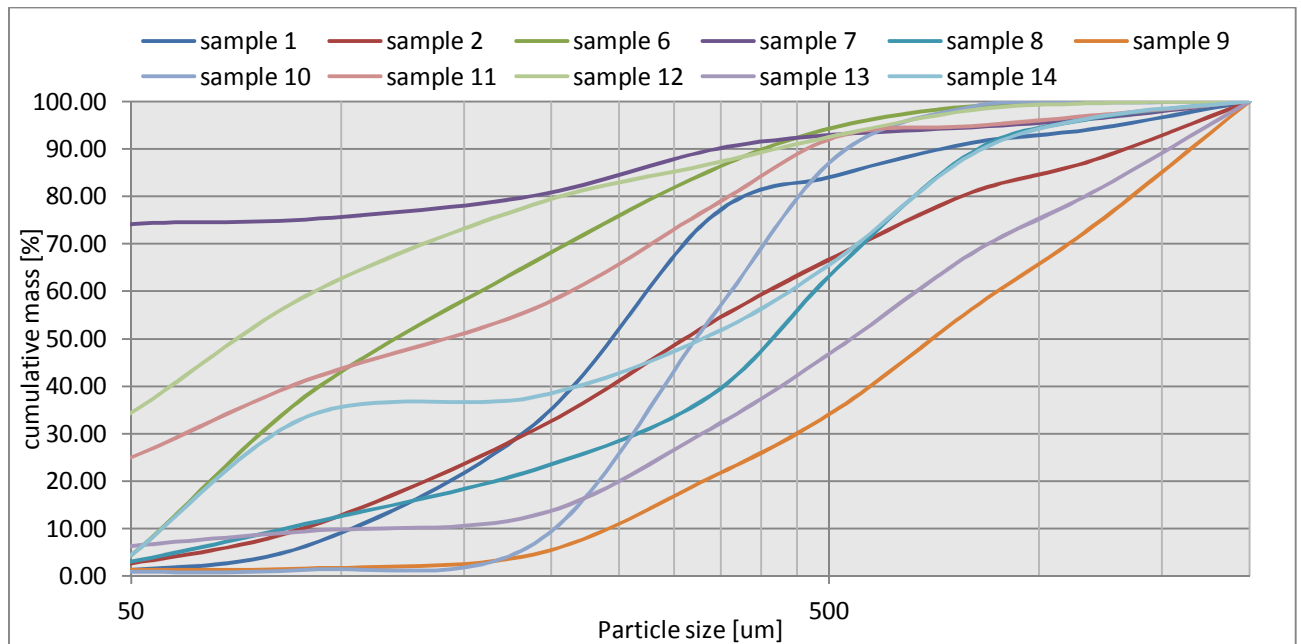


Figure 4-11 Cumulative particle size distribution, analysis by (wet) sieving

Three samples; 7, 11 and 12 consisted of considerably finer material and the sieve fraction smaller than 53 μm was analysed further using the Malvern mastersizer 2000. This device determines particle size using a laser. Figure 4-11 and Figure 4-12 show the results of the sieving and mastersizer analysis.

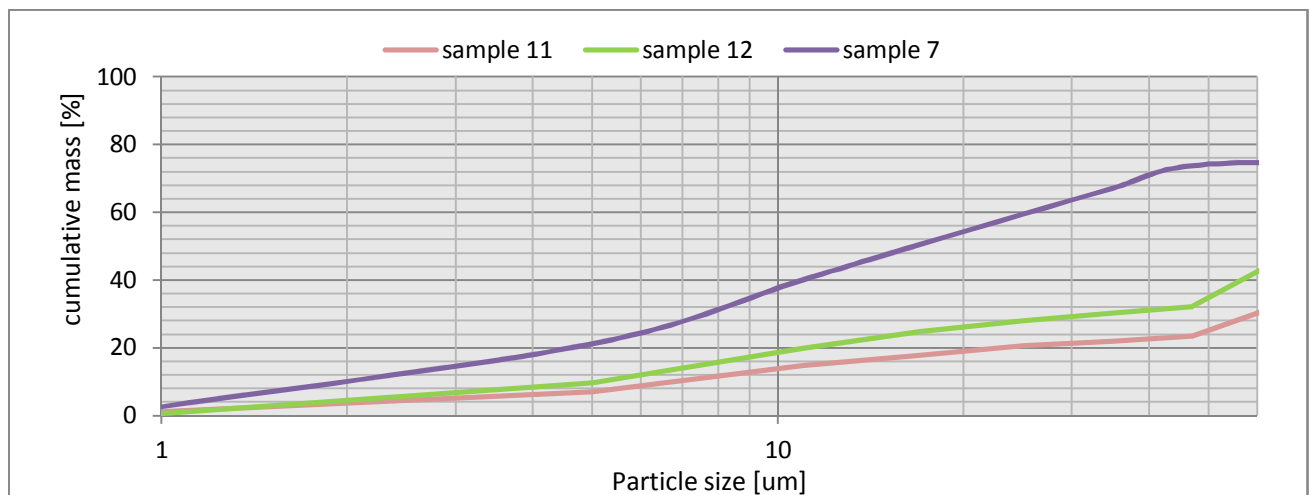


Figure 4-12 Cumulative particle size distribution based on Malvern mastersizer analysis for samples 7, 11 and 12 (containing a significant amount of fine material)

4.2.3 Settling velocity

The material gathered near the bed was used in settling velocity experiments. Several suspensions of different concentrations were made in a glass cylinder with a measuring tape attached. The suspensions were mixed gently in order to achieve a uniform concentration over the full height of the mixture column while keeping turbulent flow as low as possible. The object of the test is to measure the settling velocity in still water and any eddies would disturb the particles in the first part of the test. As the particles settled, a layer of clear, sediment free water above the turbid suspension starts to increase in height. The top level of the sediment containing column was recorded in time. This experiment was repeated for different initial concentrations of sediment taken from soil sample 7 and 12 after separating the cohesive sediments from particles left on the 53 μm sieve. Figure 4-14Figure 4-13 shows the results for one of these experiments carried out in the laboratory at Deltares.

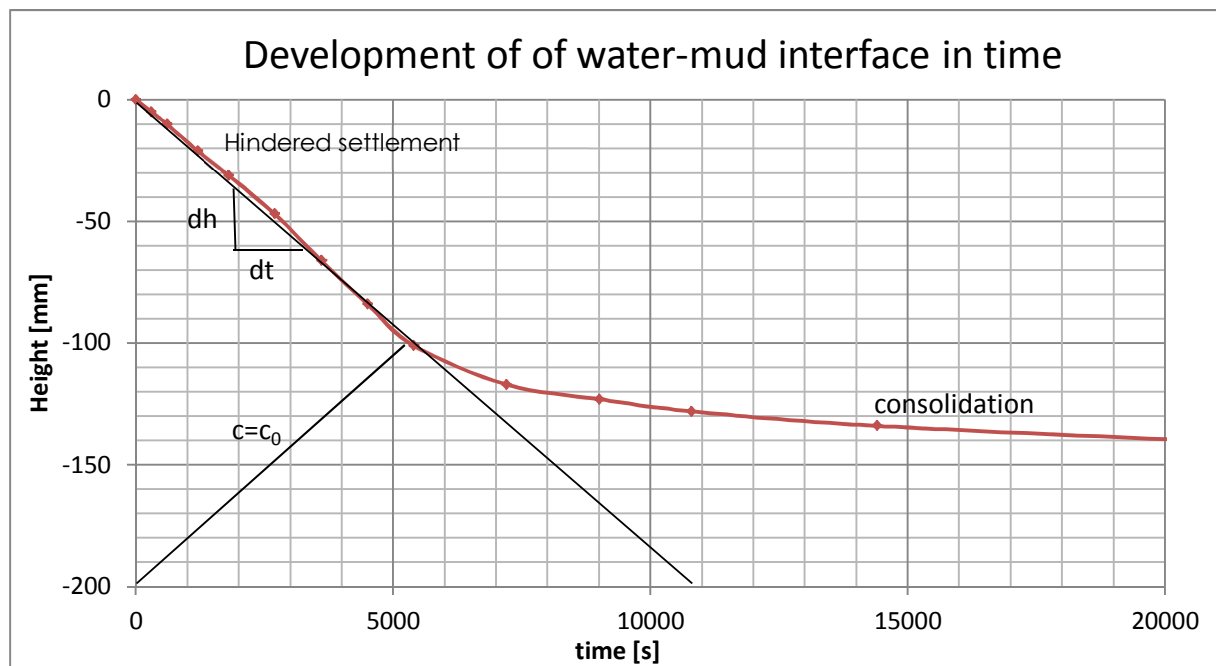


Figure 4-13 Settling velocity test of Lagoon sample, starting concentration = 20 gr/l

Initially, the interface drops at a near constant rate under hindered settling conditions. During this phase, the top part of the mixture column settles at the same velocity but as the concentrations near the bottom build up, the height of this column decreases in time. This is depicted in Figure 4-13 indicated as the left triangle bound by the y-axis and the line $c=c_0$ (concentration= start concentration, e.g. 20 gr/l). As the slope of the graph for $t=0-5000$ s is a straight line, particles settle with a near constant speed w_s , which is the settling velocity of mud flocs in the hindered settlement regime described in section 2.7.2. A. This is observed as the drop rate declines gradually until to the moment (in this example after 3 hours) a constant settling velocity is reached. The final stage starts when effective stresses begin to build up in the consolidation bed.

The settling velocity is a function of the concentration. The material from sample 7 was diluted to make several suspensions of different concentrations. For each starting concentration the development of the clear water-mud interface is shown in Figure 4-14.

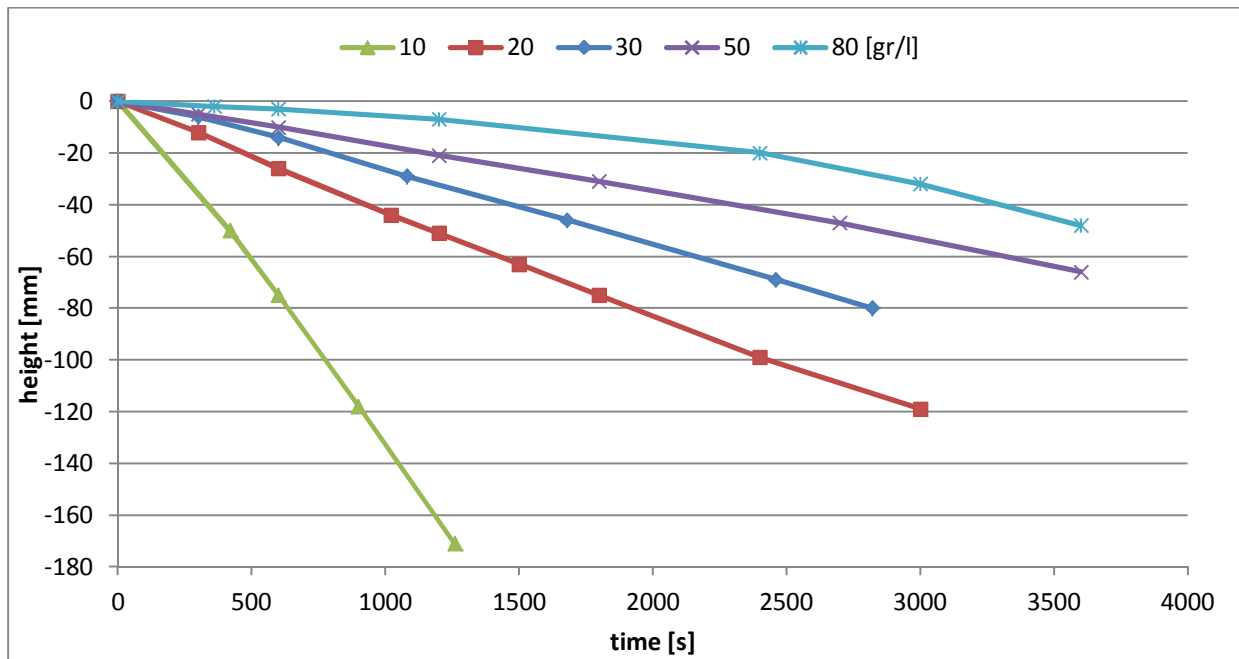


Figure 4-14 Settling curves of fall velocity tests with different start concentrations [gr/l] (up to the moment consolidation behaviour started, material: sample 7, Lagoon)

The settling velocity for concentrations 10, 20, 30, 50 and 80 g/l result from the gradient of the settling curves in the above figure and are respectively 0.135, 0.039, 0.032, 0.019 and 0.010 mm/s. Sediment concentrations in Lagos Harbour are significantly lower with only a few gr/l. Although the settling velocity increases with lower initial concentration in the measured range of 10 to 80 gr/l, does not mean that the settling velocity of sediment in a suspension of only a few gr/l is much higher than that of a 10 gr/l suspension.

Tests with starting concentration of 5 gr/l showed a low settling velocity as much of the material remained suspended for a long period. As particles must collide to form flocs and chances of collision are lowered with decreasing concentration, flocculation decreases. For very low concentrations, flocculation is limited and the particles settle slowly and individually.

Using the formula in equation 2.3 of section 2.7.3.2 and the results of settling tests, the settling velocity of a single particle, $w_{s,0}$, can be estimated. The unknown volumetric concentration, ϕ , is estimated by assuming a value for c_{gel} . The settling test results are plotted in Figure 4-15 and by fitting the formula by trial and error on the data, $c_{gel}=120$ g/l and $w_{s,0}$ becomes 0.07 mm/s.

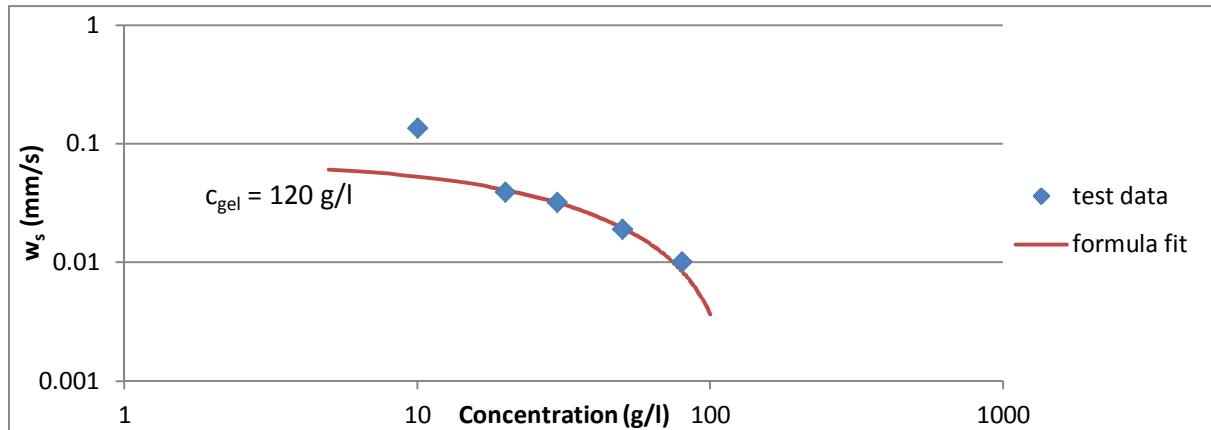


Figure 4-15 Hindered settlement formula (Eq. 2.3) fitted to settling tests data

All measured settling velocities of flocs and the calculated settling velocity of single particles are relatively low compared to the flow velocities. The cohesive material found suspended in the water is easily kept in suspension by the flow velocities common in Lagos Harbour' main channels. Sedimentation of fine sediments in these areas is therefore not expected. Sedimentation in the Lagoon and dead end branches of Badagry creek may occur.

4.2.4 Zeta-potential

The zeta-potential is a measure of the repulsive forces between particles and determines, among other factors, the ability of particles to form flocs. The electro kinetic or zeta potential ζ [mV] is the electric charge that develops at the interface between the particle surface and its liquid medium. Particles in a medium with ζ -potential close to zero tend to flocculate well while more extreme values (positive or negative) result in stable suspensions and slow flocculation behaviour. An absolute value of 25 mV can be taken as an arbitrary value that separates low-charged surfaces from highly charged surfaces.

The net charge at the particle surface affects the ion distribution in the nearby region, increasing the concentration of counter ions close to the surface. Thus, an electrical double layer is formed in the region of the particle-liquid interface (Figure 4-16, left). This double layer consists of two parts: an inner region that includes ions bound relatively tightly to the particle surface (stern layer) and an outer region where a balance of electrostatic forces and random thermal motion determines the ion distribution. The potential therefore decreases with increasing distance to the particle surface until, at sufficient distance; it reaches the bulk solution value (assumed to be zero). This decay in potential is visualized in Figure 4-16 (right). Herein is δ the layer of the stern plane shown in the left hand figure and the zeta potential is the value at the surface of shear.

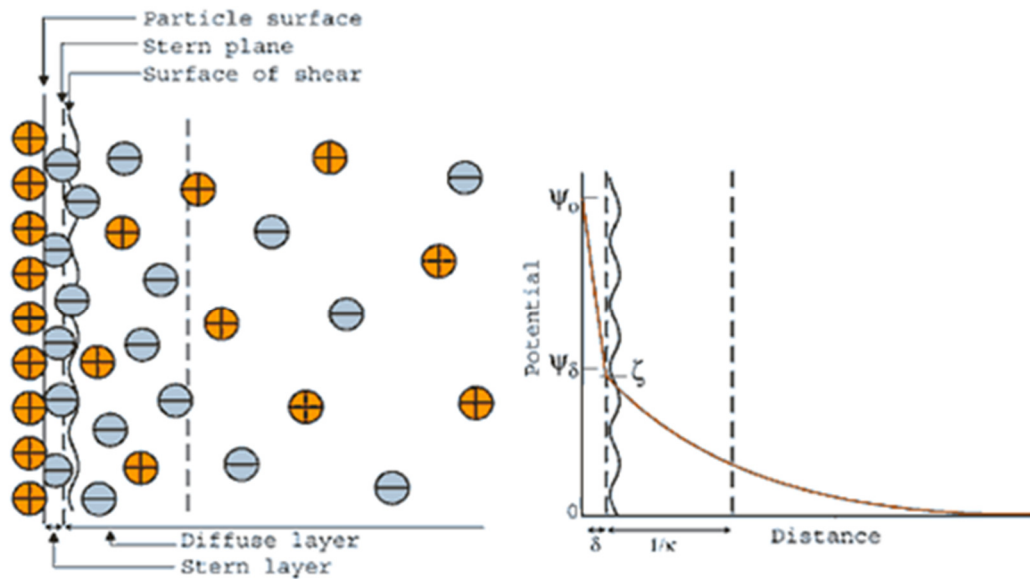


Figure 4-16 Zeta potential [Brookhaven instruments]

In an electric field, as in micro electrophoresis, each particle and its most closely associated ions move through the solution as a unit, and the potential at the surface of shear between this unit and the surrounding medium is known as the zeta potential. When a layer of macromolecules is adsorbed on the particle's surface, it shifts the shear plane further from the surface and alters the zeta potential. Zeta potential is therefore a function of the surface charge of the particle, any absorbed layer at the interface, and the nature and composition of the surrounding suspension medium.

In general, an increasing pH (i.e. a decrease in H^+ -ion concentration of the medium) yields a decreasing zeta potential thus becoming more and more negative. In a medium with very low pH value, the abundance of H^+ -ion will effectively negate the negative particle charge and has a zeta potential closer to zero.

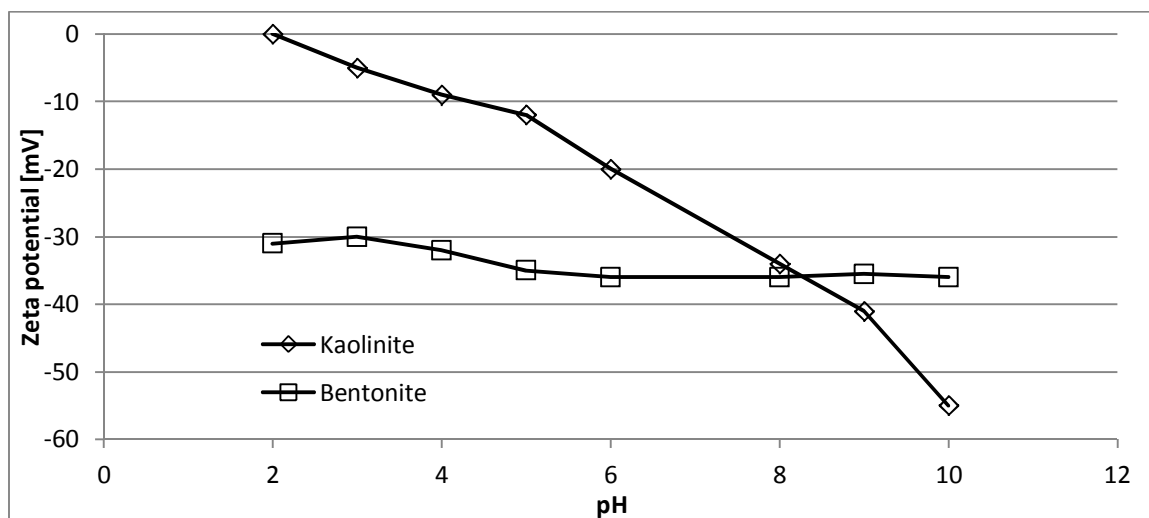


Figure 4-17 relation of ζ -potential as function of pH (Vane et al., 1997)

The pH-dependency of the ζ -potential is different for various types of clay. Figure 4-17 shows the pH- ζ relation for Kaolinite and Bentonite clay (89% montmorillonite). For pH \approx 2, ζ -potential of kaolinite is zero and much higher (absolute) for higher values pH while Montmorillonite is almost unaffected by pH and ζ is always negative.

At sample locations 7, 11 and 12, water samples were taken near the bed and the suspended material was analysed at the Deltares laboratory. Using a Malvern Zetasizer3000, the ζ -potential was measured at a salinity of 25‰, similar to the salinity of the collected water samples. For each sample, a small amount of the turbid water samples were added to filtered water taken at each sample location thus creating three dilute suspensions containing <1mg per 50 ml. Each sample was injected to the Zetasizer and, while varying the pH value via an auto-titration unit, the ζ -potential was measured at predefined intervals. The results are shown in Figure 4-18.

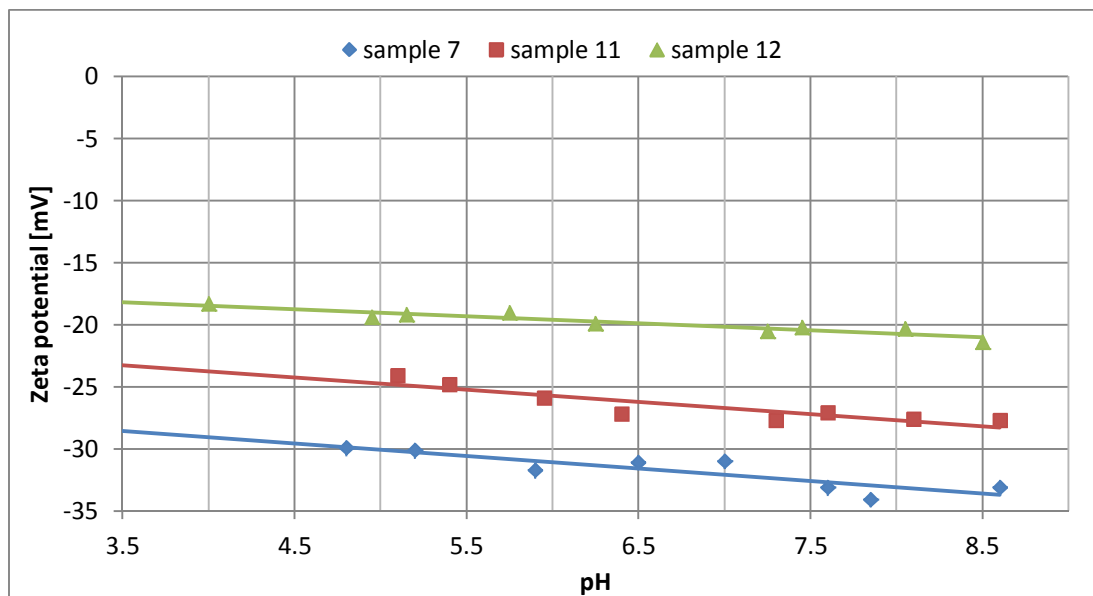


Figure 4-18 Measured ζ -potential as function of pH for samples 7, 11 and 12

The measurements cover the pH range of 4.5 - 8.5 which includes any realistic acidity possible in the Lagos system. Compared to Figure 4-17, the response of the ζ -potential to a varying pH suggests the material of Lagos is predominantly montmorillonite. While all samples show little susceptibility to H^+ - ion concentration, the absolute potential varies per sample location. The salinity of the medium does affect the zeta potential with decreasing potential as salinity increases [Delgado, 1985]. However, when salinity reaches the order of 5 ‰, a further increase in NaCl concentration no longer reduces zeta-potential. Under all circumstances experienced during the field campaign and from literature sources, salinity in the Lagos system does not drop below 5 ‰.

4.3 Salinity

On 8, 9 and 11 September 2010 the salinity was measured in the main channels of Lagos Harbour. The results are plotted in Figure 4-19. For reference to the tidal phase, see appendix A.

