Solutions to the sedimentation and maintenance of semi-enclosed channels

“How to Deal with Sedimentations in Dubai Canal?”

Hussain Hassan Khansaheb

A thesis submitted in partial fulfilment of the requirements of Liverpool John Moores University for the degree of Doctor of Philosophy

May 2024

Content

Appendices

Appendix 1:

A - Offshore Waves
B - Model Set-up: MIKE 21 SW - Model set-up used for wave transformation
C - Model set-up: MIKE 21 BW - Model set-up used for wave disturbance simulations
D - Model set-up: MIKE 21 HD/ST FM - Model setup-up used for canal stability assessment
E - Model set-up: LittoralProcessesFM - Model set-up used for beach stability analysis
F - Beach Plan form Model: Q-α Curves

Appendix 2:

A – Dubai Municipality Bathymetric Data
B – Dubai Municipality Tide Data

Abstract

Dubai Canal, a cornerstone of the city's infrastructure and tourism, is facing a pressing challenge of sedimentation. As the canal plays a vital role in navigation and tourism, addressing the sedimentation problem becomes crucial to ensure its continued significance and operational efficiency. The project aims to study the build-up of sediment in semi-enclosed channels linked to tidal basins and develop solutions to maintenance schemes. The objective was to develop a numerical modeling methodology to predict future sedimentation behaviors and