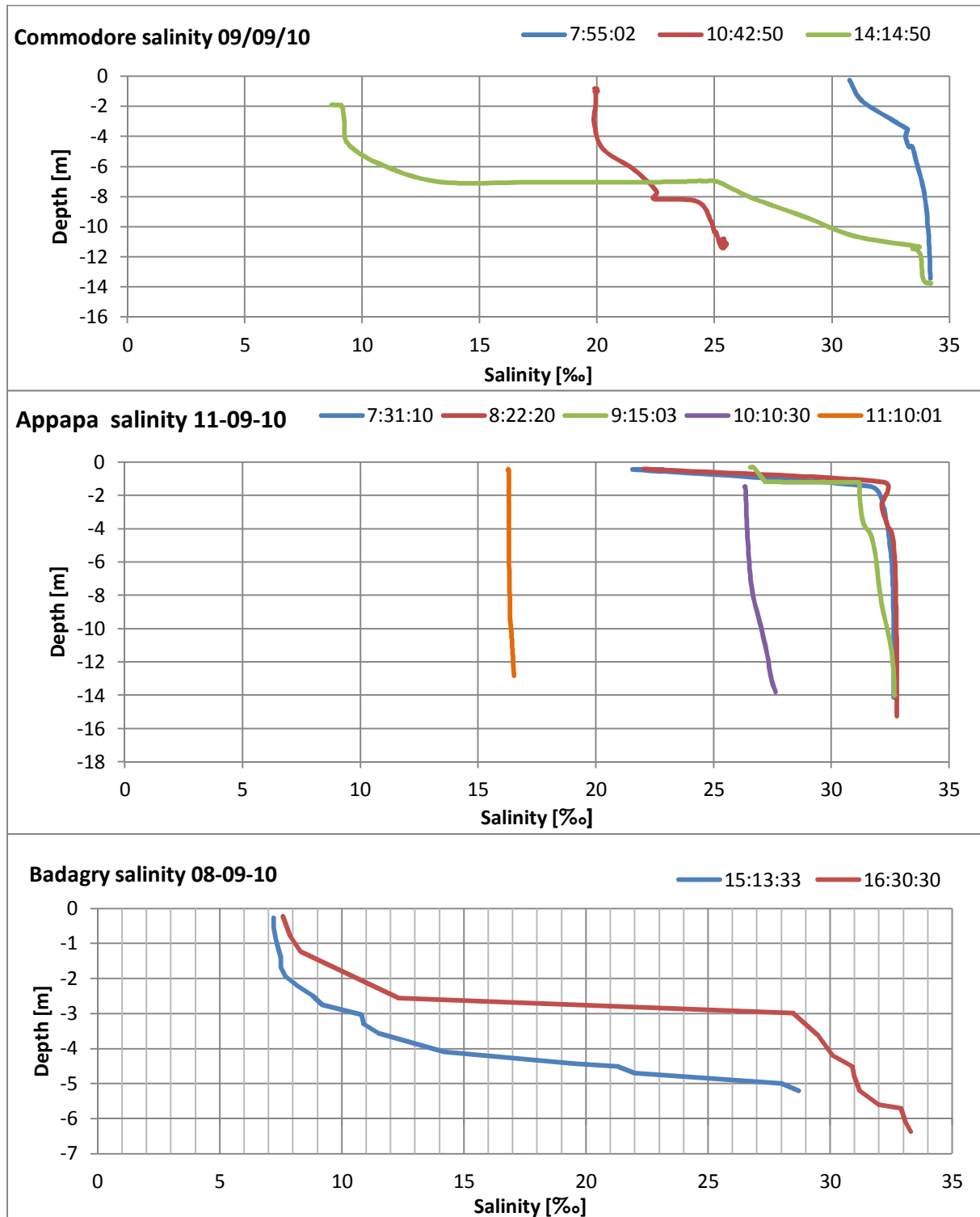


Figure 4-19 Salinity profiles of Commodore channel, Apapa channel and Badagry Creek.

The number of measured profiles is unfortunately very limited but they clearly indicate there is stratification due to salinity differences. For Commodore channel and Badagry Creek there is a strong inclination in salinity at roughly half the local depth while Apapa Channel shows a layer near the surface which is less saline than the deeper layer.

Where there is a difference in salinity, there may be a density current. The salinity profile, taken around the turning of the flow direction in Commodore channel at 14:15, shows a sharp increase in salinity. Figure 4-20 shows a plot of the velocity profile of the Commodore channel cross-section measured directly after the salinity measurement was carried out. At this point in time, the tide is turning and flood is coming in.

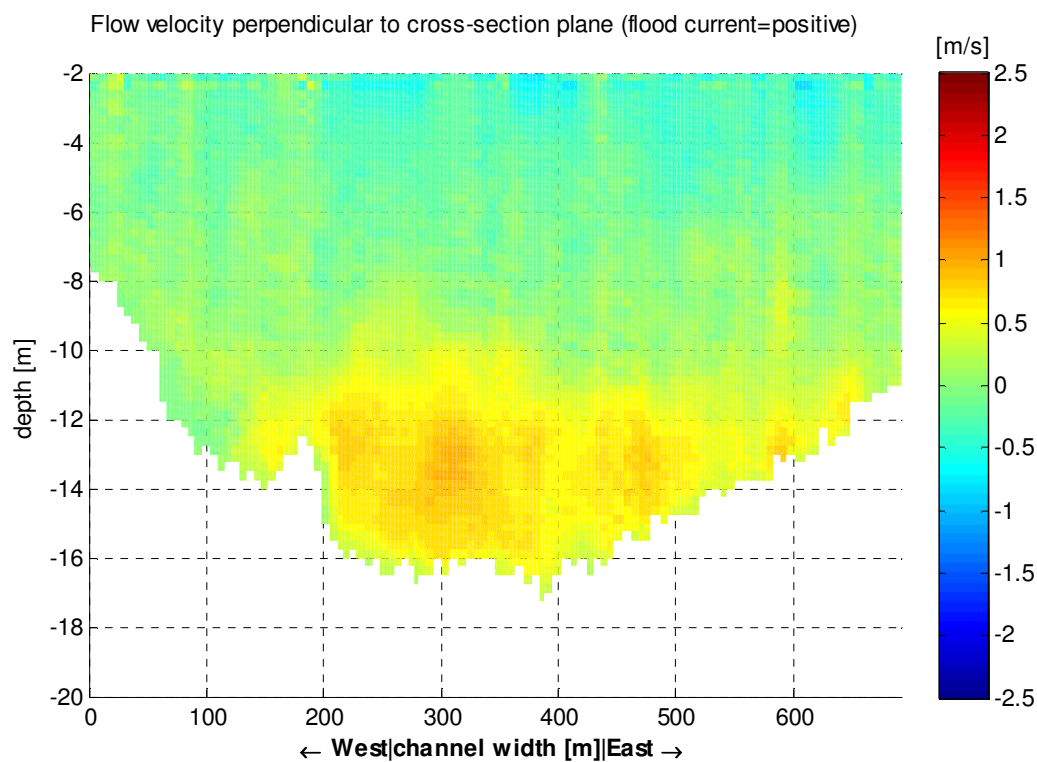


Figure 4-20 Velocity profile of Commodore Channel measured at 14:20 09-09-10

Here, a layer near the bottom is clearly visible and flows in the flood direction with current speed of 0.5-1 m/s. In the layer above up to the surface, the flow velocity is very low or even up to 0.5 m/s in the other direction. The bottom layer is more saline and is likely to be water from the ocean while the top layer is lighter water as a result of the fresh water discharge. Further from the ocean, the influence of the salty ocean water is less compared to the influence of the less saline water from the rivers and creeks discharging in the Lagoon and Badagry creek. There, the less saline layer is likely to be thicker and may even comprise the full depth. This is especially clear in Apapa channel where little stratification is measured. There, a difference in flow direction near the bed and near the surface which is not observed in the velocity profiles measured with the ADCP. Badagry creek shows however two distinct layers

of saline and fresher water. Similar results were obtained from the Badagry creek ADCP data as the cross-section in Figure 4-20. At the moment the tide turns and flood starts, salty water is flowing inwards while the top layer is still flowing in the ebb-direction.

The salinity profiles and flow velocity stratification, measured in Commodore channel and Badagry creek indicate there is a density current flowing in the flood direction as the result of the difference in salinity between the fresher water from the rain run-off and rivers discharging through Badagry creek and the ocean water. This deep, saline layer is clearly observed close to the ocean in Commodore channel and is not measured in Apapa channel.

4.4 Hydrodynamics

For comparison to other locations measured on other days it is necessary to associate the separate data sets to a variable that can be related to all locations and days. The measurements are linked to the tidal phase derived from the water level data from the nearest tide station as well as the off-shore prediction (Commodore channel location). The tidal phase will here be defined as a value 0 to 1 where 0 marks the low low-water height of the day estimated by the off-shore tide prediction on 05/09/10 20:37. The first high water is usually around 0.25, the second less extreme low water is 0.5 and so on. This period takes two full ebb/flood cycles and amounts 24 hours and 50 minutes. This value for the tidal phase will be used in this report to plot various data sets together with normal date/time stamps.

4.4.1 Water level variation

Two out of the three installed pressure sensors provided accurate tide data, the missing data from the Commodore channel location near the entrance of the Harbour is replaced by water level predictions for Lagos Bar by mobilegeographics.com.

Figure 4-21 shows the recorded water level heights of the Badagry creek and Apapa channel tide stations. Also, the astronomical tide prediction for the off-shore location close to the Commodore channel survey line is plotted.

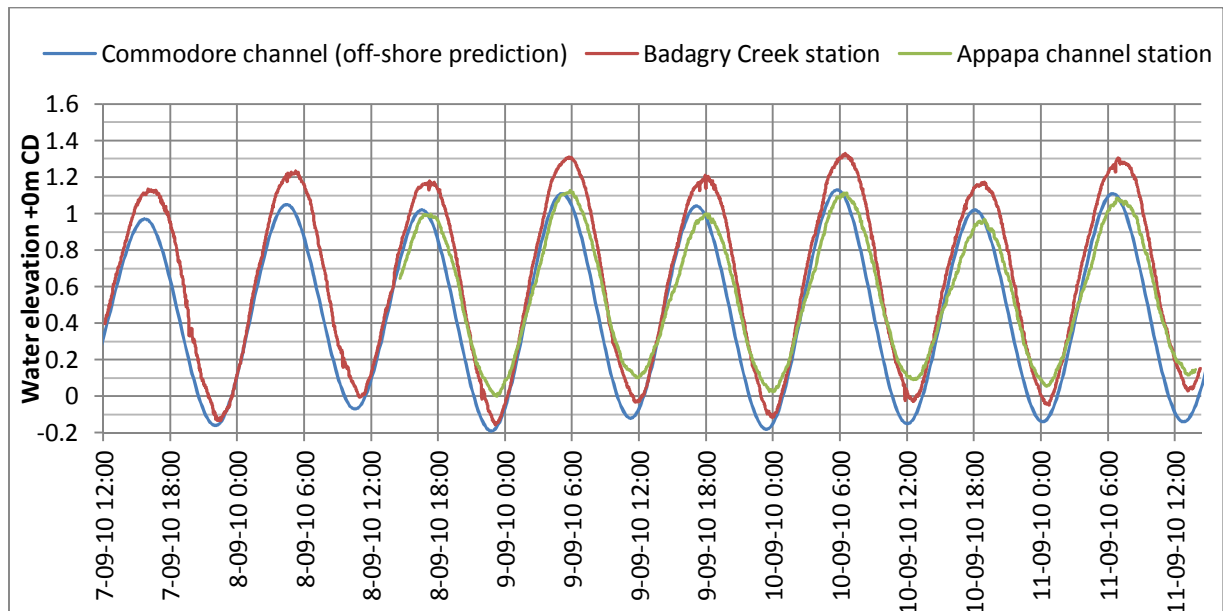


Figure 4-21 Water level variations derived from two tide stations and offshore tide predictions. 0 m + MSL = + 0.457 m CD.

Figure 4-22 displays the water level for Lagos Bar (prediction, red line) and the results from ADCP analysis of the survey data from 06/09/10 in Commodore channel near Lagos Bar. Firstly, it can be observed that the prediction fairly matches the water level data acquired from the vertical position of the survey vessel measured by the on-board GPS. The data is therefore only available on the two days survey took place in Commodore channel.

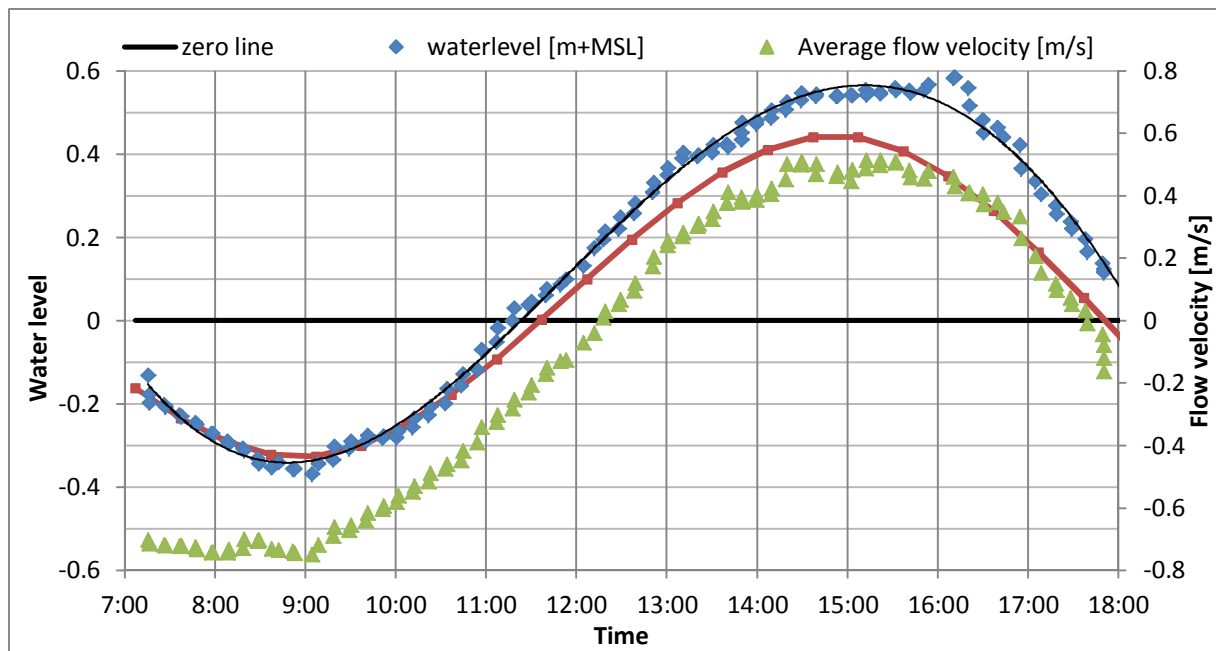


Figure 4-22 Water level prediction and measurements for Commodore channel on 06/09/10

The predictions for high-water were lower (ca. 15 cm) than measured in Commodore while the expected and recorded low-water level correspond well. The difference

between the prediction and measurements may be explained by fresh water discharge through Commodore channel and local meteorological effects (e.g. wind set-up raising the water level at sea). Figure 4-23 shows a similar graph containing the results for 09/09/10.

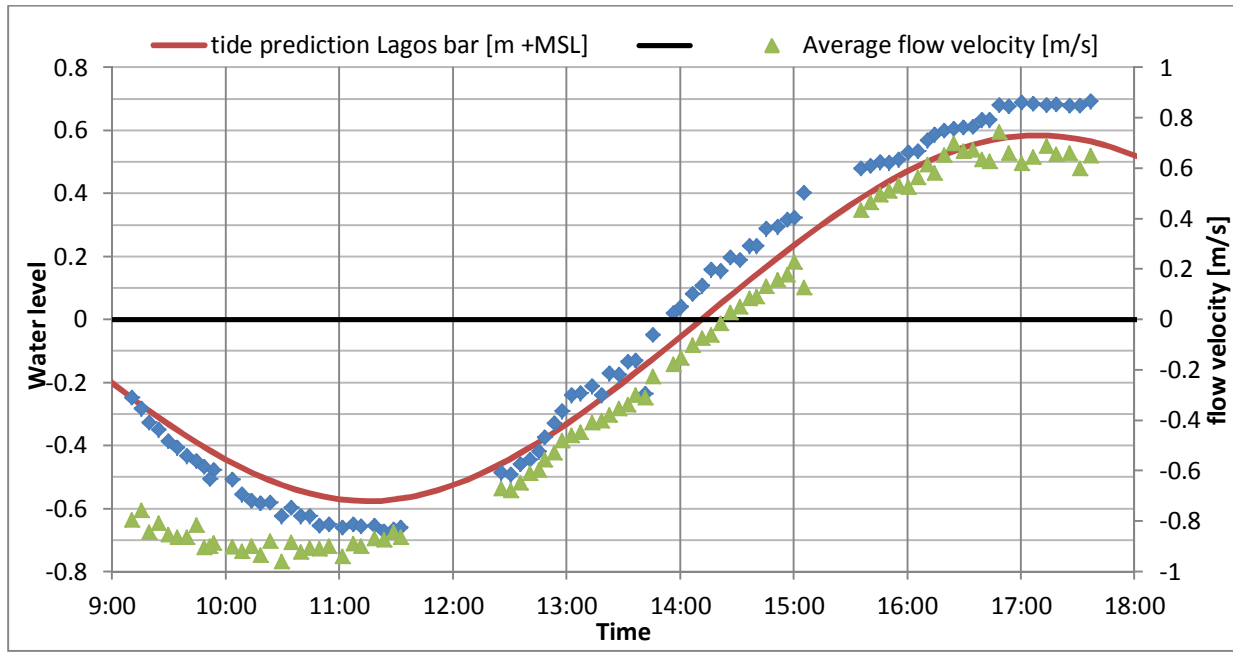


Figure 4-23 Water level prediction and measurements for Commodore channel on 09/09/10

This day, only a small difference is observed between the off-shore tidal predictions and water level height measured by the on-board GPS. The predicted amplitude is slightly lower than the measurements suggests but are still quite accurate. The difference during high water on 06/09/10 is not observed here so the assumption that rain discharge and/or wind set-up was the cause for the deviation may hold.

The graphs show that the prediction tables are a decent substitute for the bad data provided by the pressure sensor at that location. In this research the off-shore predictions will therefore be used to represent the water level in Commodore channel.

Using the figures above, another observation can be made concerning phase difference between maximum/minimum current velocity (or discharge) and high/low-water level. The maxima/minima discharges and current velocities appear to coincide with the water level extremes. In a one-end closed off basin and tidal forcing at the open end, a travelling wave may reflect at the closed end and result in a standing wave in the basin. This results in a phase difference between the max/min water levels and max/min flow velocities. As the observed phase difference in Lagos Harbour is very small, the travelling tidal wave must be damped out rather than reflected. Marshlands along the edges of the Lagoon and Badagry creek cause the wave to damp out due to friction.

Analysis of the water level data from the tide sensors placed in Badagry Creek and Apapa channel near the entrance of the Lagoon shows a phase lag. With respect to the entrance of Lagos Harbour, these locations experience high water respectively 40.5 and 41.5 minutes after high water is recorded at Lagos Bar. The distances between Lagos Bar (offshore location close to Lagos Harbour entrance) and respectively Badagry and Apapa station are 7.140 km and 9.280 km.

When assuming a mean channel depth of 10 m in the sections between Commodore channel and Apapa and Badagry tide stations, the propagation speed of the travelling tidal wave is in the order of 10 m/s ($c = \sqrt{gd}$). Instead of 40.5 and 41.5 minutes, one would expect that the crest of the tidal waves travels the distance to Apapa and Badagry in about 10-15 minutes. The measured water level (in blue) on 06/09/10 in Figure 4-22 shows a deviation of 10 minutes with respect to the off-shore prediction which suggests that local meteorological influences the phase difference as the distance between Lagos Bar and Commodore channel is less than 1 km. Rain water, discharged via the Lagoon or Badagry creek, may also increase the time difference in high/low water in Lagos harbour.

4.4.2 Discharges

The four main channels in the Lagoon tidal system are Commodore channel, Apapa channel, Badagry creek and Five Cowrie creek. For the latter no surveys were carried out due to the limited depth. On 10/09/10, discharge measurements were carried out for these channels which give, together with discharge measurements from the 2008 campaign by Royal Haskoning, an insight to the discharge distribution of the various system components. A hydrodynamic model of the system by Royal Haskoning based on the data sets and tide predictions offer indicative figures for the various channels for the neap-spring tide cycle.

Daily maximum [m ³ /s]	Commodore channel	Appapa channel	Badagry creek	Five creek	Cowie
Neap tide	7000	6500	1600	300	
Average tide	9000	7000	2100	400	
Spring tide	11000	7500	2500	500	

Table 4-2 Indicative figures of discharges to be expected in the various channels near Lagos.

The discharge through Five Cowrie creek is not likely to contribute to the sediment transport balance because of a weir near the junction with the other channels of Lagos harbour.

4.4.3 Cross-channel flow effects

The previous sections showed the flow velocities perpendicular to the face of the sailed cross-section, i.e. in the flood/ebb direction. The cross-sections were chosen as straight lines perpendicular to the channel banks. This section elaborates on the currents in the face of the cross-section and the effects on hydrodynamics of the system and sediment transport.

The following plots are made from the ADCP data of each sailed survey line. The first survey line of Commodore channel started on 07:00 and ended 18:30. A total of 127 lines were sailed. Apapa location comprises 18 survey lines between 9:00 and 16:30 and for Badagry creek 150 lines were sailed between 8:00 and 16:30. Positive values (red tones) indicate flow towards the right (east in Commodore & Apapa cross-sections, north in Badagry figure).

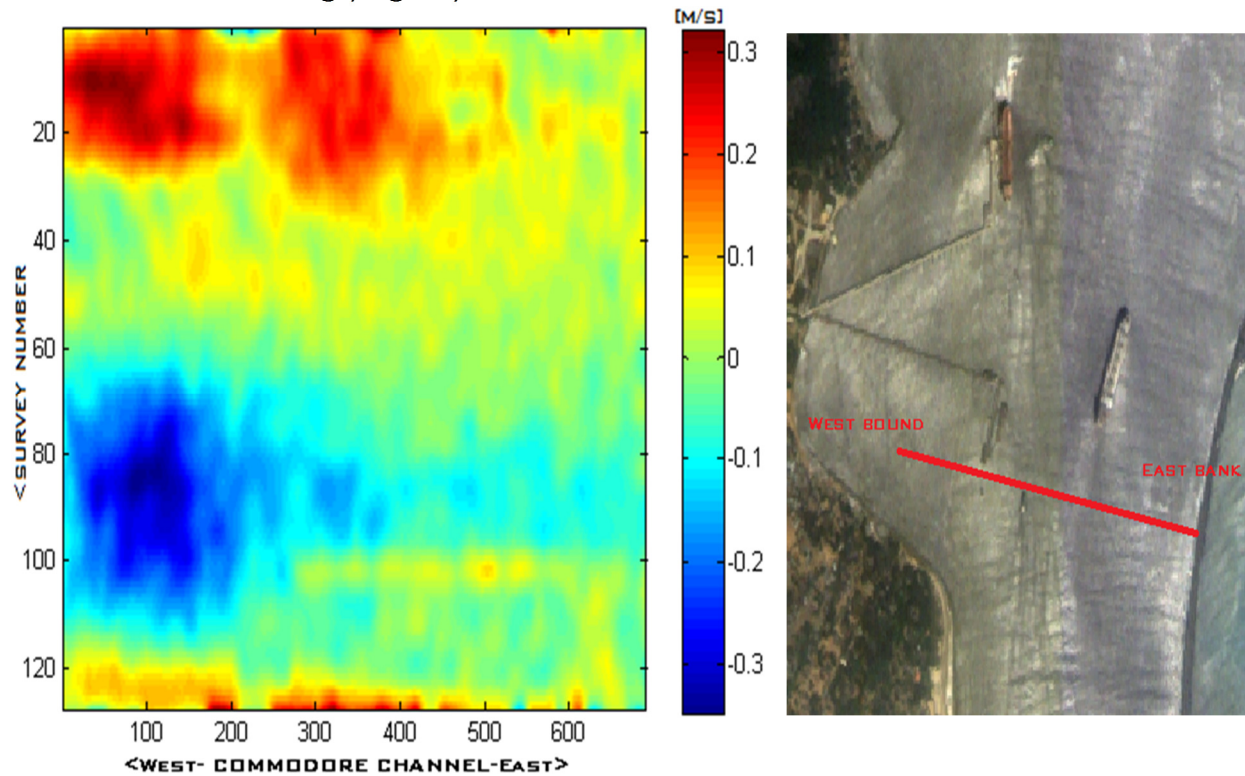


Figure 4-24 Commodore location, flow velocity in face of cross-section.

In the western part of Commodore channel, large velocities in both directions are measured compared to the rest of the channel. This is largely due to the geometry of the channel as it suddenly widens near the surveyed cross-section. This results in flow velocities up to 0.3 m/s flowing towards the centre of the channel during ebb flow and towards the west bank during flood. Sediment transported to the deeper parts during ebb will probably not return to the shallower parts as the flow velocity during flood is probably too weak to carry sediment to a level 10 meters higher.

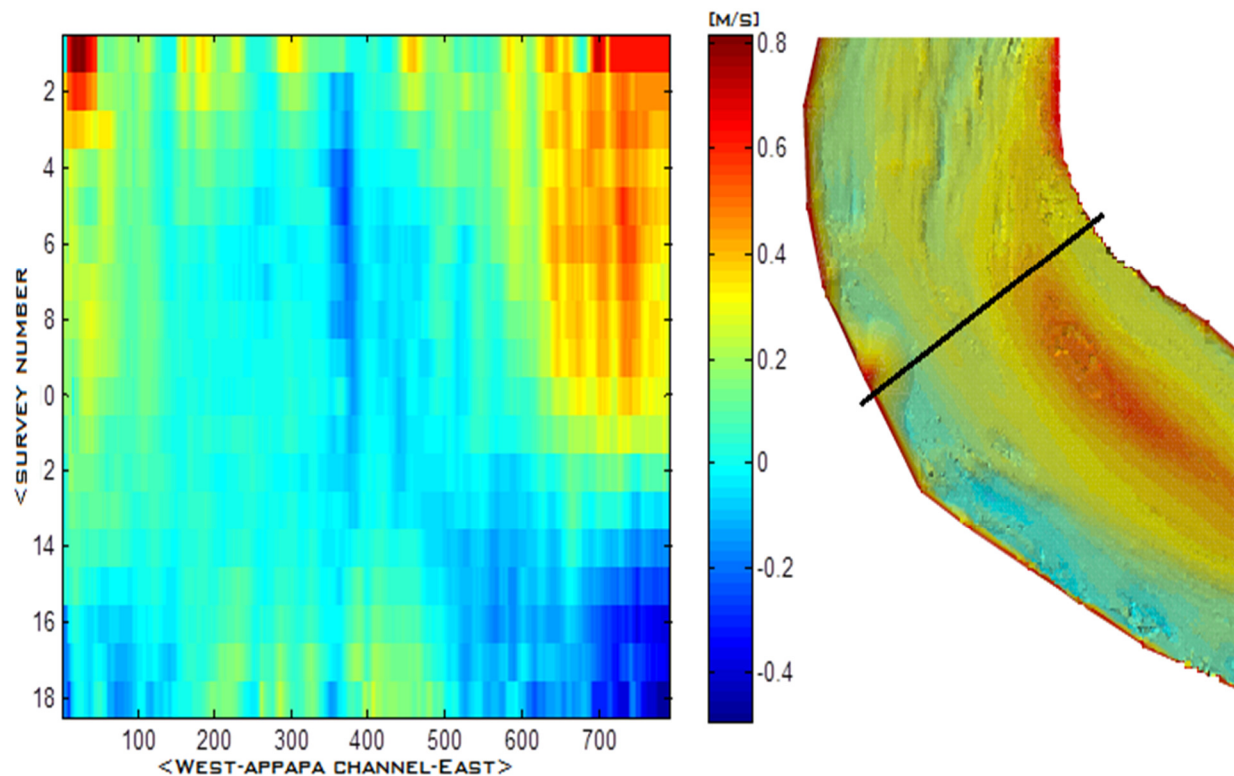


Figure 4-25 Apapa location, flow velocity in face of cross-section. Right: Apapa channel bathymetry with cross-section location.

The Apapa cross-section is located in a bend of the channel to the Lagoon. Near the East bank, maximum flow velocities are measured of 0.6 m/s towards the inner bend during ebb and 0.4 m/s towards the centre of Apapa channel during flood.

Based on the measured flow velocities it may be concluded that the main channel in the outer bend, the shoal and the smaller channel in the inner bend are not in equilibrium. The magnitude of the flow velocities is strong enough to move sediments including coarser material which have been found at this location.

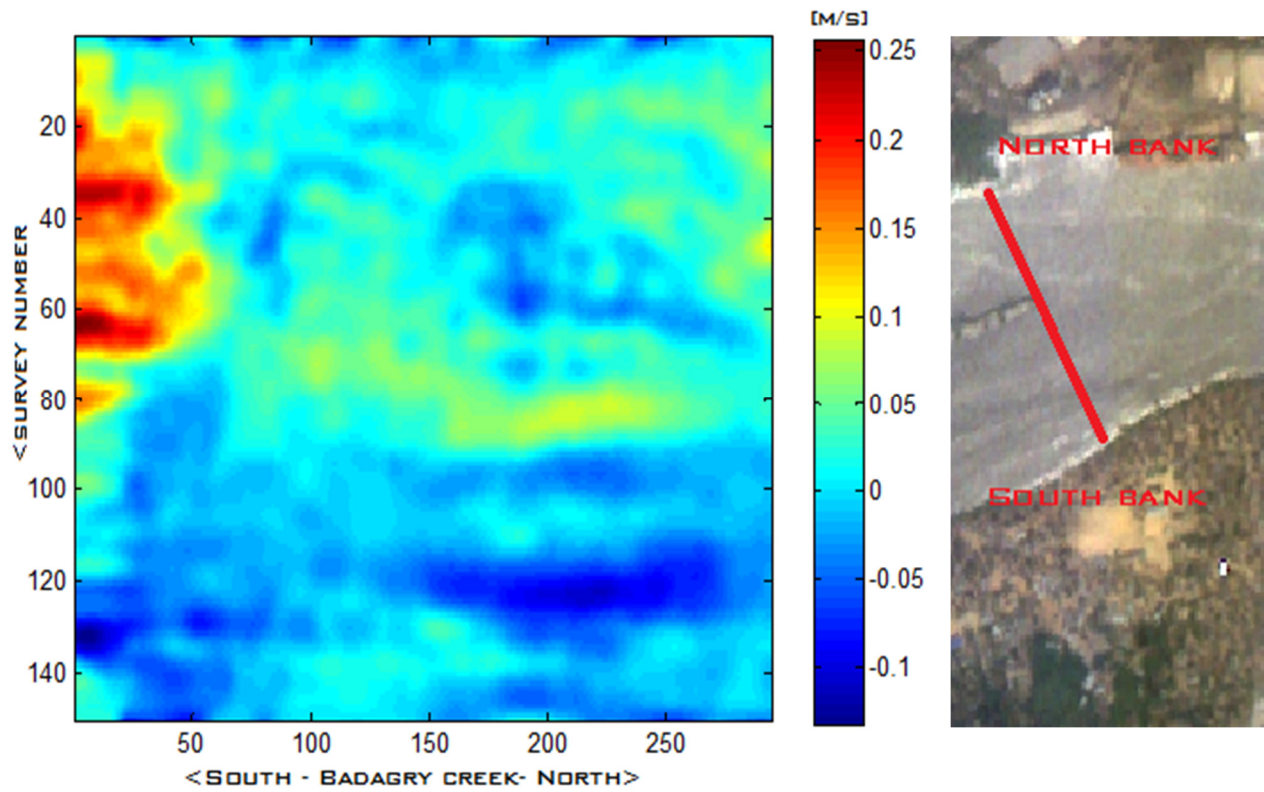


Figure 4-26 Badagry location, flow velocity in face of cross-section.

The flow velocities perpendicular to the ebb/flood direction in Badagry creek are only very small. For the deeper northern half of Badagry creek along which the quays are located, the flow velocity in the plane of the channel' cross-section is less than 0.1 m/s.

4.5 Sediment concentration measurements

Sediment transport is distinguished in two categories: sediment moving as bed load and sediment particles suspended in the water column and transported by the flowing water. The suspended sediment is measured by OBS turbidity sensors and derived from ADCP backscatter intensity. Sediment particles moving very close to the bed as bed load could not be measured during the field campaign.

4.5.1 Instrument calibration

Suspended sediment concentrations (SSC) were measured using a series of OBS turbidity sensors and an ADCP instrument used to measure channel cross-section profiles. This section explains how the data obtained during the field campaign is converted into concentrations in g/l.

4.5.1.1 OBS turbidity/suspended sediment concentration calibrations

For this study, 2 types of OBS sensors were used. The array of 7 OBS sensors placed in Commodore channel had a range up to 500 ftu (formazin turbidity units). One sensor, with a range of 0-1000 ftu was used to measure concentrations throughout Lagos Harbour and water samples. All sensors have been checked on whether they returned similar results for constant concentrations by measuring the concentration of several test suspensions. The results proved that all sensors performed properly.

The material used for OBS calibration tests was obtained from the material recovered at sampling location 12. The material found here consisted of loose mud and was sampled in an area prone to accretion. This material is likely to be freshly deposited and may therefore be a reasonable representation of the suspended and bed load material transported in Lagos Harbour. The sediment selected for OBS calibration consists for 52% of sand, 32 % fines (silt & clay) and 16 % organic material (shells & vegetation).

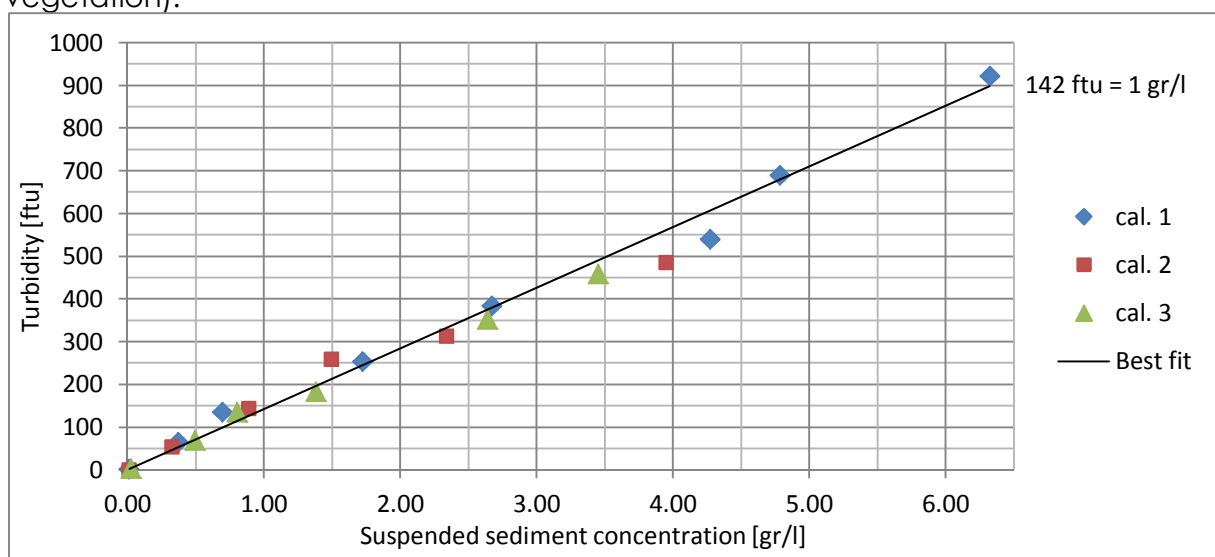


Figure 4-27 Calibration curve obtained from obs sensor calibration test in laboratory

The OBS calibration test were carried out 3 times for both types (sensor type used in array of 7 OBS twice) and the results are plotted in Figure 4-27. All sensors show similar results for the calibration test where pre-weighed quantities of sediment were added to clean water and plotted against the measured turbidity.

The linear best fit has a slope of 142 ftu to 1 gr/l or 1 ftu to 7 mg/l. Typical values for the ftu to mg/l relation is provided in literature (Guillén, 2000) and ranges 1.39-1.81 mg/l per ftu for fines and 8.13-10.4 mg/l per ftu for sand. As the calibration material consisted of sand and fines the found relation is very well possible. A major uncertainty concerning applicability of this relations remains as the 7mg/l to 1 ftu is to be used for all sensors. Considering the composition of the material that will pass an OBS placed near the bottom is likely to be different to that being in suspension high in the water column, errors in the turbidity-SSC conversion may occur. When assuming a 1.4 mg/l to 1 ftu ratio for clay, the converted concentration will be overestimated by a factor 4.

4.5.1.2 Backscatter to SSC conversion

The ADCP measures the backscatter intensity in Counts and is converted to acoustic backscatter [dB] by the following formula (Deines, 1999):

$$S_v = C + 10 \log_{10} \left[\frac{T_T R^2}{L P_T} \right] + 2\alpha R + K_c (E - E_r)$$

Herein, S_v acoustic backscatter [dB], C is a constant [dB] specific to the ADCP, T_T is the transducers temperature [°C], R is the (slant) range along to beam to the scatters in the target cell [m], P_T is transmit power [W], L is the transmit pulse length, α is the attenuation coefficient (energy absorption by water) [dB/m], K_c is a scale factor [0.4 dB/count], E is the relative backscatter equal to echo intensity [count] and E_r is the received noise [count]. The values for C , K_c , L and P_T are characteristics of the ADCP while T_T , R and E_r are measured during operation. The variable E is the intensity returned to the transducer and is a measure for the concentration of scatterers, e.g. suspended sediment. Water attenuation, α_w , is computed from temperature, salinity and to a lesser extend pressure (depth). Other contributions affecting attenuations are gas bubbles in the water, especially due to ship propulsion screws (so called prop wash) and sediment particles between the transducer and the target cell.

Figure 4-28 displays the data points where OBS and ADCP data overlap. The backscatter intensity was extracted from the ADCP surveys near the OBS array at several moments in time and at depths similar to the sensor positions. Each point is plotted against the corresponding turbidity measurement value converted to sediment concentration using found relation in section 4.5.1.1. The sediment concentration [gr/l] relates to acoustic backscatter S_v [dB] as $SSC = 5.48E-5 \cdot S_v^{2.076}$ [gr/l]. The correlation isn't very strong due to many variables affecting the relation, sediment size distribution and differences the temperature and salinity over the measured depth, being important factors. Also, errors in turbidity measurements are considered an important contributor to the large bandwidth of the data points.

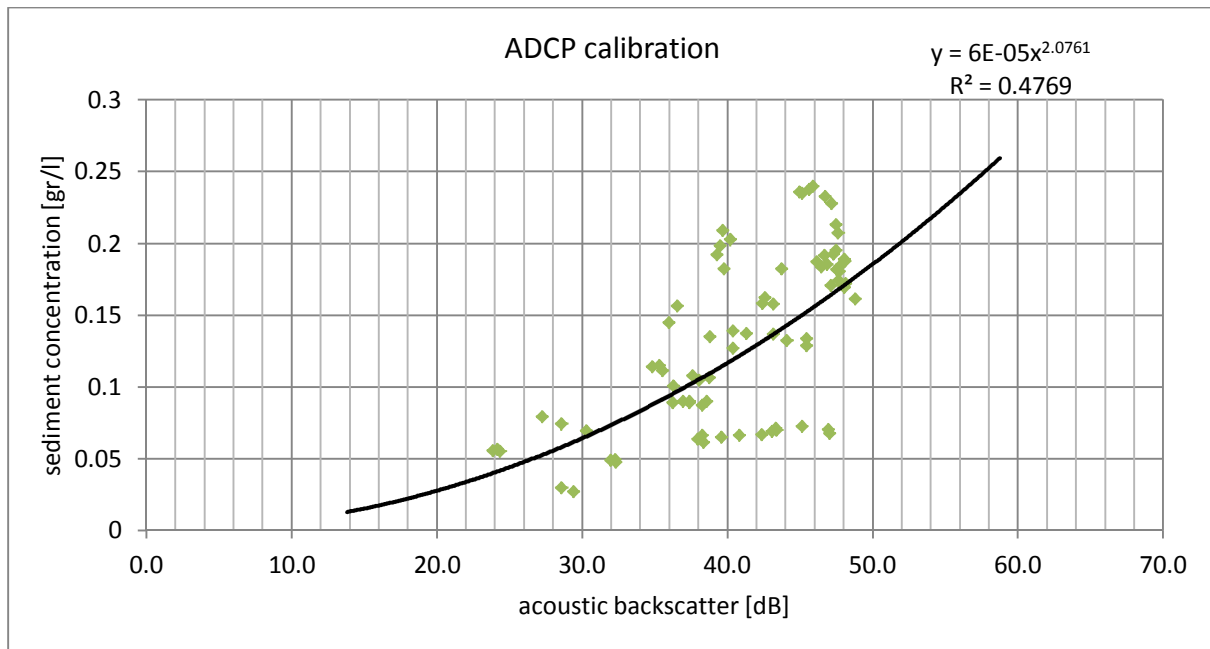


Figure 4-28 Calibration curve for backscatter intensity to sediment concentration

The computed acoustic backscatter S_v is computed using the relation found in the ADCP calibration to produce SSC profiles of all the measured cross-section. The material passing the OBS sensors and ADCP on which the measurements were calibrated is not likely to be the same to the material measured on other survey locations or at different survey times. The particle size influences the acoustic backscatter and is stronger for larger particles. The ADCP is less susceptible for very small particles ($<4 \mu\text{m}$, e.g. clay) and will underestimate the concentration when most of the suspended material consist of fine sediments. Alternatively, ADCP measurements of large sand particles are overestimated and produce a higher measured concentration. However, due to the reversed susceptibility to particle sizes of the OBS sensor calibration, both effects may (partly) cancel each other out. Still, a wide band of data point remain left for ADCP dB to SSC calibration and a correlation coefficient of only 0.47 is poor. Data acquired by using this method is not very reliable so any converted SSC measured by the ADCP is therefore treated as such.

Ideally, regular calibration using water samples during various phases of the tidal flow and for each location is required for an accurate representation of the suspended sediment. During the 2010 measuring campaign, the circumstances and lack of time and equipment needed for proper calibration was not available.

As a consequence, since the calibrated OBS data series are the only reference available, the results from the ADCP are not to be expected very accurate. The author of this thesis estimates the error to be in the order of a factor 2-3 based on the calibration curves in Figure 4-27 and Figure 4-28 and susceptibility to particle sizes. As better data sources are not available for this study, the ADCP and OBS results will still be used. It is to be understood that, although many results are quantified for the purpose of comparison and analysis of the results, the error margin is too high to bind

any conclusions to the quantified results. The measurements may however still be adequate to a qualitative approach.

4.5.2 OBS Suspended sediment measurements

The OBS turbidity measurements in Commodore channel comprise two data sets: September 2010 and March/April 2011, both registering in formazin turbidity units [ftu]. Section 4.5.1

4.5.2.1 September 2010 data

Of the 7 sensors installed, 6 sensors (0.5 -12 meters above the bed) provided reliable data. The bottom sensor, placed at 0.25 m high generally recorded much lower concentrations than the sensors above. It is not likely that the suspended sediment concentration is continuously lower than in the region above, so the sensor must not have worked properly or may have been installed incorrectly. Another option may be that the sensor was placed in a scour hole caused by the pillars nearby. Either way, the data will not be representative for other locations in Commodore channel at 0.25 m height and the data from sensor 1 will therefore not be taken into account for further analysis. Figure 4-29 through Figure 4-31 shows the results of the OBS turbidity data for 3 days of measurements. Each sensor represents the turbidity in formazin turbidity units at a specific height above the bed. The average concentrations on all days for each height are presented in table 4-3.

Height above med [m]	0.25	0.50	1.00	2.00	4.00	8.00	12.00
Avg. turbidity [ftu]	12	53	35	34	32	25	22

Table 4-3 3-day average turbidity [ftu] for each sensor height

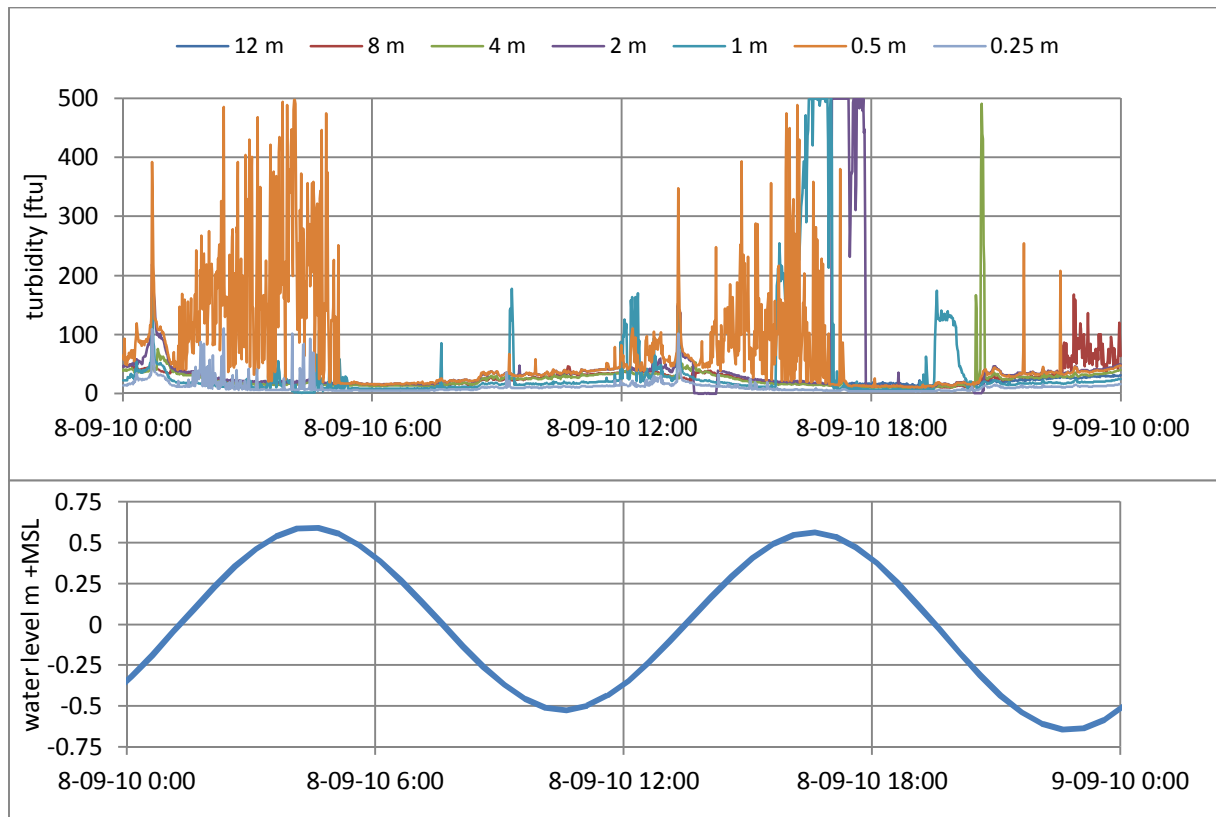


Figure 4-29 OBS data for 7 heights above the bed and water level variations from 08/09/10 to 09/09/10.

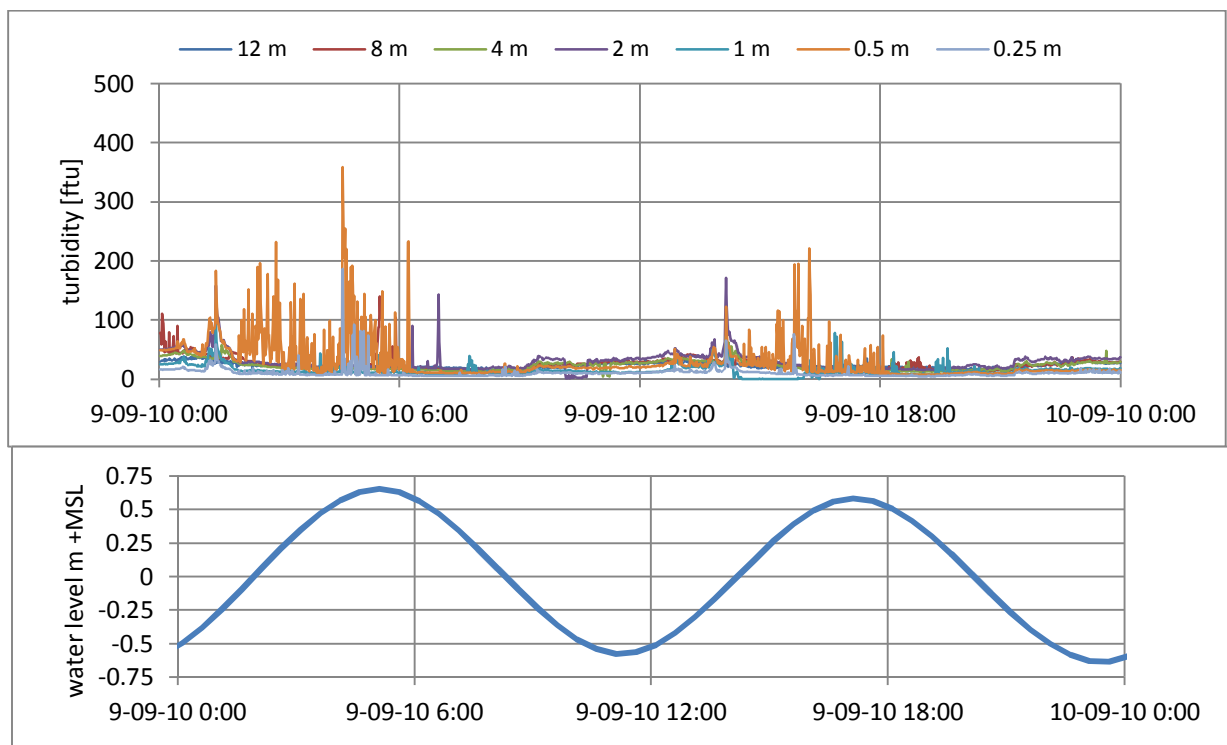


Figure 4-30 OBS data for 7 heights above the bed and water level variations from 09/09/10 to 10/09/10.

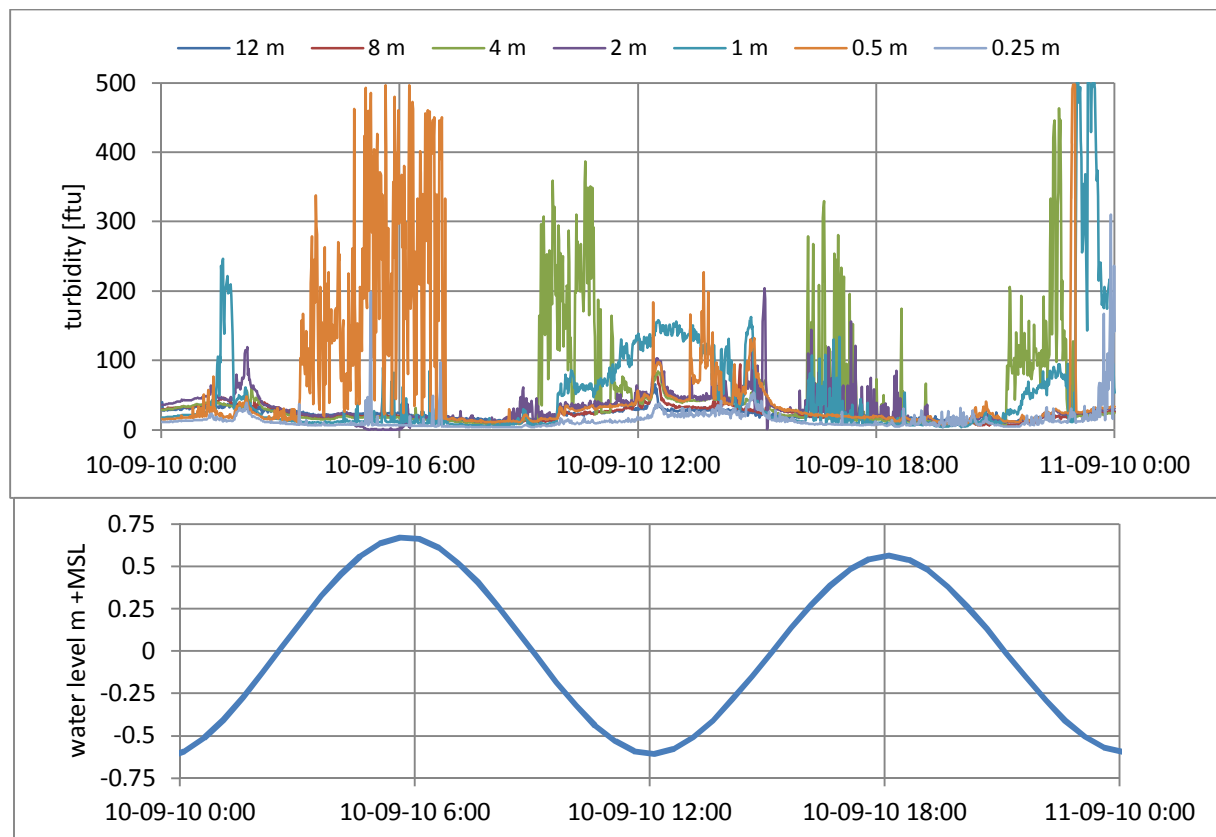


Figure 4-31 OBS data for 7 heights above the bed and water level variations from 10/09/10 to 11/09/10.

Most sensors, especially those higher in the water column, generally show a recurring pattern of higher sediment concentration roughly every 12 hours. Concentrations in the higher regions of Commodore channel vary during this 12 hour cycle roughly between 15 and 45 ftu.

The sensor placed 0.5 m from the bottom and the 4 m sensor on 10/09/10, shows different behaviour. These sensors show large variations of recorded sediment concentrations for reoccurring periods several hours long, yet only during incoming tide. It is interesting that these periods of highly alternating but generally high sediment concentrations are rarely registered by more than one sensor. The sole exception is the peak measured by three sensors on 08/09/10 around 16:00. The 1 m and 2 m sensors also show periods of high concentrations but the measurements by these sensors are far more consistent. On 08/09/10, both sensors reach the maximum value of the OBS of 500 FTU (~ 3500 mg/l, section 4.5.1.1), but unlike the 0.5 and 4 m sensors, these sensors don't register heavy variations but a sustained period of high concentrations. Whereas single peaks ('spikes') may be caused by a faulty measurements or, for instance, a passing fish, the long sustained periods recorded by the sensors placed at 1 and 2 meters from the bed are not likely to be caused by anything besides suspended sediment.

How the data from the 0.5 m sensor is to be interpreted is a bit more arbitrary. It might be because a bad sensor or poor cable connection, but as the sensor records quite reasonable values for the rest of the measurement duration, this is not likely. A

second option is that the measured values are correct and are caused by rapidly changing sediment concentrations as the result of, for instance, near-shore wave action on the beaches west of the entrance to Commodore channel. The sediment laden incoming tide may carry the ocean bed material to Commodore channel and may be registered by the OBS. As the OBS sensors take a measurement every minute it is possible to record large variations due waves with periods up to 15 seconds.

For this theory to hold, the suspended sediment must have been confined to a narrow layer. The salinity profiles in section 3.4 and velocity profiles presented in section 5, shows that a two layer system occurs as flood currents start near the bed while the water near the surface still flows seawards. This layer of more saline water is generally several meters thick as can be observed in Figure 4-19. It is possible for suspended sediment to be confined within this deeper layer and high concentrations may therefore not be observed by sensors outside this layer. It is also possible for sediment from within the tidal system flowing seawards via ebb currents in a layer above the salt wedge. In this case, high concentrations are more likely to be found in the region above the saline, deep layer. Situations where the maximum sediment concentrations appear to be confined to layer higher in the water column are observed on 10/09/10.

It is however not very plausible that virtually no mixing has occurred within one of these layers. The thickness of the salty layer near the bottom and less saline near the surface may vary over time but are generally several meters thick. A period of high sediment concentration caused by waves at sea may bring sediment in suspension but will be mixed by turbulent flow. Eddies near the tip of the breakwater and sudden widening of the Commodore channel cross-section will mix any narrow sediment laden layer. The result should be registered by more than one sensor, especially near the bottom where multiple sensors were installed close together.

An explanation for the abrupt changes in concentration may lie in the disturbances caused by the pillar near the OBS sensors. As water flow around the pillar, the flow velocity increases locally and creates a turbulent flow in the wake 'behind' pillar. Although the average flow velocity is not significantly higher in the wake than would have been without a pillar, flow velocities on a very small scale may exceed the threshold of motion for erosion of the local bed. A closer analysis of this option is given in section 5.1.

The other possibility is that the OBS results contains a large amount of errors and should be ignored. If this is the case, a different approach concerning the interpretation of the OBS data will help to determine whether there is net sediment import or export of the tidal system. Here, the data is manipulated to produce more consistent trends in the sediment concentration development. Figure 4-32 shows the results of the OBS turbidity data converted to milligrams per litre using 7 mg/l to 1 ftu (see section 4.5.3). The sensors closest to the bed (sensors 2-5) represent a layer of 8 meters thick close to the bed which will now be referred to as the bottom layer. The top layer ranges from 8 meters above the bed to the surface and is represented by the other 2 sensors (6-7). Both layers heights are roughly equal.

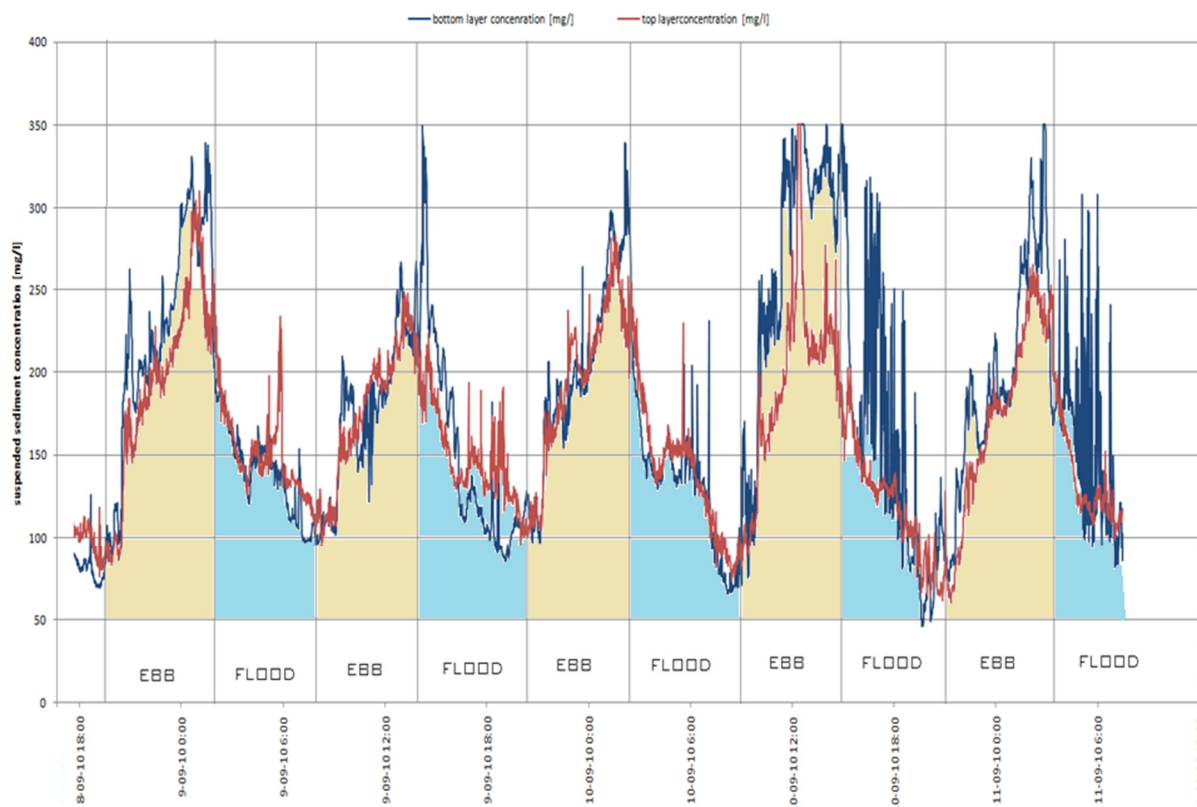


Figure 4-32 Suspended sediment concentrations measured by OBS sensors and estimated absolute flow velocity for the top and bottom layer.

The OBS data shown in the figure above is modified and smoothed to better represent trends in sediment concentration development. Obvious measurement errors like a sudden extremely rapid increase and drop in sediment concentrations (spikes) were discarded. Also, extreme concentrations measured at one sensor while the other sensors each show different and coherent results were deleted from the data. After that, the data with 1-minute measurement interval was smoothed via spline interpolation and the results averaged in two groups, the bottom layer and top layer. By manipulating the data this way, a lot of detail is lost in the process and thus the concentration profiles depicted in Figure 4-32 no longer reflect possibly real extreme concentrations. It does however; provide a rough picture of the sediment concentrations over time. This method seems to add more uncertainties but may be a better representation of the concentration profile in the undisturbed main channel of Commodore as any measured effect caused by e.g. a wreck close to the OBS location is tried to compensate for.

As can normally be expected, the concentrations closer to bed are higher than near the surface. Maximum concentrations, both near the bed as well as near the surface, roughly occur every 12 hours. The relation between absolute flow velocity and suspended sediment concentration isn't very strong and maxima don't occur simultaneously. In general, peak concentrations are observed at the end of each period of ebb flow and seem to increase until the turning of the tidal flow. Local maxima are experienced at maximum flood as can be observed best on 09-09-10 or 10-09-10 at 06:00. The maxima during flood are relatively small compared to those

measured at the end of ebb flow. This suggest that the material transported during ebb consist of finer material that is brought in suspension more easily and/or is the result of material from Badagry Creek, Apapa channel or the Lagoon that is merely kept in suspension. It seems that very little material from the Atlantic Ocean enters Lagos tidal system as the concentration continues to drop until ebb flow starts again.

An alternative visualisation of the manipulated turbidity data is presented in Figure 4-33. Here, the data isn't grouped in two layers but interpolated over the vertical where the y-axis represents the depth ranging down to – 15 m, the local depth at the OBS sensor array.

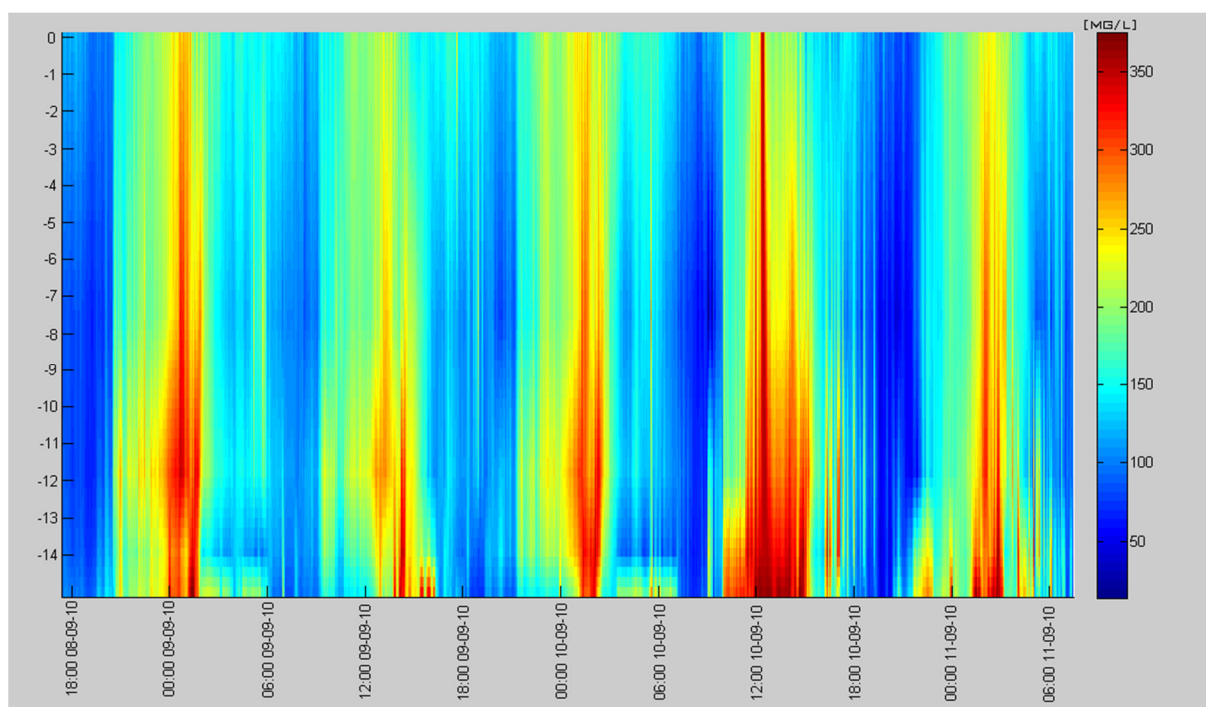


Figure 4-33 Depth interpolated sediment concentrations from OBS sensors data

Figure 4-33 shows that the sediment concentration near the bed and higher in the water column drops very quickly to lower concentration levels. As the particles settle over a distance of up to 15 meters to the bottom in a relatively short period (<1 hour), the settling velocity must be much higher than the values obtained from the settling tests. Especially since the flow velocities in the field are relatively high. Also, a minimum value of 50 mg/l is nearly always present over the whole water column. This indicates there may be two types of sediment passing the OBS station: a fraction of very fine material, e.g. clay particles and organic material with very low settling velocity accounting for the minimum concentration measured and a fraction of heavier particles with higher settling velocity, e.g. sand. The sandy material is brought and kept in suspension only when the flow velocity exceeds a threshold value for motion.

The samples taken at the OBS location confirm this theory as a coarse sand sample (#1) was collected and although only few water samples were taken, they all contained a small amount of fine material (concentrations 100-150 mg/l). The water

samples consisted of slightly turbid water in which hardly any solids were visible. Only after a few days, a small trace of sediment appeared at the bottom of the bottle. The question of why the sediment is brought in suspension in large concentration only every 12 hours and not every time the flow velocity exceeds a threshold value for motion remains. Chapter 5 further elaborates on this subject.

4.5.2.2 OBS Suspended sediment measurements: April 2011 data

Recently, additional suspended sediment concentration data obtained during March/April 2011 by same method as the September 2010 data series has become available for this study. These measurements were also carried out by DEEP by commissioned by Haskoning. The data measured in Commodore channel comprises of a single OBS time series of a location close to the 2010 OBS sensor location and water level data. The OBS was installed at a height of approx. 1 m above the bed. For comparison to the data obtained during the 2010 campaign, one representative day (same phase in spring-neap cycle) is presented below.

The top graph of Figure 4-34 shows the turbidity at 1 meter above the bed at a nearby location with respect to the 2010 OBS location. The 2011 position is located about 700 meters inland (north) of, and installed to a similar structure as the 7 sensors used in 2010. The difference may be that during the 2010 campaign, the sensors were attached to a drop line from a mooring platform which was at some distance to other structures while the 2011 sensor was installed at a platform with several structures nearby. The flow around the pillars of these structures may alter the local sediment concentration.

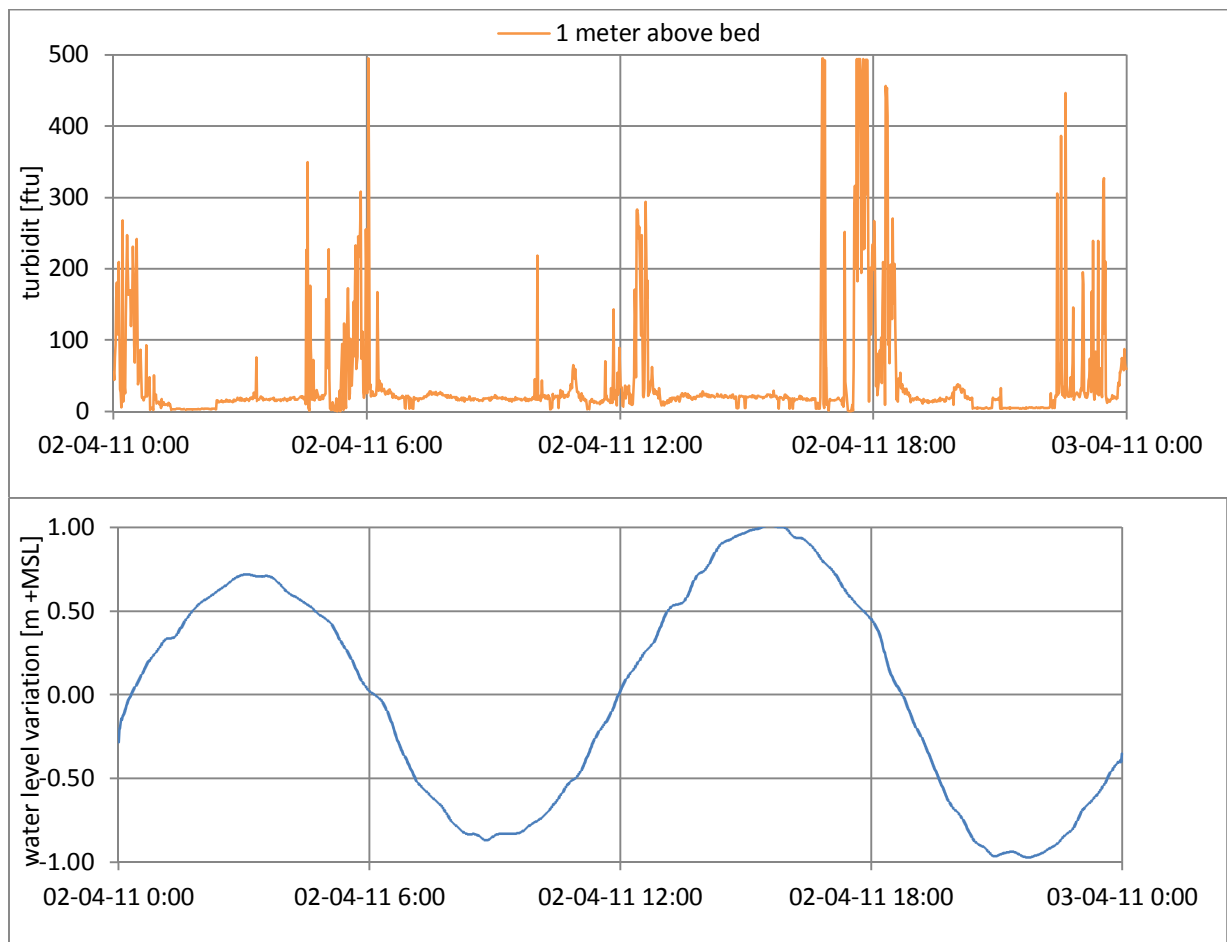


Figure 4-34 OBS data at 1m above the bed and water level variations from 02/04/11 to 03/04/11.

Although the 2011 sensor is estimated to be placed at 1m above the bed, it shows more comparison to the 0.5 m data of 2010. Other than the uncertainty in the installation height, it is possible that the 2011 data and the 0.5m 2010 data are more comparable as the local water depth will differ between these locations. Therefore, as the 2011 data shows the strongest resemblance to the 0.5m 2010 data, comparing these two datasets instead of the 1.0 m 2010 sensor, may be justified. The turbidity doesn't drop below a near constant level of around 20 ftu except for some short periods of near zero turbidity. Similar periods were occasionally found in the 2010 data sets. This may be attributed to errors in the measuring or data logging systems.

The lower half of Figure 4-34 shows the water level variation as there is no data available for flow velocity. During the 2010 campaign it was observed that maximum/minimum water levels coincide with peak flood respectively ebb velocity. The turning of flow directions fairly coincides with zero-crossing of the water level as well. The measured turbidity on 02/04/11 shows behaviour typical to the spring tide during which the 2010 data was collected as well. A plot of the entire 2011 dataset is presented in appendix C.

The 2011 data shows a pattern of distinct periods with increased and rapidly fluctuating turbidity. The difference compared to the 2010 data is that the periods of rapid fluctuations in the 2010 data occurred only twice a day and during incoming tide. The 2011 data shows a pattern reoccurring 4 times a day. This may be explained as the 2011 OSB location differs from the 2010 location. If the disturbed flow around the pillars of the jetty on which the sensors were placed are causing the observed behaviour, it is possible that the measured turbidity is affected by pillars both sides of the 2011 location. Whereas the 2010 turbidity may only be influenced by pillars upstream of the flood current.

The other difference to the 2010 data is that the periods of rapidly fluctuating turbidity occur around the zero crossing (0m +MSL) of the water level variation which coincides with slack water. The 2010 measurements show strong fluctuating turbidity levels during the first half of the flood period so there is a deviation of approx. 2 hours.

If the sediment concentration is related to the flow velocity, large concentrations are not expected during slack water conditions. A gradient in salinity may affect the flow velocity so slack water at the surface may not coincide with slack water near the bed. This has been observed in the 2010 data, yet the time difference between the extreme water level and maximum sediment concentration is stronger in the 2011 data. Besides, a strong density current is not expected during 2011 measurements as they were taken in the dry season and gradients in salinity is negligible.

The 2011 campaign did not include flow velocity measurements in Commodore channel and these must be carried out to find the cause of this phase shift.

4.5.3 ADCP results: Suspended sediment profiles

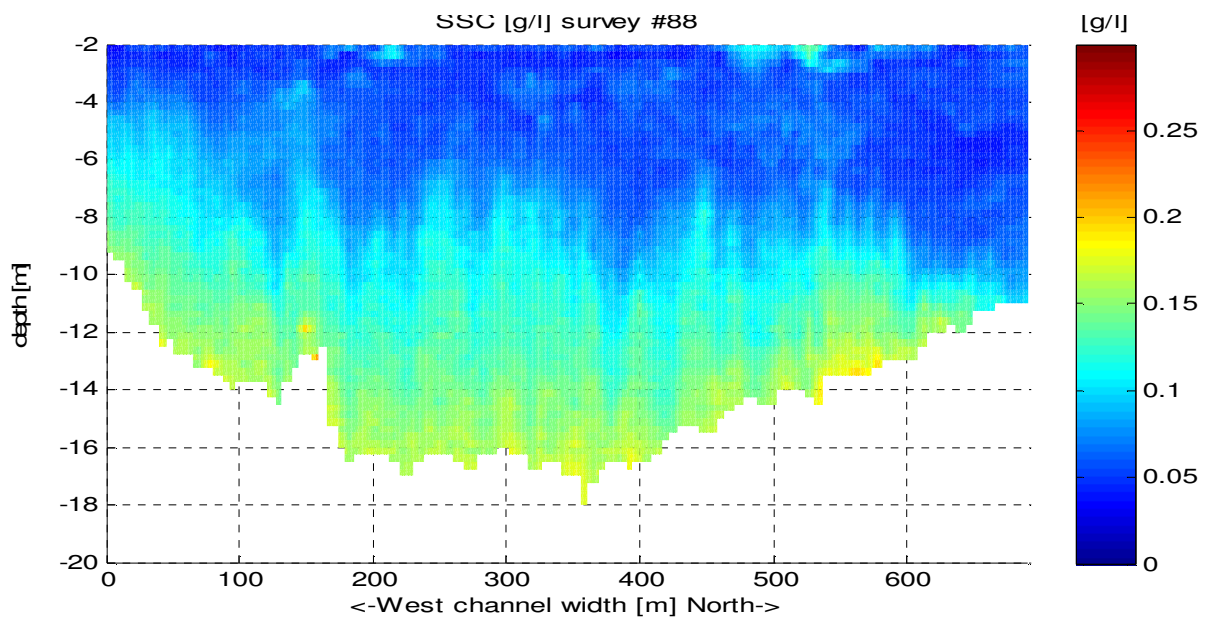


Figure 4-35 Suspended sediment concentration of Commodore channel cross-section sailed on 06/09/10 at High-water.

Figure 4-35 shows an example of the suspended sediment concentration calculated from ADCP measurements of a sailed cross-section (Commodore Channel). The depth range spans from -2 m from the water surface due to a blanking distance of the ADCP instrument down to bottom of the channel. The coloured squares displayed in Figure 4-35 represent measuring cells which returned non-zero data for both backscatter intensity and flow velocity. Measuring cells positioned near bed sometimes returned either zero velocity or zero backscatter intensity and were excluded from the calculations.

Two limitations apply for measuring velocity and backscatter intensity near the bed as a result of the used equipment. Firstly, the ADCP measures cells with predetermined height, set at 0.25m. Therefore, a layer of thickness 0-0.25m exists between the deepest valid measurement and the actual bed (in cases where the bed level is easily defined). When the bed level is not clear, due to a layer of loose mud with increasing density as depth increases rather than stiff soil, a second limitation arises. Sediment transport that occurs in a slow moving layer with high density will not be observed by the ADCP but may have a large impact to the transport volumes in the system. The maximum echo intensity the ADCP can record is 240 counts which, when measured near the bed, amount to ca. 1200 mg/l. These intensities were not recorded by the ADCP. A fluid mud layer will be much denser so if such a layer is present at the measuring location, the deepest valid ADCP measuring cell will be above the density boundary of 1200 mg/l.

Figure 4-36 displays the ADCP results for 4 days of surveying on all three locations. All concentrations are plotted against the tidal phase specific to each location. For each survey, a distinction is made between the bottom (1m closest to the bed) and

top layer (bed level +1m –surface). For reference, a tidal phase of 0.5 is at maximum ebb velocity and 0.75 corresponds with maximum flood.

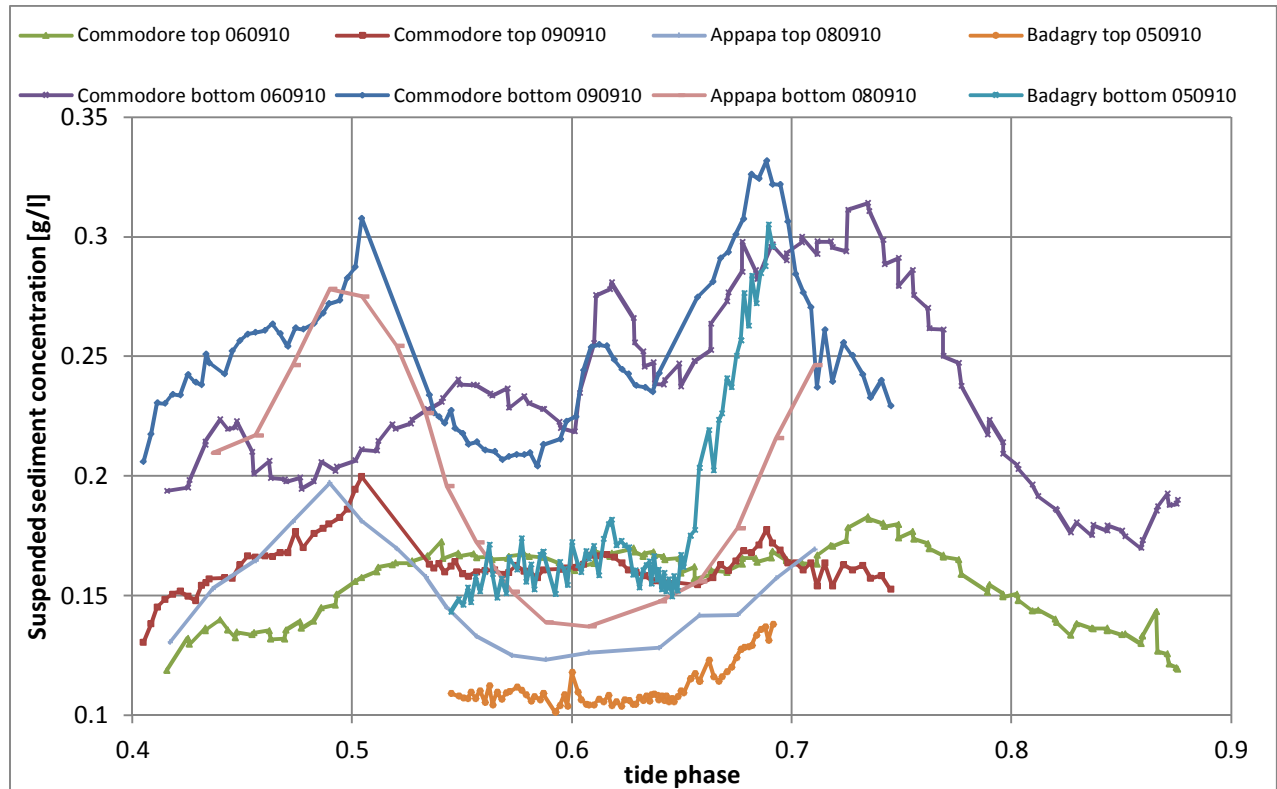


Figure 4-36 ADCP suspended sediment concentrations

From the figure above, it can be observed that the concentration of sediment in the top layer is fairly constant and it is the concentration near the bed that shows large variation as the local flow velocities change.

A concentration below 50 mg/l is never recorded which complies with the OBS measurements. Although these are average values for the entire cross-section (in two layers), the maximum concentration measured in Commodore channel of over 160 mg/l is significantly lower than the averaged concentrations measured with the OBS sensors which are roughly twice as high.

This error margin complies with the uncertainty of the ADCP results derived from the poorly correlated calibration curve and is therefore possibly responsible for the deviation in results. It does however not explain why the ADCP nearly constantly underestimates the sediment concentrations compared to the OBS sensors. The best-fit curve of Figure 4-28 is derived by comparison of ADCP and OBS data points collected on 09/09/10. The measured turbidity (by OBS) is very low during this period so the ADCP is not calibrated well to high concentrations. Considering the entire OBS and ADCP data sets, a more realistic estimation of the sediment concentration is suggested. The calculated SSC values are multiplied by a factor 2 to better correspond with the OBS data on which the ADCP data was calibrated after all.

Section 5 elaborates on sediment transport rates and uses the adjusted calibration factor for transport rate calculations. Figure 4-37 shows the same data as Figure 4-36 , now using the adjusted calibration constant.

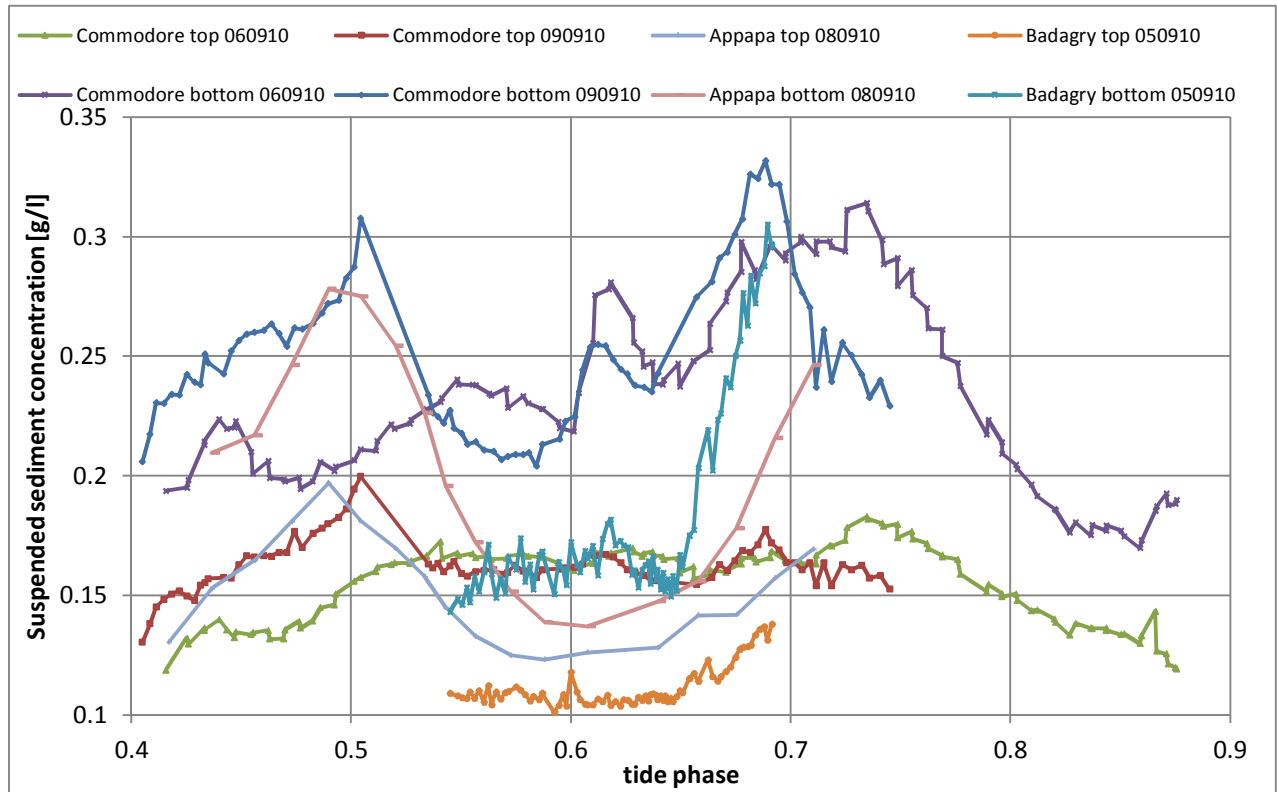


Figure 4-37 Adjusted ADCP suspended sediment concentrations

4.5.4 Conclusions

The material found on the bed of Lagos Harbour' channels can be divided in two categories: (medium) course sand found primarily in Apapa and Commodore channel and fine sediments found in the Lagoon and Badagry Creek. Whereas the bed of the Lagoon contains consolidated clay, the material found in Badagry creek is likely to be freshly deposited. Sediment analysis indicates the material has a common source.

Water samples taken in the area contain very fine particles with concentration in the order of 150-200 mg/l. The settling velocity for these particles is measured to be less than 0.01 mm/s. As the flow velocities in the main channels of Lagos Harbour are quite large, it is concluded that the sedimentation problem of Lagos Harbour' main channels is not caused by settling of suspended material.

Suspended sediment concentration is measured by ADCP and OBS instruments and each data set has its flaws. The turbidity data is converted to suspended sediment concentration via the relation found during laboratory calibration tests with suspension of known concentration. This relation is influenced by the particle sizes of the suspended material and, as the suspended material passing the sensors in Commodore channel come vary in particle size over the tidal period, the measured concentrations are considered inaccurate. This has in turn an effect of the ADCP data as it is calibrated on a limited set of simultaneously acquired OBS measurements.

The SSC data from the OBS sensors are likely to be disturbed by the pillars near the OBS location. Flow around these pillars may cause high sediment concentrations where these are not experienced in other part of Commodore channel. These measurements are, although accurate for the OBS location, not representative for the entire channel.

For Apapa and Badagry, only SSC data from the converted backscatter intensity is available but for Commodore channel, there are three options:

- ADCP data, inaccurate but consistent and uninfluenced
- OBS raw data, valid for the OBS location but not representative for the entire Commodore channel cross-section
- OBS data with irregularities filtered out, more realistic representation for Commodore channel but unreliable

These options are elaborated in section 5 and separate sediment transport calculations are computed for each option.

5. INTERPRETATION

In this chapter the measured data will be analysed. This is presented per main channel in Lagos Harbour separately.

5.1 Commodore channel

5.1.1 Hydrodynamics

5.1.1.1 Discharge

The discharge through the various channels of the tidal system is mainly saline water, especially during the dry season. During the rainy season, salinity may drop considerably as fresh water discharge may play a more prominent role. There is no data on the fresh water discharge during the measuring campaign. It is however assumed that, since Commodore channel is the only connection between the Lagoon and the ocean, an equal volume of water enters the system as it is carried out. This is without rain or river discharges. From the discharge measurements derived from the ADCP flow velocity profiles, the difference in discharged volumes may be estimated. By adding the surface area of each ADCP cell and multiplying it by the flow velocity cell by cell, the discharge is calculated. As the survey session on 06/09/10 is only 11 hours long, the remainder of the ebb-flood-ebb-flood period is estimated by extrapolation of the data. Here, two layers are distinguished: a 1 meter thick layer closest to the bed and the top layer represent all cells above. The distinction is made to separate the sediment laden layer near the bed from the layer above where a near constant sediment concentration is measured (section 4.5.3). Note that the bottom and top layer defined here are not the same as those defined in section 4.5.2 where the bottom layer is 8 meters thick.

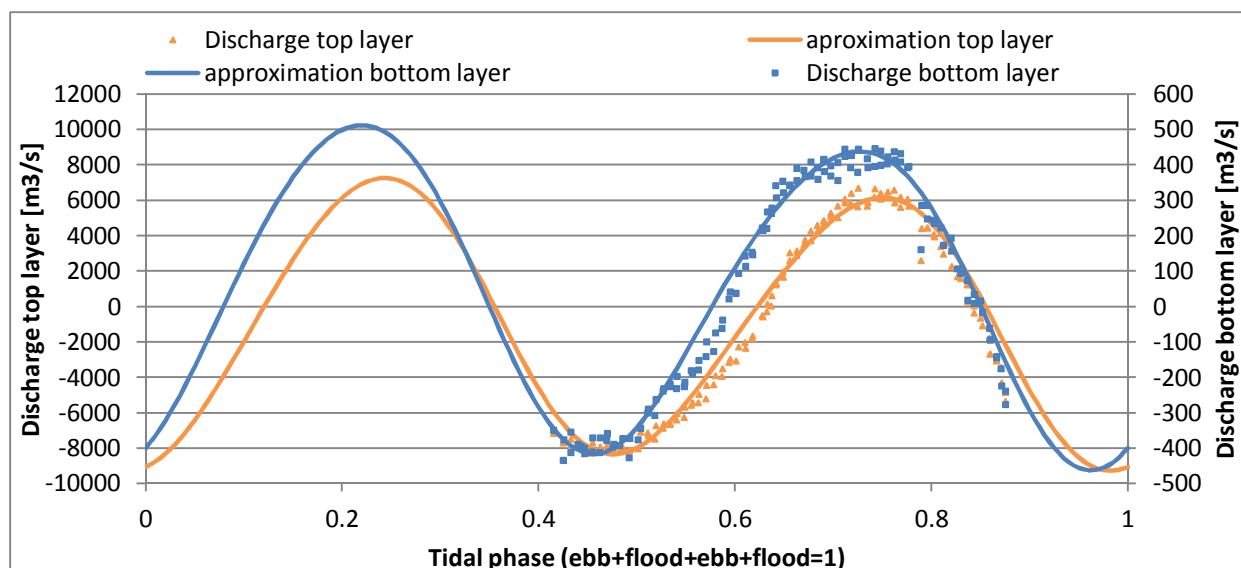


Figure 5-1 Measured discharge in Commodore channel on 06/09/10 and approximation by sine functions for bottom and top layer.

The orange line in Figure 5-1 represents the top layer and when integrated over a full ebb-flood-ebb-flood period, amounts up to a net discharge in ebb direction of 1000

m³/s. it is plausible this is caused by fresh water discharge as has been suggested in section 2.6.4. The difference between stronger and weaker tides is in the order of 10-20% due to the daily inequality of the tide. The blue line, representing the discharge close to the bed, shows different results. As the layer is only 1 meter thick and the flow velocities near the bed are lower, it is not surprising the discharge is only small compared to the discharge in the top layer¹.

While the turning of the flow directions towards ebb occurs simultaneously for the top and bottom layer, this is not the case when turning towards flood. Now, there is a difference of nearly an hour between the moment the flow near the bottom turns towards flood and that of the top layer. This is caused by a density driven current which is elaborated in the next section. The effect of the density current on the discharge near the bed is significant as there is a net flood directed discharge of 35 m³/s. As the next section illustrates, the thickness of the saline layer near the bed varies over time, so the integrated net discharges depends on the defined layer heights. The calculated net discharges are presented to provide the order of magnitude and to illustrate that the net discharge is ebb directed near the surface and flood directed near the bed.

5.1.1.2 Velocity over depth

The previous section as well as section 4.3 indicates a two layer flow regime due to a difference in salinity. The salt water near the bottom is heavier and a density current exists.

The following figures display several phases of the tide for three locations in Commodore channel: near the west bank (close to the OBS location), mid channel and near the east bank. The bottom half of each figure depicts the water level variation on 09/09/10 where the coloured part indicates the survey period that day.

Three distinct times were selected from the survey data illustration the flow regime during maximum ebb velocities, slack water and during flood conditions. The y-axis of Figure 5-2 ranges from -2 m to -15.5 m with respect to the water surface on a logarithmic scale. This axis is chosen to better illustrate the fact the flow does not follow a logarithmic profile². The other figures are plotted on a linear y-axis scale. The displayed flow velocity is measured as the velocity component perpendicular to the face of the cross-section.

¹ Note the different axis scales

² Under stationary flow conditions (e.g. a river with constant discharge), a flow velocity profile plotted on a logarithmic scale shows a straight line.

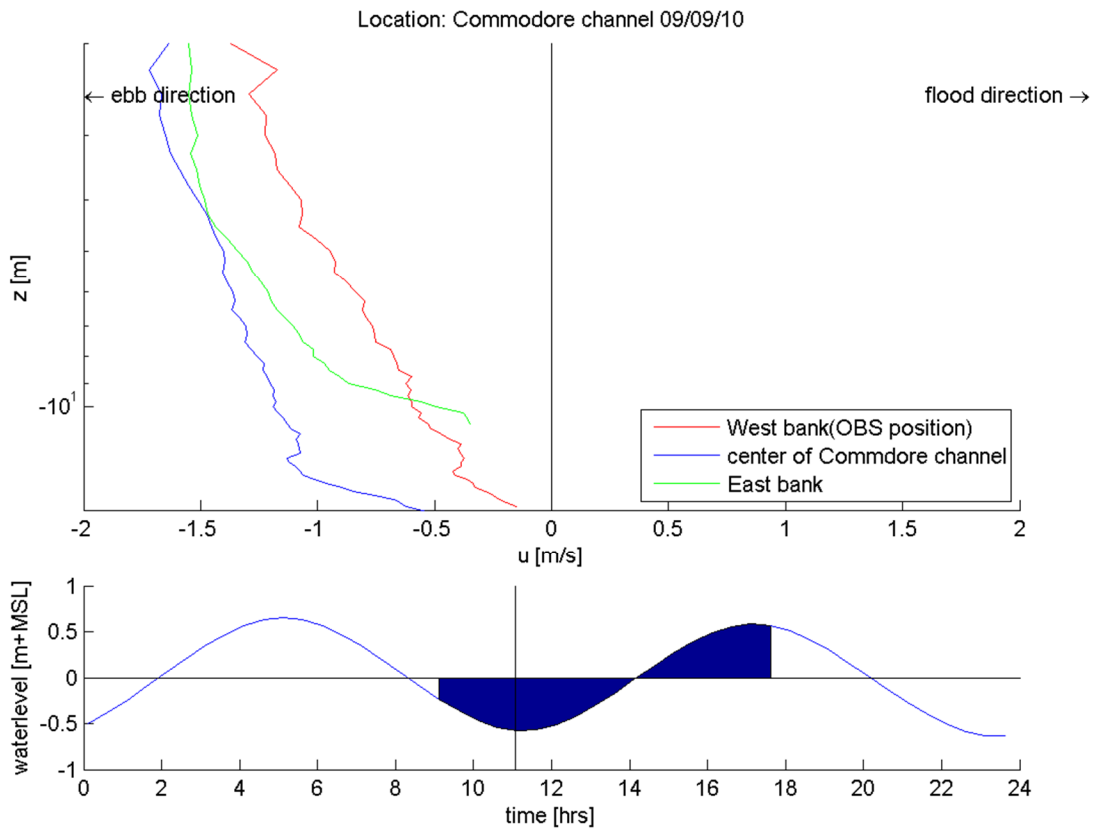


Figure 5-2 Flow regime during ebb flow

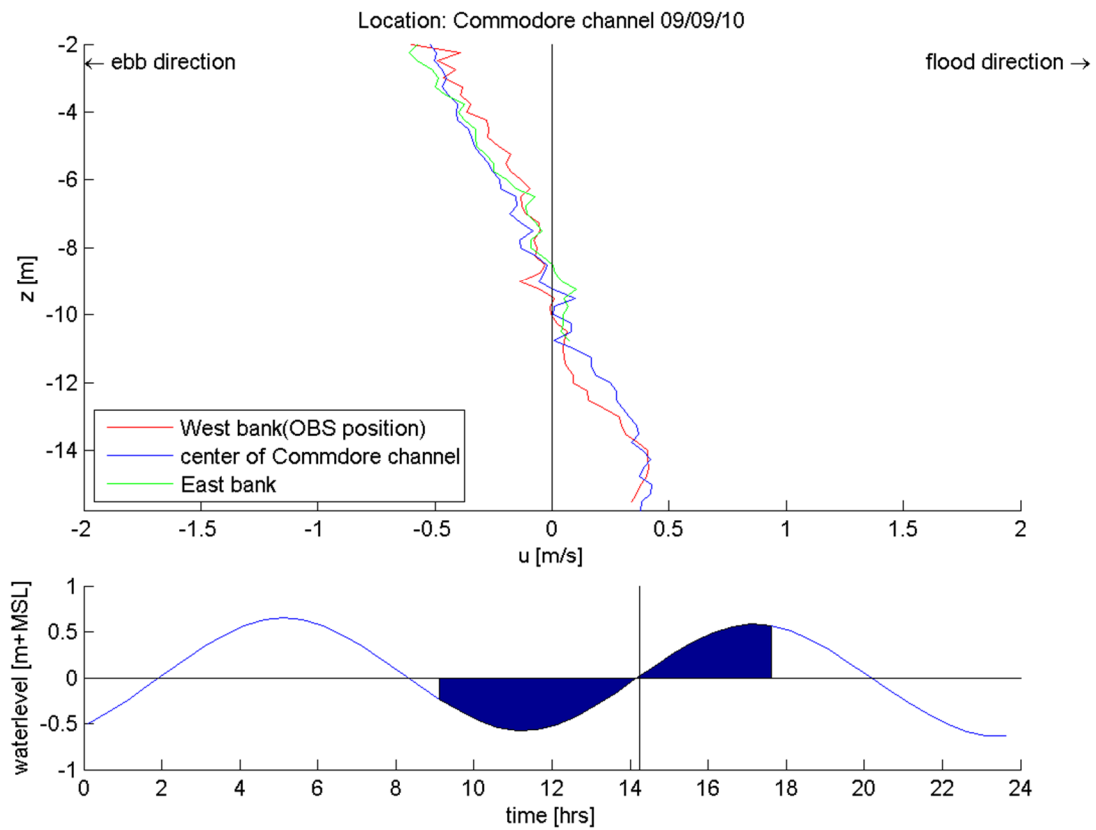


Figure 5-3 Flow regime at MSL

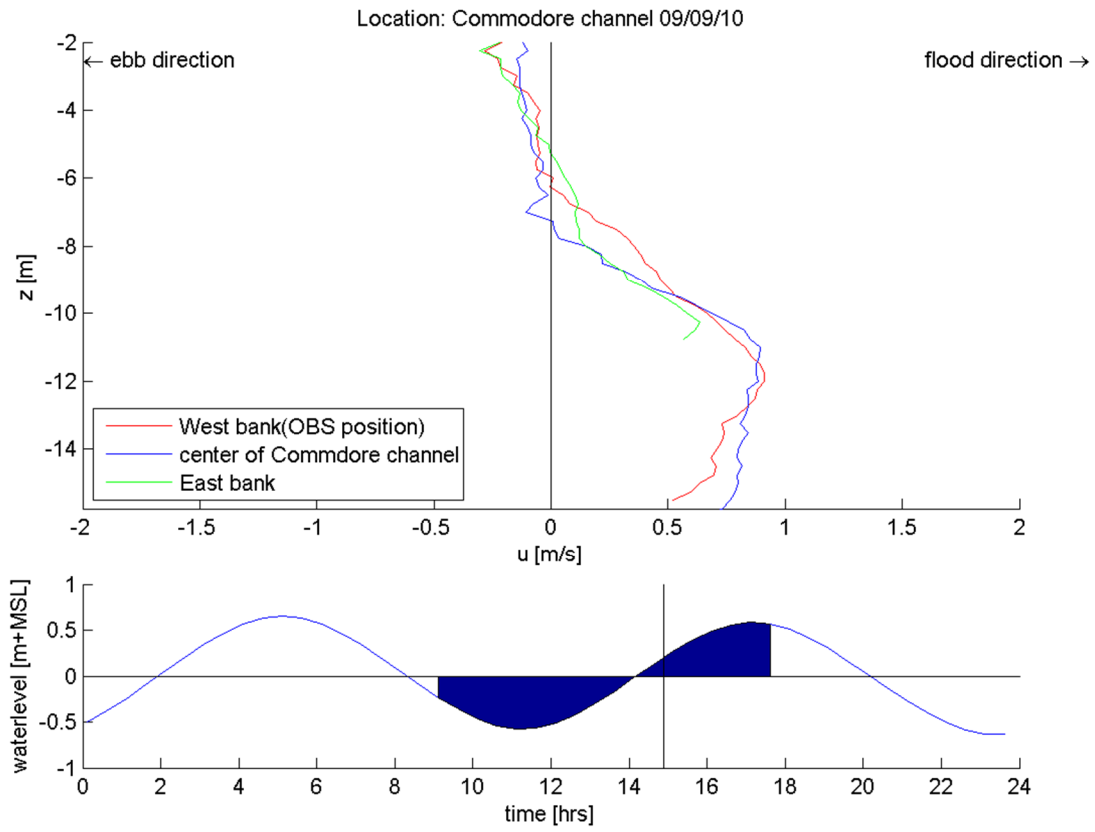


Figure 5-4 Flow regime during flood flow

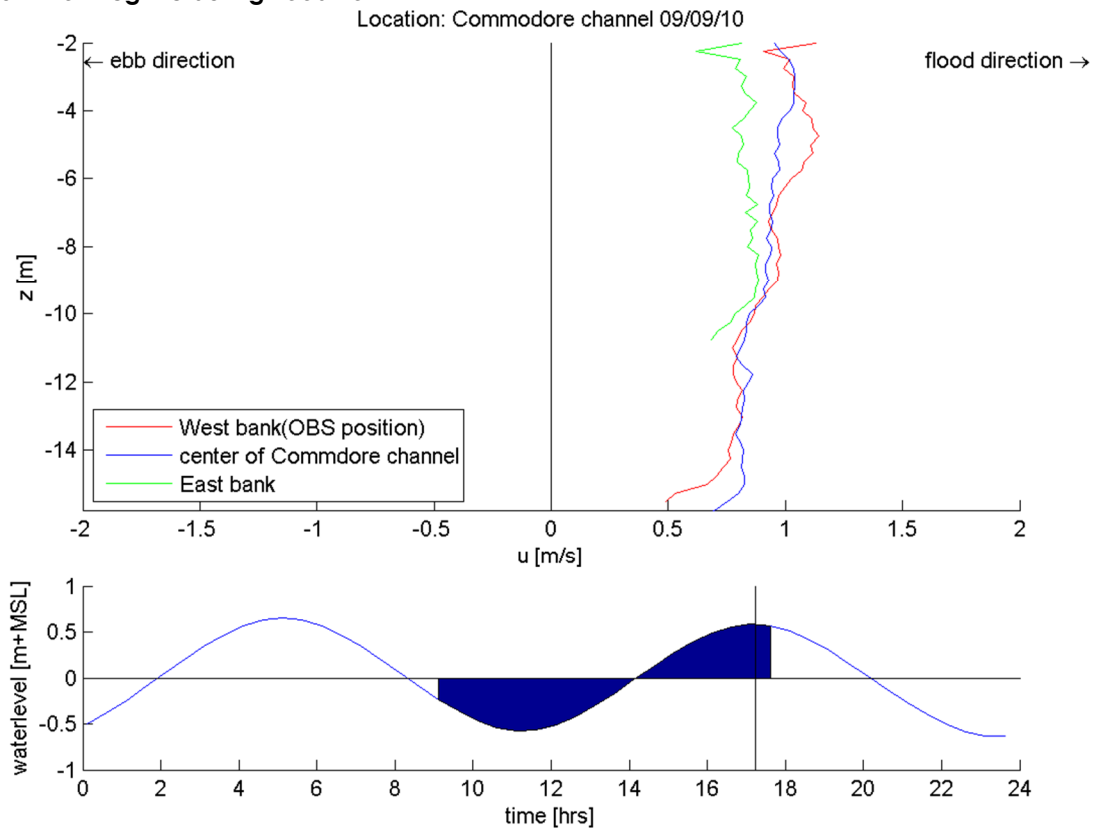


Figure 5-5 Flow regime during high water

At the turning of the tide towards flood (Figure 5-4) the density driven current near the bed is clearly visible. While the higher part of the cross section is still flowing out, the tide has already turned near the bed. The flow velocities near the bed are quite strong with nearly 1 m/s difference relative to the flow near the surface. In time, the water level rises to its maximum of 0.5 m above MSL and the salty layer increases in thickness from only a few meters from the bottom to -5 m MSL in two hours. At the maximum mean flood velocity, this salty layer covers the entire depth of 15 m. The transition of flow velocity between the two layers is gradual and this intermediate layer generally extends to a few meters in thickness.

The profiles shown in green represents the data collected near the east bank of Commodore channel where the local depth is slightly less with 10 m. Figure 5-5 displays the bulge in the velocity profile well. It also indicates that the flow velocity measured closest to the bed is still over 0.5 m/s, more than sufficient to maintain fine material in suspension. As slack water conditions only apply for a short period and fine sediments settle slowly, very little material will be deposited in Commodore channel. This is also suggested by the bathymetric charts of this region.

5.1.1.3 Local flow regime at OBS location

As mentioned in section 4.5.2, one possible explanation for the rapid changes in concentration during flood may lie in alternating local flow velocities due to flow around the pillars of the platform. The previous section learns the flow velocity measured close (40 m 'upstream' of the platform and near the bed are in the order of 0.5-1 m/s. These flow velocities are strong enough to bring and keep fine material in suspension. Larger grains have large settling velocities and may or may not be transported under these conditions.

The settling velocity for particles collected from the bed near the OBS location was not determined by a laboratory test. When considering sand particles, the settling velocity can easily be calculated and the material found in this part of Commodore channel with D_{50} of 250 μm is in the order of 4 cm/s (van Rijn, 1993).

The Rouse number is a non-dimensional number which is used to define a concentration profile of suspended sediment. It also determines how sediment will be transported in a flowing fluid. It is a ratio between the sediment fall velocity w_s and the upwards velocity on the grain as a product of the von Kármán constant k and the shear velocity u_* (Whipple, 2004).

$$P = \frac{w_s}{ku_*}$$

If the Rouse number is larger than 2.5, the grain's settling velocity is much larger than the upward-directed component of the turbulence. The grain tends to stay close to the bottom in this case and transport of sediment will be in the form of bed load.

For Rouse numbers is less than 0.8, the flow is turbulent enough to keep the grain fully suspended (wash load). The transition zone ranges 0.8 to 2.5 and the grain is partly suspended and regular contact with the bed may occur. For particles to be detected by the OBS sensors, more than 50 cm from the bed, the Rouse number must be low.

When assuming a Chézy coefficient of $45 \text{ m}^{0.5}\text{s}$, and mean channel velocity ranging 0.5 to 1.0 m/s, the shear velocity³ becomes 0.04 - 0.07 m/s. The corresponding Rouse numbers are 1.39 to 2.43. These values indicate the sandy sediment found at the OBS location can be partly brought in suspension and is likely to stay in the bottom half of the local water depth. As the local bed consists of a variety of particle sizes, lower flow velocities may stir up the finer fractions of the bed material.

This simple approach indicates the bottom 6 (0.25 - 8m from the bed) sensors could be measuring locally eroded sediment although it may be assumed that the bed near the pillars has reached equilibrium and erosion may be limited. The OBS data suggest only the sensors in the lower 4 m register significant concentrations of suspended coarser material. The approximation by Rouse no longer applies when the flow regime is disturbed by for instance a pillar as is the case for the 2010 OBS location.

The flow near the OBS sensor location is expected to be disturbed by the pillars of the platform the sensors were installed on. The local flow velocity and shear velocity greatly depends on the local bathymetry and obstacles. As the water flows around the pillar, it is accelerated and creates a wake behind the pillar. Flow velocity around the pillar may amount 1.3 times the normal current speed. Directly behind the pillar, up to several diameter lengths, the flow is greatly reduced. At the interface, vortexes occur and last for some distance and time before they dissolve. The flow pattern around a pillar is illustrated in the figure below.

³ $u_* = \bar{u} \frac{\sqrt{g}}{c}$

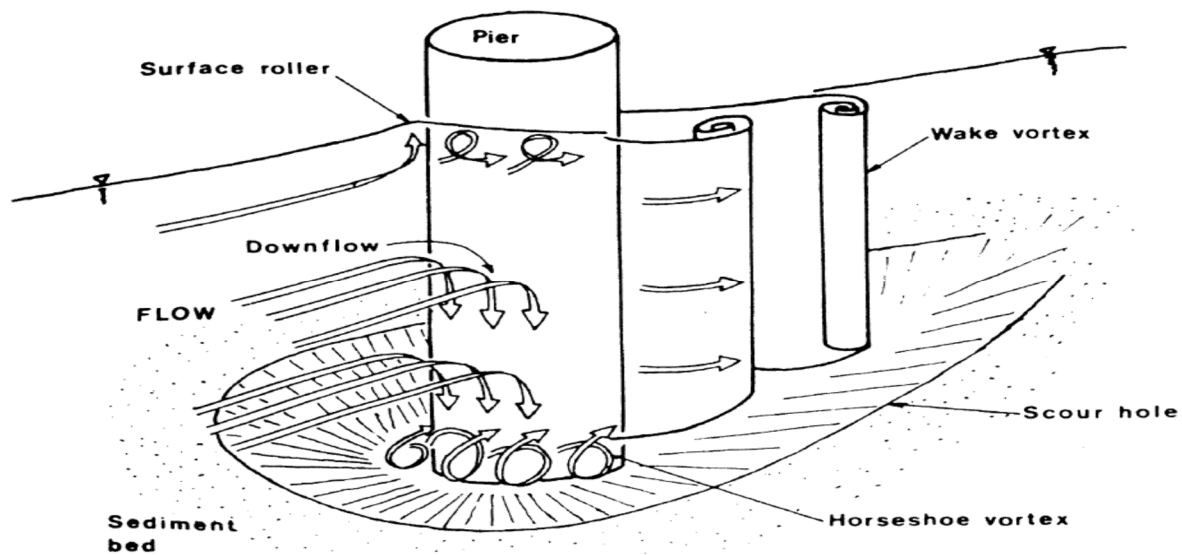


Figure 5-6 Flow pattern and scour near pillar (Melville, 1988)

Typical time scales of the vortices are estimated by the Strouhal number. The vortex frequency can subsequently be calculated with:

$$St = \frac{fD}{u}$$

Where St = Strouhal number, f = frequency [Hz], D = characteristic length [m] (e.g. pillar diameter) and u = current velocity [m/s]. The Strouhal number is a function of the Reynolds number and is typically 0.2 for turbulent flow. The characteristic time scale of the vortices, with flow velocity approx. 0.5-1.0 m/s and pillar diameter 75 cm, is 5 seconds. The length scale is several meters as the main flow conveys the vortices by advection. The measuring interval of 1 minute of the OBS sensors is not sufficient to detect these small scale variations and cannot be confirmed with current knowledge. It is however possible that the flow around the pillars is seriously disturbed and may be the cause for the behaviour shown by the OBS sensors.

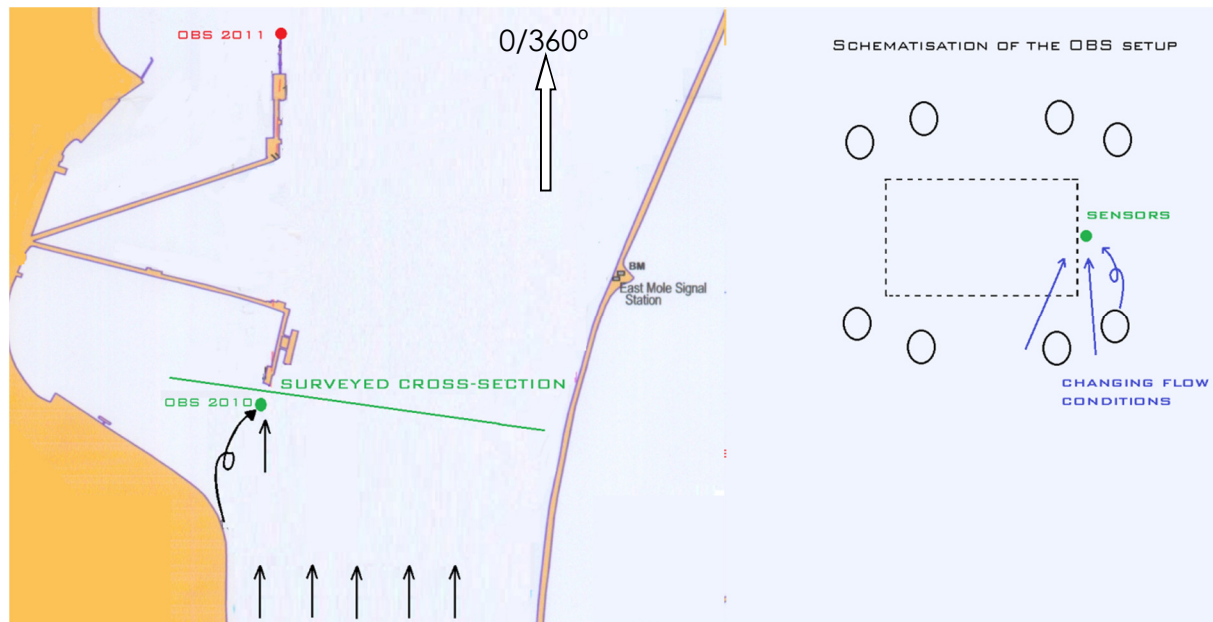


Figure 5-7 Schematisation of the 2010 OBS setup and location. The OBS 2011 data was installed at a similar jetty several hundreds of meters north.

The above figure illustrates the possible flow near the OBS location. Due to the sudden widening of Commodore channel and other local features in the bathymetry, large scale disturbances in the flow may alter the flow direction and therefore the approach angle of the pillar. As the flow direction varies, the OBS sensor may measure low turbidity when it is in the wake of the pillar and just moment later be in the zone with high turbulence. A way to check whether large scale eddies alter the flow direction on a time scale up to a few minutes is to look closely at the measured direction of the flow. During the 2010 campaign, on one day both the turbidity as well as the flow direction was measured. The results are presented in the next section.

5.1.1.4 Flow direction

Figure 5-8 and Figure 5-10 show the variation in flow direction on 09/09/10 close to the bed. As mentioned before, the highest concentration fluctuation was measured by the sensor at 0.5 m from the bed and mainly during the beginning of the flood period. The direction of the flow at this height is plotted against time together with the measured concentration in Figure 5-8. In this figure it can be observed that the flow direction varies considerably in time. The flow directions were measured during the sailing of the ADCP cross-section and approaches the OBS location up to 50 m (north of OBS site). The effects of the large scale disturbance in flow direction might be more noticeable if surveyed closer to the OBS location. However, Figure 5-8 shows adequately that there is a rapid and significant change (data is collected several minutes apart) in direction. Large scale disturbances may have various origins (e.g. moles, widening of channel) and have characteristic length scale of several to a few hundred meters (depth-width of channel). The corresponding time scale of the

disturbances, with flow velocity of ca. 1 m/s, range roughly 0.5 to 5 minutes. This time scale is also observed in the flow direction and turbidity data.

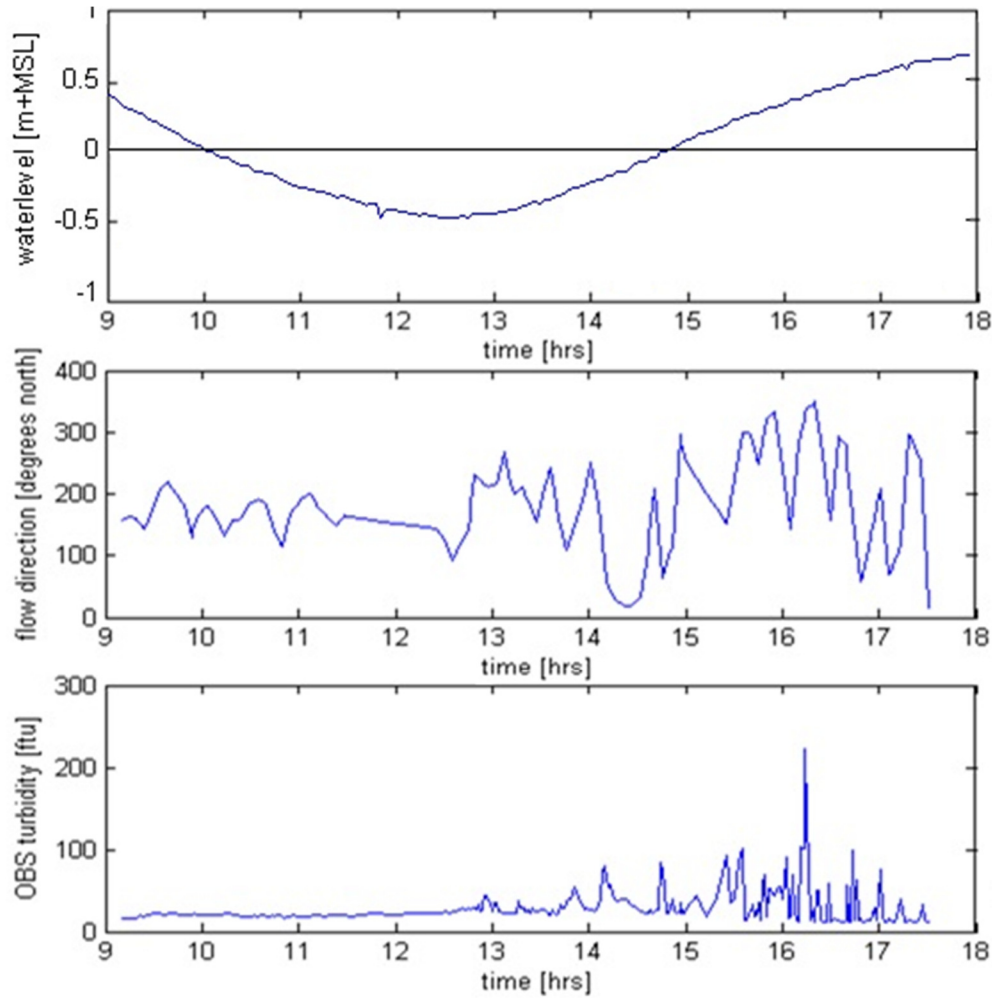


Figure 5-8 Flow direction and turbidity at 0.5 m from the bed on 09/09/10

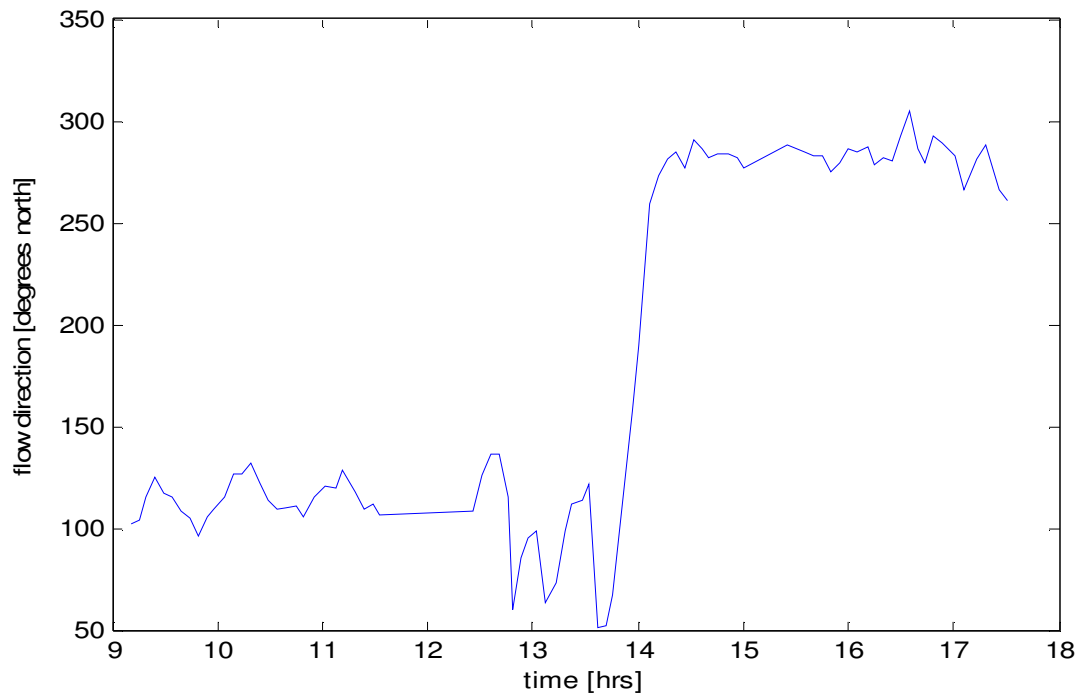


Figure 5-9 Flow direction over time in the centre of Commodore channel on 09/09/10 at 0.5m from the bed

Above figure shows the same principle as Figure 5-8 but for the centre of Commodore channel. Here, large eddies seem to have no effect on the flow direction as it is fairly steady.

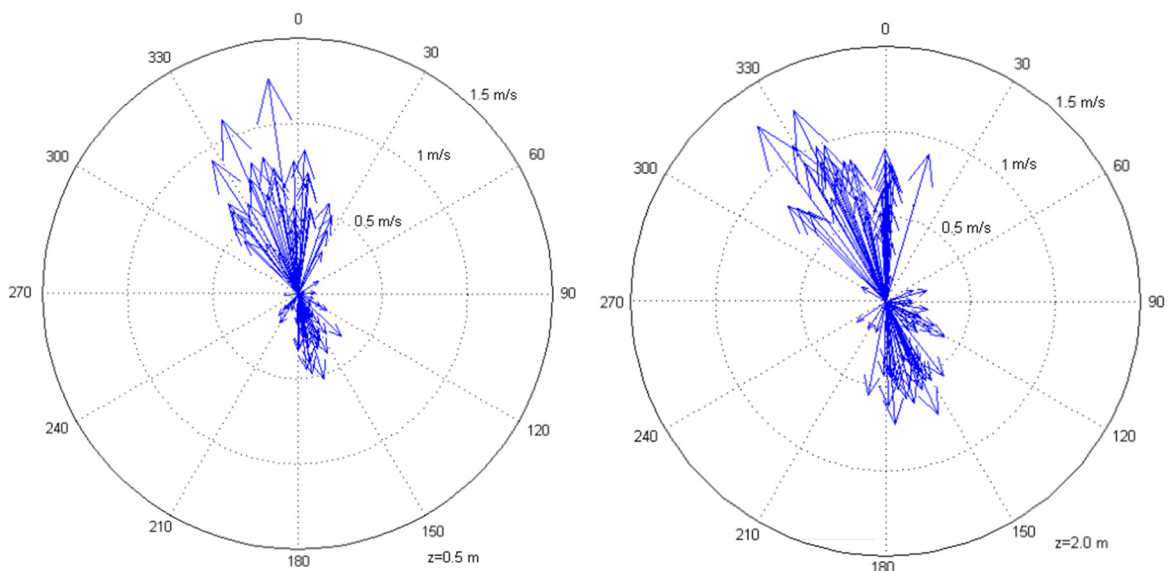


Figure 5-10 Flow directions and speed during ebb (due southeast) and flood (due northeast) in close to the OBS sensors in Commodore channel on 09/09/10. Height above the bed: 0.5 m (left) & 2.0 m (right)

The above figure displays the flow direction at 0.5 and 2.0 m from the bed of the entire survey day at a position 40 m north of the OBS location. It shows the variation

in direction and current velocity (length of arrows). For the flood period (due north by northwest), the flow direction sways about 70 degrees while the ebb flow is more stable as the general flow direction is 165 degrees north with a 15 degrees deviation. In contrast with the general velocity pattern measured over the entire cross-section, the flow velocities during flood are stronger than during ebb flow. Commodore channel discharges more water during ebb than during flood, presumably due to the added discharge of rain. As this effect is mainly noticeable higher in the water column as the less saline water floats on the heavier salty water. In deep areas, such as the OBS location, the larger flow velocities are measured during the incoming tide.

Although the OBS location is at some distance from the velocity/discharge survey line, it is plausible that the same variation in velocity and direction occurs near the sensors. This strongly suggests that the high turbidity levels measured during flood may be caused by local processes.

5.1.2 Interpretation of measured turbidity

The hypothesis pitched in section 4.5 concerning the soundness of the measurement results of the OBS sensors is stated as follows: A large fluctuation in the currents created by detached flow (e.g. due to protrusions/obstacles along the channel banks) cause deviations in flow direction. Now, the OBS sensors sometimes measure concentration in the wake of the platform's pillars and at other times in full flow strength. Different types of sediment are assumed to pass the sensors, depending on the direction of the current.

Under ebb flow, the concentrations are quite uniformly measured over the depth and gradually increase as long as ebb flow occurs. It is assumed that this material is fine grained and is supplied to Commodore channel by rivers and creeks discharging in the Lagoon or Badagry creek. During ebb flow, there exists no correlation between the concentration and mean flow velocity in Commodore channel. It can be concluded that erosion of local material due to flow induced stresses doesn't occur. During the ebb phases, large turbidity values are recorded for short periods, lasting only a few minutes up to one hour. A single 'spike' may have been a measurement error or perhaps a passing fish or piece of rubble. It is also possible that e.g. plastic bags becomes stuck to a sensor for some time and block the sensor's 'view'. Examples are shown in Figure 5-11 around 20:00.

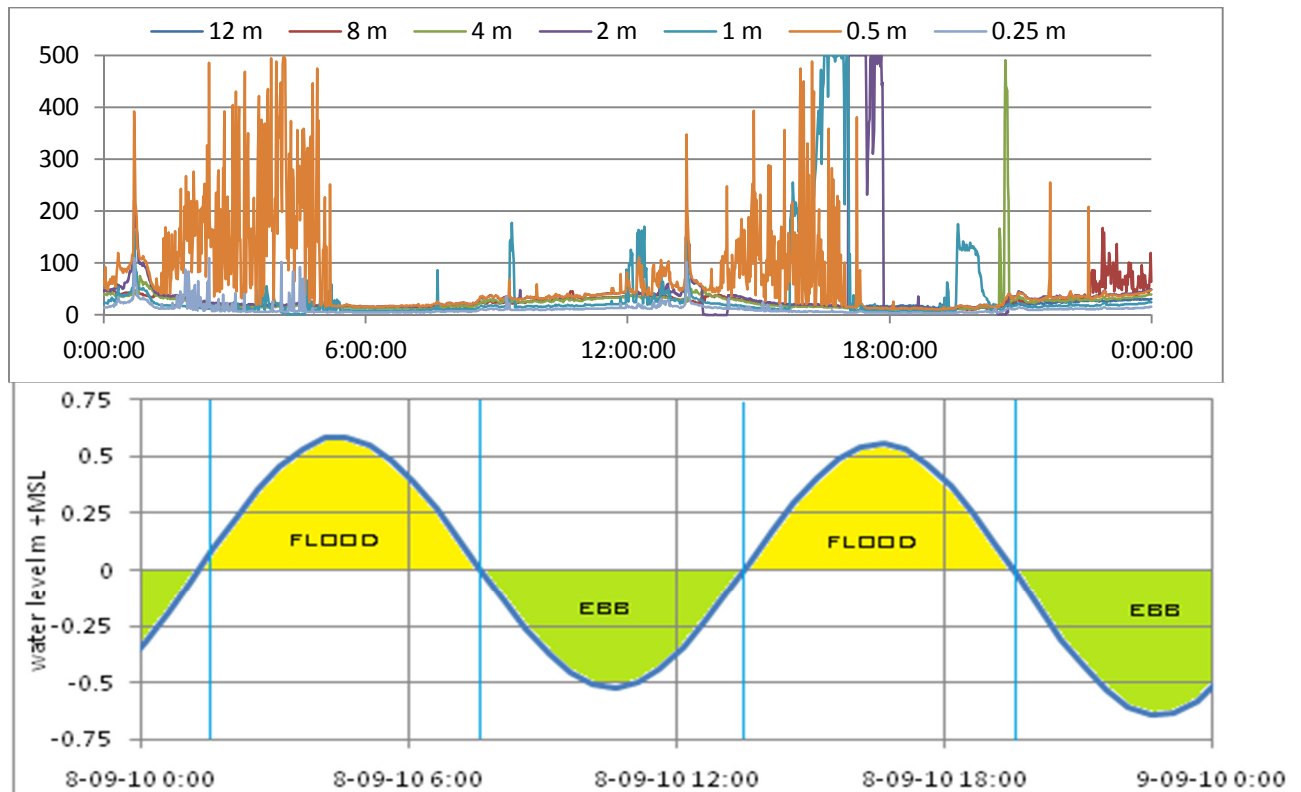


Figure 5-11 Measured OBS results: suspended sediment concentration in mg/l on 08/09/10. The bottom figure displays the water level variation as no flow velocities are measured on this day. The phase difference between maximum/minimum water level and flow velocity is negligible.

During flood, the pattern changes as the turbidity at most sensor heights seem to drop except for a few near the bed. Periods of rapidly changing but generally high turbidity are recorded. The material causing the turbidity is assumed to be sand as the settling velocity of silt and clay is too low to show such behaviour. It is assumed that changes in the local flow pattern, caused by a varying flow direction upstream of the pillars, determine whether the sediment's critical flow velocity is reached. As the above figure illustrates, turbidity at sensor 0.5 m increased at the beginning of the flood period, even when the depth-average flow velocity in Commodore channel is still close to zero. It should be noted that at the turning of the depth-average flow direction towards flood, the flow near the bottom is already significantly stronger (section 5.1.1.2). Yet, flow velocities near the bed at this moment in time are lower than during the maximum ebb when the concentration was low.

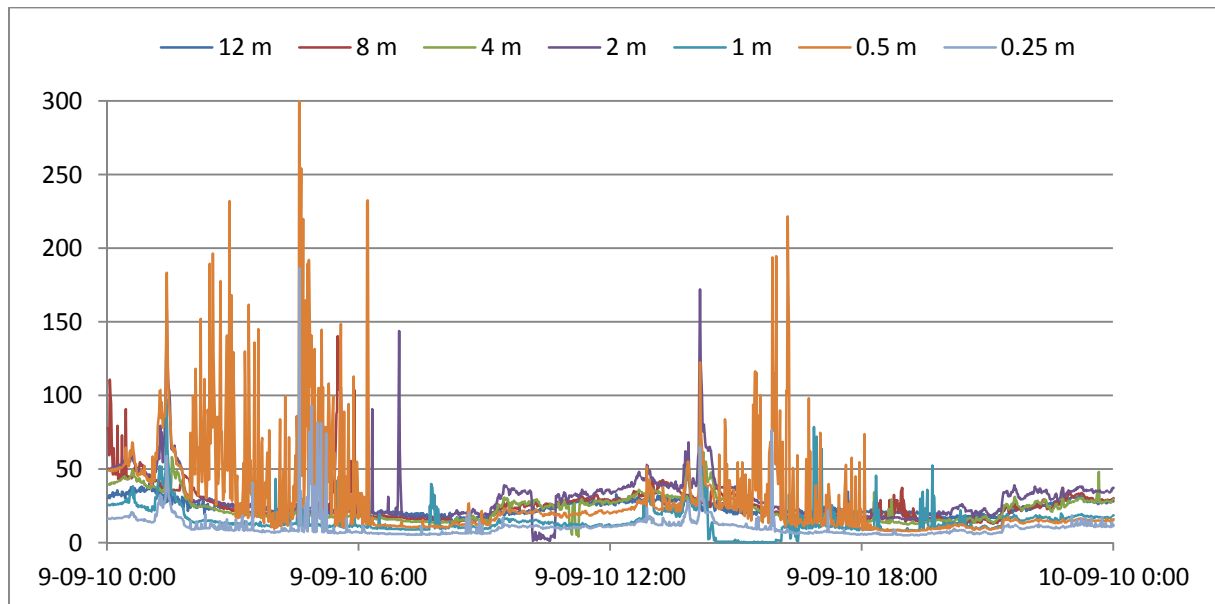


Figure 5-12 Measured OBS results: suspended sediment concentration in mg/l on 09/09/10

The results of the 7 OBS sensors for 09/09/10 are plotted in Figure 5-12, the day the channel was surveyed by the ADCP. The measured concentrations were relatively low compared to other days. The higher sensors, from 2 m up to 12 m from the bed, register more or less the same concentrations and are generally higher than measured by the sensors placed at 0.5 and 1 m from the bed. It is generally expected that the suspended sediment concentration increased with depth, but this is clearly not true for Commodore channel during the field campaign. Although high concentrations were measured near the bed for short periods, the concentration during ebb flow are lower than those higher in the water column.

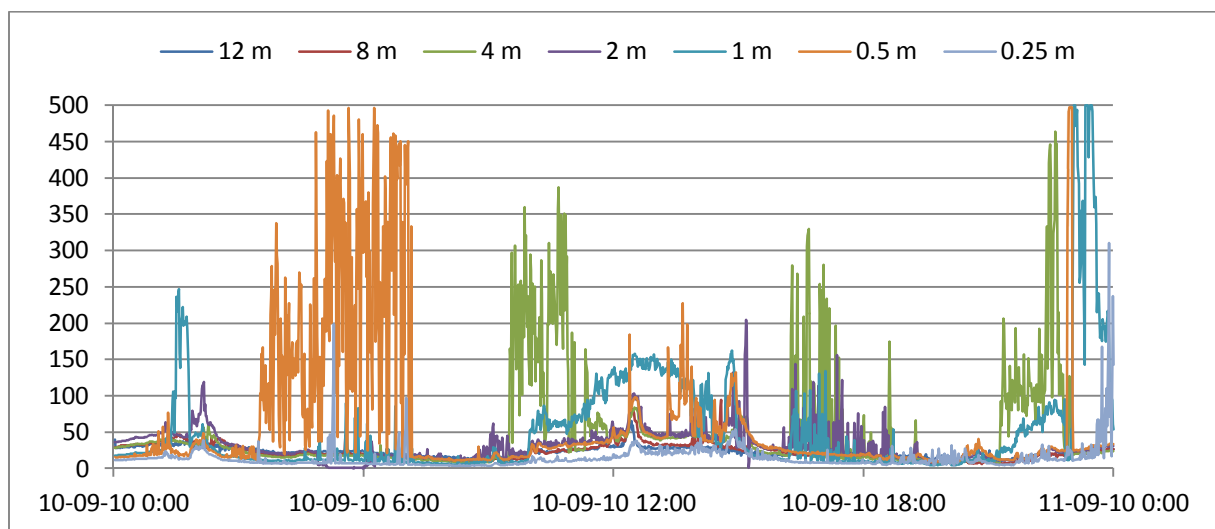


Figure 5-13 Measured OBS results: suspended sediment concentration in mg/l on 10/09/10

The third day (10-09-11) of turbidity measurements provides discussion material. Here, the behaviour previously recorded only by one sensor (0.5 m) is now shown by sensors installed at 4 m and 1m from the bed. The above figure shows high turbidity for these two sensors around noon and 23:00 on 10/09/10. These are ebb periods, during which this behaviour hasn't occurred on other days. The flood period around 17:00 shows familiar turbidity patterns although the 0.5 m sensor now does not respond. If sand particles reach up to 4 m from the bed and are also registered by the sensor at 1m, why don't the 0.5 and 2.0 m sensors respond? The explanation might lie in a complex bathymetry with abrupt differences in depth. Also, wrecks are common in Lagos harbour and may have an effect, at least under certain conditions.

The OBS technology is in general very reliable and certainly when bio-fouling doesn't play a role (only long periods of measurements). This and previous sections showed that the OBS results are plausible and the data is therefore accepted as such. Due to the (assumed) complexity of the flow and bathymetry near the OBS location it will be very difficult to confirm the hypothesis, even with a repeated measuring campaign. The question arises whether this would be useful anyway as the purpose of the turbidity measurements was to gain insights on the concentration profile of Commodore channel. The complex bathymetry and flow pattern near the OBS location may not be representative for the rest of Commodore channel.

To answer whether there is net import or export of sediment through Commodore channel the following scenarios are elaborated:

- the measured OBS data is used to represent Commodore channel
- the OBS data is manipulated such that extreme turbidity values are deleted if much higher than other sensors
- where available, ADCP data is used to represent sediment concentration

5.1.3 Sediment transport

For Commodore channel, two sources of SSC data are available, converted turbidity data from OBS sensors and the ADCP backscatter measurement results. The calculated transport rates based on the OBS data is probably more reliable as the ADCP is affected by calibration errors. However, ADCP results measured in the centre of Commodore channel are more representative for the entire channel than the data turbidity from the OBS location as it is heavily influenced by local factors. Both methods are used and presented in the figures below.

The measuring period of nearly 9 hours on 09/09/10 in Commodore channel does not cover a full ebb and flood cycle. The shaded part of the bottom plot in Figure 5-14 shows the surveyed period with respect to the tide. The sediment transport rate is calculated by multiplying the local flow velocity with the sediment concentration. It is assumed that the sediment particles have the same velocity as the water. This simplification may be justified for fine material but is not valid for the larger grains. This results in an overestimation of the transport rate if the sediment is not fully suspended,

which is the case for larger particles. Quantification of this error is very difficult as no data is available on the size distribution of the suspended particles.

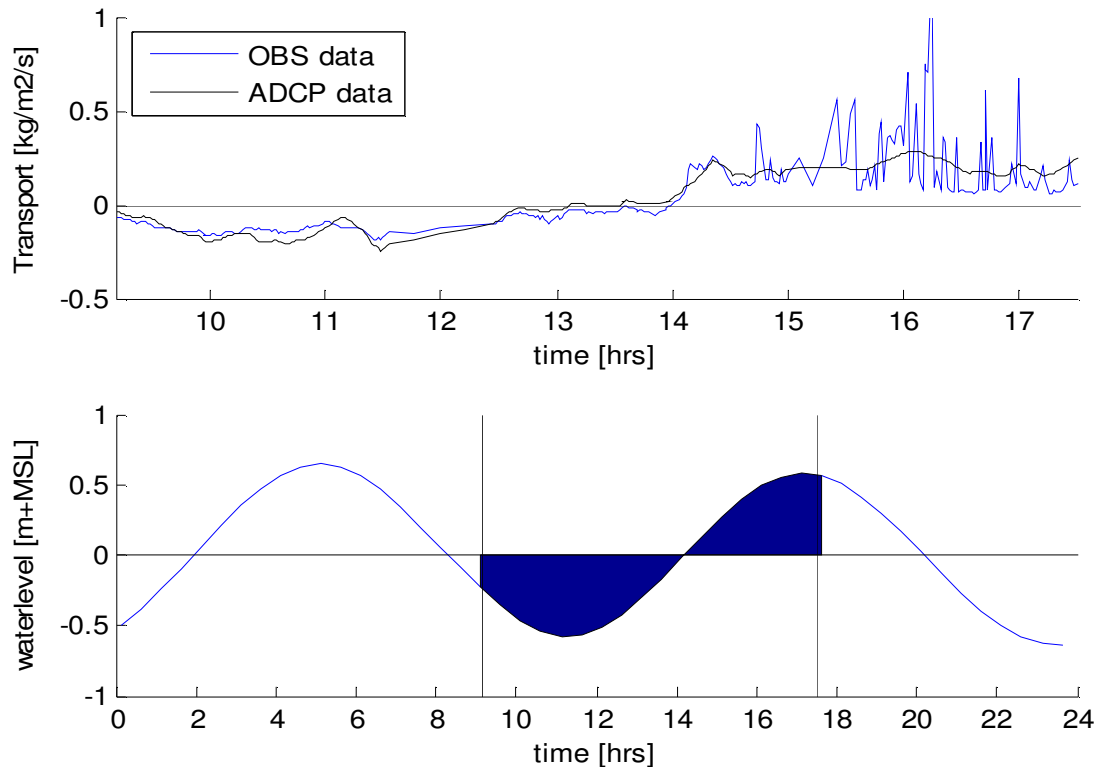


Figure 5-14 Calculated sediment transport based on OBS and ADCP data at 0.5m above the bed.

The ADCP estimations of the suspended sediment concentration have been scaled (see section 4.5.3) to fit the fairly reliable part of the OBS measurements (the steady measurements during ebb periods). The top half of Figure 5-14 shows the results of both the OBS measurements and the ADCP results at 0.5 m from the bed. The rapid change in concentrations in the flood period is not measured by the ADCP. This is expected as the ADCP survey location is at some distance from the disturbances influencing the OBS measurements.

Both the OBS as the ADCP record higher sediment transport rates during the flood near the bed (Figure 5-14). At the beginning of the flood period the density current has a strong effect of the flow near the bed. However, the sediment concentration does not directly correlate to the flow velocity and the increased sediment concentration during flood is not the result of solely the increased flow velocity caused by the density current. Both the ADCP and OBS data shows that similar flow velocities during ebb flow do not result in the same sediment concentrations. The data indicates that the suspended sediment concentration at the surveyed cross-section in Commodore channel largely depends on the supply from other parts of the system and the ocean.

In order to compare turbidity to ADCP backscatter, conversion to a single parameter is required. The measurements are converted to kg per square meter of channel cross-section per second and range up to 1 kg/m²/s. As mentioned in section 4.5.3,

errors occur in the conversion to mg/l and these transport rates consequently contain those errors as well. Although only part of the flood period is measured, it can clearly be observed that the transport rates are higher in the flood direction.

When using the OBS data as a source for calculating transport rates, the results near the bed are greatly influenced. When extrapolated over a full ebb and flood period, the net transport close to the bed adds up to 40 kg of sediment⁴ to be transported per square meter of Commodore channels cross-section (OBS data). This value is about 5 times lower when using the ADCP data. The net transport near the surface is in the ebb direction and is roughly 3 to 4 times higher than near the bed. The estimated net transport rates in related to depth are shown in the figure below.

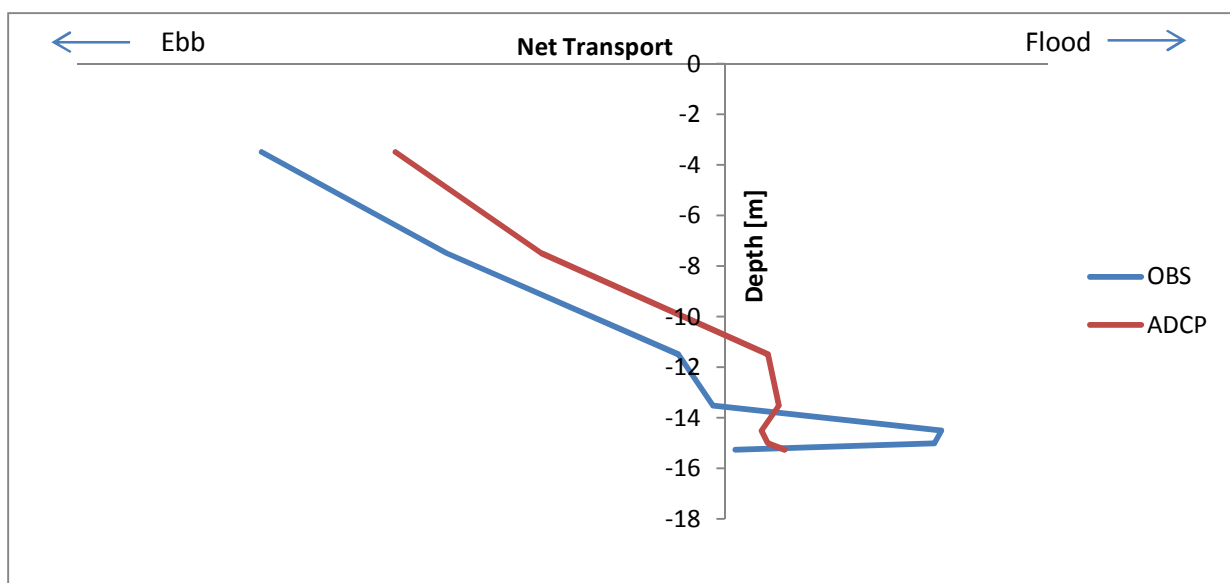


Figure 5-15 Estimation of net transport over depth integrated over an ebb-flood cycle. Left of y-axis indicates transport in ebb direction, right of the y-axis means net transport in flood direction. Y-axis indicates depth [m].⁵

From these results it may be concluded with some confidence that the net transport near the bed is in upstream (flood) direction and transport rates higher in the water column are larger and in ebb direction. The influence of rain run-off in the system is assumed to be significant as the supply of fines is thought to be increased during ebb periods as well as the water discharge.

⁴ Note that the numbers mentioned in this section are presented to give an idea of the order of magnitude and are meant for comparison to other values only.

⁵ The net transport plots in this section don't show transport volumes (note 4). The plotted scale is linear. The dimension of the plotted results is sediment mass per m² cross-section per ebb-flood cycle.

5.2 Apapa channel

For Apapa channel, only one day of reliable measurements are available. The results of the ADCP survey in this channel are displayed on the figures below. Two distinct moments were selected to illustrate the behaviour of Apapa channel: during low and high water.

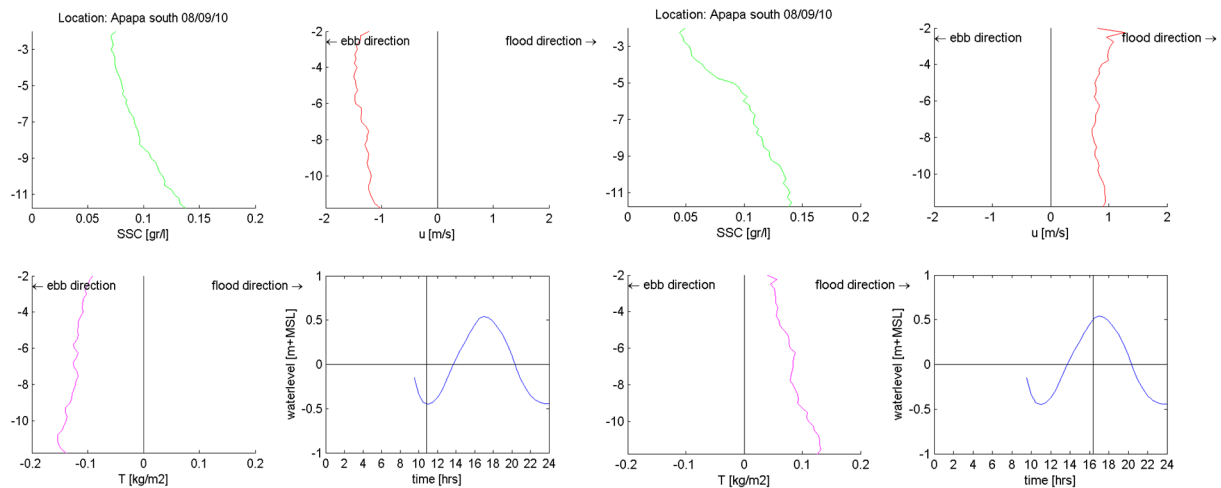


Figure 5-16 SSC, flow velocity and transport rate over depth in Apapa channel at two moments in the tidal phase.

The sediment concentration, in the top left frame of both figures, is increasing with depth. The concentration is fairly stable during the entire survey with maximum concentration during slack water conditions about half that of during high flow velocities.

The flow velocity in Apapa channel is about 1 m/s during low and high water and is near uniform over the depth. At the turning of the tide, a clear density current was visible in Commodore channel. This is not observed in Apapa as the flow direction is near constant over the water depth as well. This complies well with the measured salinity profiles which also indicated no stratification of currents.

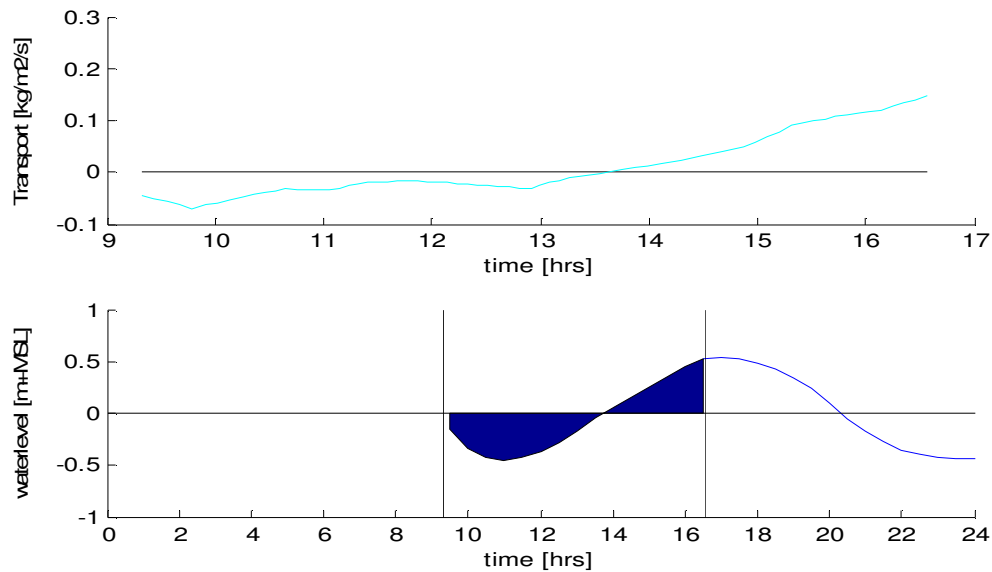


Figure 5-17 Calculated transport rate based on ADCP data surveyed on 08/09/10 at 0.5 m from the bed

As the suspended sediments results and flow velocities measured by the ADCP are fairly consistent and stable in time, the transport rates are too. Figure 5-17 shows the calculated transport rates over the surveyed period of the tide at 0.5 m above the bed.

The transport rate near the bed during flood is significantly higher than during ebb flow while the ebb and flood flow velocities are about the same. A possible explanation is that the measured sediment is coming from Badagry creek. As the sediment is transported out through Badagry during ebb it flows consequently through Commodore channel. As the flow direction turns, this sediment (now in Commodore channel) may be transported towards the lagoon. As the current set of data contains no current velocity data of more than one channel at the time, this cannot be checked. So, additional measurements, simultaneously in Badagry creek and Apapa channel are needed to confirm whether this is the case. A numerical model of Lagos Harbour may provide an answer to this hypothesis as well.

An alternative explanation may lie in the density current observed in Commodore channel. Although no such current is recorded in Apapa channel, sediments transported through Commodore to the junction between the two channels may be transported through Apapa. In this case, the higher concentrations are not caused by local erosion due to higher flow velocities in Apapa but the results of additional supply at the downstream boundary of Apapa. Again, additional measurements or numerical model simulations may confirm the hypothesis.

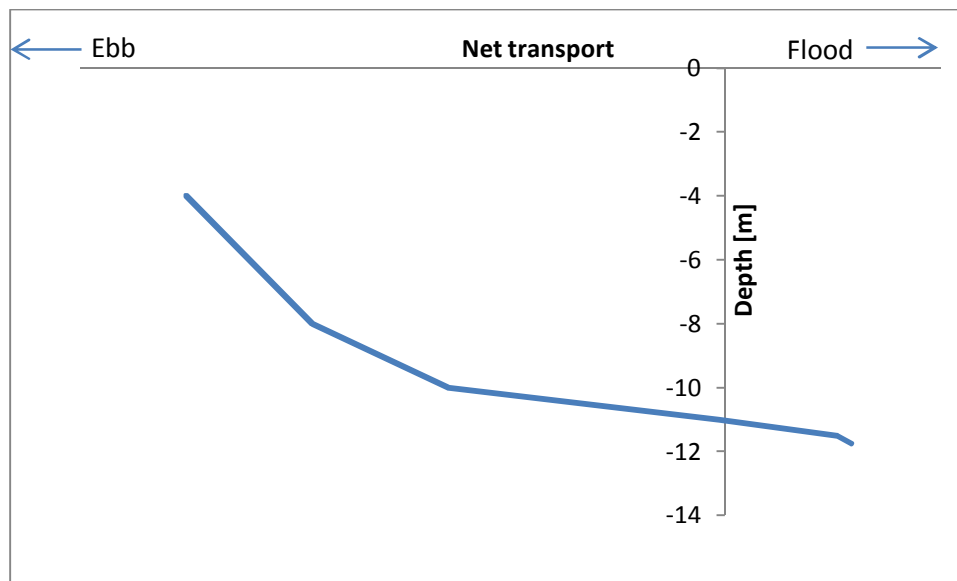


Figure 5-18 Estimation of net transport over depth integrated over an ebb-flood cycle. Left of y-axis indicates transport in ebb direction, right of the y-axis means net transport in flood direction. Y-axis indicates depth [m].

Transport rates in Apapa are predominantly in ebb direction and decreasing with depth. Near the bed, the net transport is in flood direction. These results indicate there is net sediment transport through Apapa channel towards Commodore channel and, likely, out to the ocean. Near the bed a relatively small amount of sediment is transported in flood direction. Whether this is true for Apapa channel in general or just this surveyed day is hard to say. As the shaded part in Figure 5-17 shows, only part of the flood period is surveyed and the net transport rates rely on extrapolation of the data. This method comes with great uncertainty and chances for a completely different outcome are significant. It is therefore premature to draw any conclusions on the transport volumes through Apapa without additional data.

5.3 Badagry Creek

Badagry creek is a bit different to the other main channels that compose Lagos Harbour as the fresh water influence is much stronger. The effects of the added fresh water discharge to the tidal motions cause the ebb discharge to be significantly higher than flood discharge. The other effect of fresh water, a possibility of density currents, is illustrated in the figures below at two moments in time: at the turning of the tidal flow.

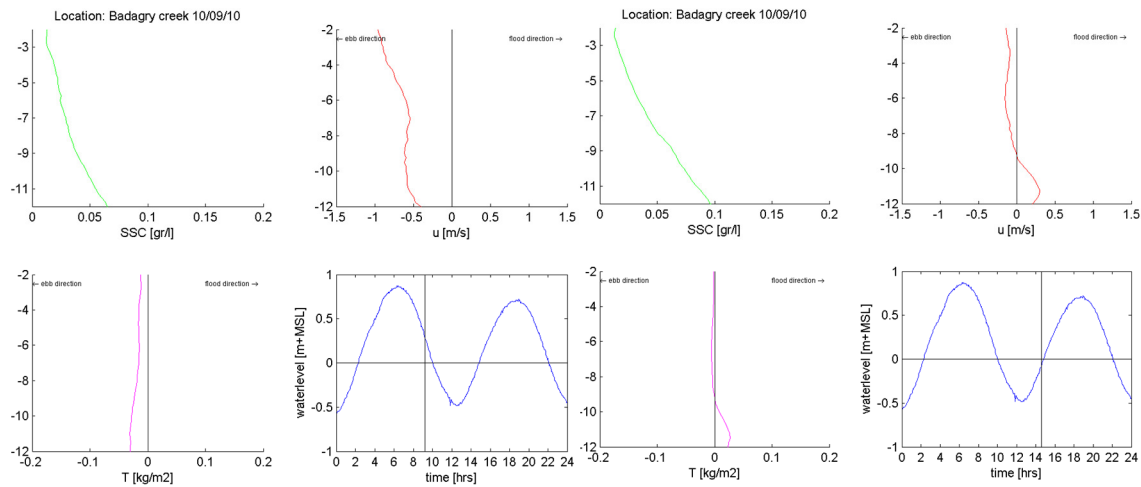


Figure 5-19 SSC, flow velocity and transport rate over depth in Apapa channel at two moments in the tidal phase.

Note that the flow velocity in Badagry creek at the crossing of mean water level (\neq MSL) is already in ebb direction. The flow direction is outgoing over the full depth, whilst at the turning towards flood (right figure), a density driven current is observed. The flow near the bed is flowing in whilst the water above is flowing in the ebb direction. SSC is higher after a period of ebb flow as the supply from the creeks and rivers inland supply Badagry with fine sediments. The sediment distribution is what can normally be expected in channels with steady flow, increasing with the depth.

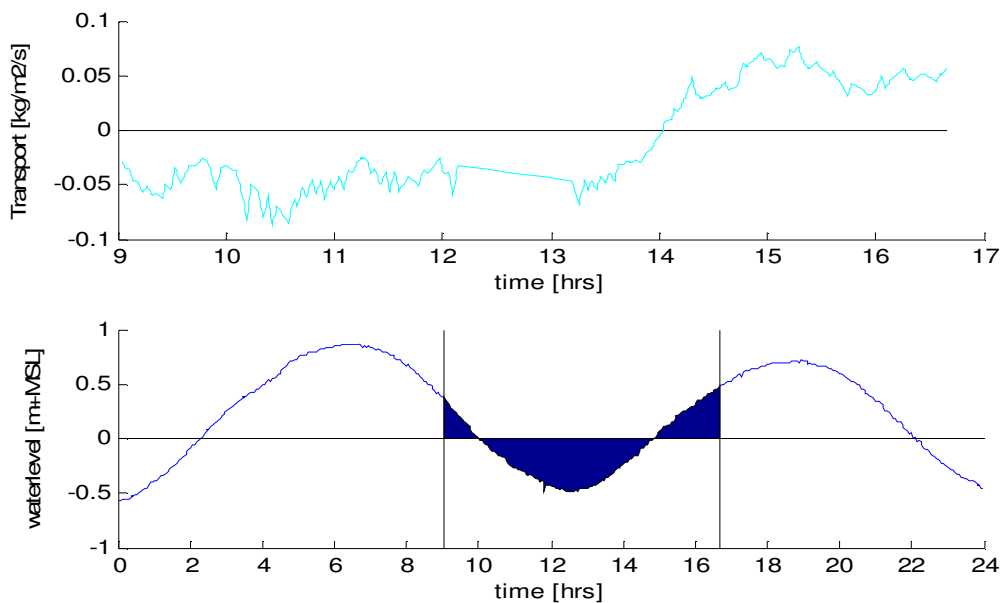


Figure 5-20 Calculated transport rate based on ADCP data surveyed on 08/09/10 at 0.5 m from the bed.

As the discharge, and consequently mean flow velocity, is larger in ebb direction than flood direction, it is not surprising that the net transport is outbound to sea. The transport rates are highest in the layer ranging from the surface to roughly minus 8 meters.

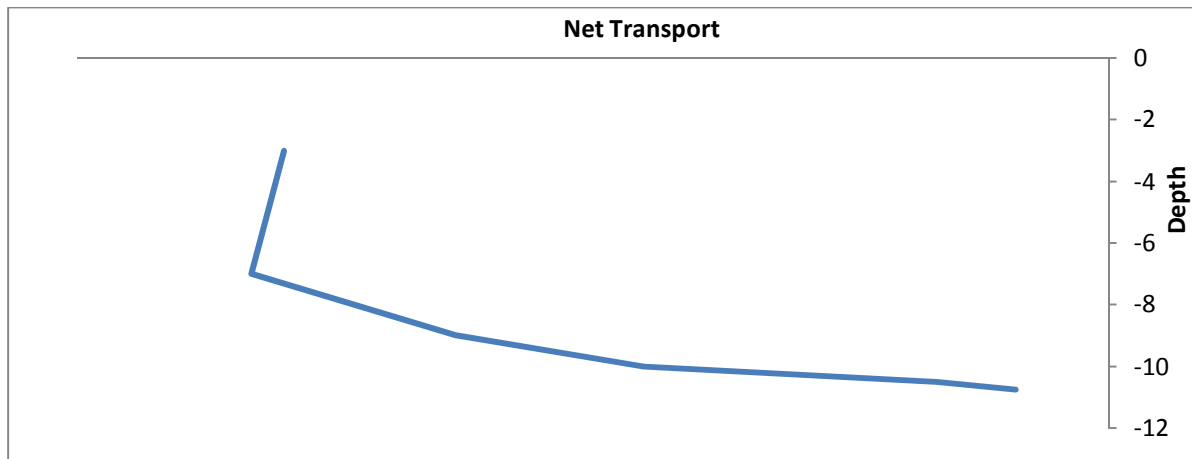


Figure 5-21 Figure 5-22 Estimation of net transport over depth. Left of y-axis indicates transport in ebb direction. Y-axis indicates depth [m].

As mentioned, the flow velocity, SSC and thus transport rates greatly depend on the fresh water discharge through Badagry. As these results were measured during the rainy season, the conclusion of net sediment transport towards Commodore channel may still hold but are likely to be less substantial in the dry season. When considering the long term morphology of the entire system, it can therefore not be concluded that Badagry is transporting sediments towards Commodore channel without further justification in the form of measurements during the dry season.

6. CONCLUSIONS, DISCUSSION & RECOMMENDATIONS

In this final chapter of the thesis, the conclusions are presented as well as recommendations and suggestions for future studies. The significance of this report and its conclusions depend on the reliability of the measured data and methods used. A discussion on the reliability and applicability of the results is presented in section 6.2

6.1 Conclusions

The main objective of this thesis was to gain first insights into Lagos Harbour system. This thesis must therefore be regarded as an exploratory study on which future studies may elaborate rather than a report which provides a full analysis of the system.

The reason why this area is interesting to investigate is the potential growth of port activities in Lagos and the problems that come along with the need for deeper navigation channels. Also, the current dredging strategy was experienced to be ineffective for combating the siltation of the channels. The research question became clearer as knowledge about the system accumulates:

- Is there import of sediment to the entire Lagos Harbour system?
 - What is the source of the sediment?
 - Supply of material by rivers discharging in the system?
 - Import of marine sediments during flood, sand/silt/clay?
 - More supply from river than transported out to sea?
- Does the sediment get deposited in the channels?
- What role do density currents play in distribution of sediment?

This section will elaborate on these questions.

6.1.1 Sediment balance of Lagos Harbour

It is a bit ambitious to draw a conclusion on the sediment balance of the entire system as too little information is available. Chapter 5 shows there is sediment export of fine material in the high part of the water column through Commodore channel during the survey period. Whether there is net export or import near the bed is less clear as the density current is a major influence to the transport rates and is dependent on the seasonal variation in the salinity profile.

6.1.1.1 Sediment sources

Two types of sediment are being transported: fine material carried over the whole water depth and coarser sediments near the bed. The OBS data suggests the fine materials are transported during outgoing tide while the higher flow velocities and turbidity are measured during flood periods. The coarser material may be supplied by the long shore current, transporting sand into the system during flood. Fine

material is not found on the bed in Apapa and Commodore channel yet it is found in Badagry creek. If there is a supply of fine sediment from the ocean, it is not likely that large amounts will settle on the bed in Apapa and Commodore channel as the flow velocities are high compared to the settling velocity. The material may however settle in the dead end branches of Badagry creek or the Lagoon and find its way back to other parts of the system in a later stage.

Alternative sources of sediments are the local rivers discharging in the Lagoon and Badagry creek. There are numerous streams and drainage canals in the area ending in either Badagry or the Lagoon and may carry sediments into the system. If the streams supply fine sediments to the system, it would explain why the cohesive sediments are only found on the bed in Badagry and the Lagoon. As flow velocity are modest in these areas, the cohesive material may not be suspended and remain close to the bed. As the flow velocity increases in the main channel of Badagry creek and between the bridge pillars between Apapa and the Lagoon, this material may be eroded and transported out to the ocean without settling in Commodore channel.

As the sand/silt/clay distribution presented in section 4.2.2 indicates that the bed material found throughout the surveyed area has a common source, it is likely that only one of the above suggested sources is true. With the use of particle tracking methods, the true source of the material may be determined.

6.1.1.2 Settling of fine material in Lagos harbour' main waterways

Based on the experiences of the users of Lagos Harbour, the hypothesis at the start of this thesis was that large transport volumes of very fine, poorly flocculated material was to be expected. Ships (un)loading at the quays of Lagos Harbour experienced heavy siltation around the ship after some days. While this hypothesis may hold for Badagry creek, this is hardly the case in for the quays along Apapa channel. There, almost no cohesive sediments were collected by sampling and the bed forms visualised by multi-beam bathymetry surveys also indicate there is very little fine material to be found.

Badagry creek does seem to hold large volumes of fine, soft material and this is confirmed by several samples. The Badagry sediments contain a large amount of organic material and montmorillonite clay. The zeta-potential test carried out on the sediments in the Lagoon and Badagry creek confirmed a low reaction to a change in acidity, typical for this type of clay.

Fall tube tests showed that the settling velocity of the material was very low with less than 0.1 mm/s. Although these test were carried out under hindered settlement conditions, the settling velocity of particles under low concentration conditions are not significantly larger. When considering a flow velocity in Apapa channel near the bed, which regularly exceeds 0.5 m/s for sustained periods of time, fine sediment will not be deposited on the bed but remain in suspension over large distances. The flow velocity in Badagry creek is smaller and as the top layer of the bed is composed of

soft material, the fine sediments may move as a fluid layer. To confirm this theory, more research is needed in Badagry creek.

6.1.1.3 Density currents

During the 2010 measurement campaign, density currents were observed in Commodore and Badagry channel. In these channel, there is strong stratification of brackish water near the surface and salty water near the bed. During the turning of the tide towards flood, large turbidity values and significant flow velocities were measured. This results in a net flood transport in the layer close to the bed and will likely consist of sandy material from the ocean.

In Apapa channel, such a layer was not encountered as the turning of the flow direction occurs simultaneously over the entire water depth. This is supported by the salinity profiles which show no stratification in salinity. Although the salinity does vary with time, it is near constant in the entire channel as the water from the Lagoon is mixed thoroughly when passing the bridge foundations between the Lagoon and Apapa.

Badagry creek does show stratification of salinity and currents although the net discharge is much stronger compared to the effect of the density current and little upstream transport is measured near the bed. It seems clear that, at least during the rainy season with large fresh water discharges, there is net transport towards Commodore channel.

6.1.1.4 Import or export of sediments into/out of the system?

With the data currently available, it is not possible to conclude whether there is import of sediment to the system. It seems that more sediment is leaving the system than enters through the mouth at Commodore channel. For Apapa channel holds that stronger current speeds are measured during ebb as well as higher concentrations of suspended sediment. This would indicate export of sediment from the Lagoon towards other parts of the system. Whether the Lagoon is accumulating sediment or gets deeper depends on the supply by the various small rivers discharging in the Lagoon.

A conclusion on the upstream boundary of Badagry creek is equally hard to draw, large volumes of sediment seem to leave Badagry creek via Commodore channel towards the ocean but the supply at the upstream side might be even more. As dredging operations are constantly required and a thick layer of soft material seems to build up at the end of the maintained area, this is a serious option.

Nevertheless, transport of sediment from the Lagoon towards the deeper channels is certainly possible but not very likely. If material erodes from the Lagoon it will remain suspended due to the low settling velocity of the clay. This way, the sediment will never be deposited and poses no problem to the channels navigation depth.

6.2 Discussion & interpretation of measurements

6.2.1 Soft layer thickness

The results from the dual frequency echo sounder indicates a layer of soft material is generally present throughout Lagos harbour. The thickness varies locally from 0 to 1.2 meters and is 30 cm thick Commodore and Apapa channel.

In the maintained part of Badagry creek, the thickness was smaller, probably due to the dredging operations. Near the banks and side channels of Badagry creek, soft clayey material was found abundantly. Based on the results from the echo sounding and sampled material it is likely that the top layer of the bed observed by the echo sounder represents a layer of fine material.

In Commodore and Apapa channel however, no fine material was collected from the bed. Detailed bathymetric charts reveal a bed with features like sand dunes, scour holes and steep slopes. Large volumes of soft material are not to be expected as such a layer will not form these features. As the soil samples and bedforms both clearly indicate a sandy bed, the layer measured by the echo sounder must be different to the material in the soft layer in Badagry creek or non-existing at all. As it is almost certain that the top bed of Commodore and Apapa channel mainly consists of sandy materials and will not show different reflections to the sub layers, it is therefore assumed the measurements in this section of Lagos Harbour are incorrect.

The latter is not unlikely as the returned signal of the echo sounder is very unclear to interpret if the bed is very irregular. This is certainly the case when surveying the sand dunes. The result would have been better if a core sample of the bed was taken in each area to check the difference in material in both the soft top layer and the subsoil and provides a calibration for the measured thickness.

6.2.2 OBS turbidity data

The data acquired by the OBS sensors are of questionable reliability. There seemed to be one sensor to provide inaccurate results (0.25m above the bed), and others show hard to explain behaviour from time to time. The sensor closest to the bed may have been positioned in the scour hole caused by the pillars nearby and may have been under the 'action'. Although there is often a reasonable explanation for many of the anomalies, the question remains whether the data is representative for the study area. When the objects near the OBS location are the cause of the unexpected results, it cannot be assumed that the measured concentrations are an accurate representation of the real concentration in other parts of commodore channel. Single or short periods of extreme values (high and near zero) may have been caused by passing rubble which is not uncommon in Lagos.

When compared to the 2011 data, many of the anomalies found in the 2010 data set returned. This means that the measured values are describing real physical processes or a flaw of the (identical) OBS devices. Either way, there is no reason not to trust the data collected by the sensors. It would have been better if the sensors could be placed out of the area of influence of e.g. pillars or wrecks. By installing the

sensor on a frame and placing it in the channel, disturbances may be avoided (Figure 6-1).

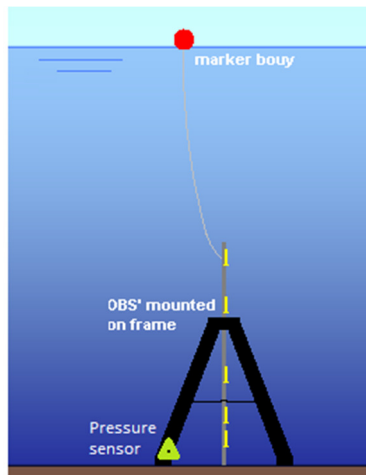


Figure 6-1 Improved OBS setup

Using a setup like the above figure, it is also interesting to mount an ADCP to monitor the flow without the restriction of only being able to survey during day hours.

ADCP data using a survey vessel only covers part of the tidal cycle and as the day to day shift in phase is limited; all the ADCP results from this campaign are measured in the same tidal phase.

6.2.3 Applicability of ADCP results

The flow direction and velocity data provided by the ADCP are consistent and fairly reliable. However, due to improper water sampling capabilities, the ADCP results concerning sediment concentrations are poorly calibrated. Although the measured concentrations display reasonable figures and show the expected behaviour of the system fairly well, it is not reliable enough to draw any quantitative conclusion on. It is the different sensitivity on varying sediment sizes that make the ADCP very susceptible to even minor changes of the conditions. Based on other sources of information, it has become clear that the main channels: Commodore, Apapa and Badagry are substantially different environments. Differences in the suspended material and salinity/density profiles are to name a few. The ADCP hardly responds to very fine particles and this effect should be compensated by correcting the measured concentrations.

The quantity of the data was disappointing as well. Many surveyed cross-sections turned out to be useless due to a high bad data percentage. It is believed the waves and strong currents played a role as the stability of the survey vessel seemed to correlate with the number of missing data points. If there was more time to redo the measurements of particularly bad surveys this problem could be dealt with. But as the time schedule already was pressing beyond its limit, each incomplete survey line sailed stretched the data coverage of the system even thinner. Apapa channel seemed to suffer most of the survey limitations as only on day of data was useful.

ADCP results ideally need regular calibration for each location and phase of the tide as the sediment characteristics may change significantly. Only a few hydrographical survey companies have sufficient experience and the proper calibration methods to accurately measure suspended sediment concentrations. It has become clear that to this properly, a lot of survey time should be invested in the calibration procedure. The equipment, training and recourses were not available during the 2010 campaign to do so. Classifying the ADCP sediment concentration data as worthless might be a bit exaggerated, but it is safe to say that to use an ADCP for SSC data acquisition has been a bad decision given the circumstances. There was certainly not enough time to survey the three cross-sections as they were carried out and to do the extensive calibration process as well. And there is to consider the lack of a laboratory to do the calibration test in as well. The velocity and directions of the flow is on the other hand of decent quality.

6.2.4 Seasonal influence

Strong seasonal variations are expected as the discharge of rain run-off may play an important role in the hydrodynamic behaviour of the system. Not only does the ebb flow depend on the volume of fresh water to be discharged, the density driven transport of sediments near the bed is dependent on the stratification of salinity.

In Apapa channel, the salinity and thus density is nearly uniform over the whole depth, except the top one or two meter. A significant difference in the turning point of the tidal flow between the layer close to the bed and the water above has not been measured. It gives in an insight on how the hydrodynamic behaviour will be in the dry season for Commodore and Badagry creek. As the tidal currents during flood nearly equals that of ebb, little net transport is to be expected during the dry season in either direction. This should be confirmed by similar measurements covering the dry season.

6.3 Recommendations

The collected data is shown to be insufficient in quality and quantity to fully explain the behaviour of Lagos Harbour system. In order to better understand the mechanisms responsible for morphological changes in the system, more research is needed. This section elaborates on the need for future studies to confirm the hypothesis and observations presented in this thesis.

6.3.1 Improved study

This study has revealed some of Lagos Harbour system's characteristics but there's still much to discover and to verify. The first and main recommendation is therefore to redo the 2010 measuring campaign in both seasons and much more thoroughly. The mayor drawback on this study is the lack of sufficient, reliable data. Also, more effort if needed to gather enough data of various parts of the tidal system, preferably with multiple survey units. As for the 2010 campaign, one survey vessel was available for three very distinct study areas (the main channels).

The ADCP is still a useful tool for measuring discharges and flow velocities. Although more difficult to install, and ADCP may be mounted on a frame below water and monitor the current velocity for extended periods of time. This is particularly useful for modelling the various channels of the system when using more ADCP set-ups as flow velocities are known of all channels simultaneously. The added costs of multiple ADCP set-ups can be too high however.

Additional sampling in the whole system is highly recommended as a large variety of sediments were found. Especially the material in Badagry creek where a layer of soft material of up to 50 cm in thickness is expected.

6.3.2 Alternative Dredging method

The current method for maintaining the desired channel depth is by TSHD dredging and mostly takes place near the quays of Badagry creek. There, the dredging tracks are visible in the soft layer thickness profiles of the creek. TSHD is therefore proven to be effective but not very efficient as the dredged volumes greatly exceed the dredged dry mass. The density of the slurry in the hopper's hold is very low and the vessel is literary carrying water to the sea.

When a hopper pumps the dredged material into the hold, the heavier particles should settle and the excess water flow overboard. As the concentration of sediment in the hold increases via dredging, the amount of sediment lost due to overflow losses increases as well. As the overflow losses over a period of time equal the amount dredged in that period, the hopper is at its practical capacity and will sail to a dump location.

The settling velocity of the material found at Badagry creek in the top layer of the bed is very low so the dredged material will hardly settle. It shouldn't take long before the density of the hold equal the density of the dredged mixture and overflow

losses are substantial. This results in a low practical capacity and many trips to the dumping location.

A more promising method of keeping Badagry creek deep enough for shipping is to use water injection dredgers. These types of dredgers are much cheaper to operate and do not require to sail back and forth to the dump site. The dredge head may be very similar to that of a TSHD, but is optimised to bring as much sediment in suspension without pumping the material into a ship' hold. Instead, this method relies on the ebb flow to transport the suspended sediment out to sea. This method works particularly well with fine sediments as they are easily eroded and stay in suspension long enough to be transported over great distances. As no fine material is found in Apapa and Commodore channel, it is very well possible that when water injection is used during ebb flow, it will remain in suspension and eventually be carried out to sea.

The possibility of suspended material to be transported to and settle in the Lagoon instead should be investigating before attempting such dredging strategy. A method of testing whether this poses a serious problem to the Lagoon, a particle tracking test could be carried. Alternatively the suspended sediment plume could be mapped by ADCP SSC measurements.

For maintenance on the Commodore and Apapa navigation channels, the TSHDs currently in use suffice as it mainly concerns coarse sand. If the siltation problem of Badagry creek is solved using different dredging equipment, these TSHDs should have no problem maintaining Apapa and Commodore channel.

An alternative may be found in the use of a sediment by-pass transporting sediment from the west-side of the west-mole past the east-mole. This method requires only the construction of a pipe across Commodore channel and a dredge-pump station on the west-mole. As sediments from the west are transported past the entrance to Lagos Harbour, less material will be imported during flood periods and will have a positive effect on shoreline erosion east of Lagos.

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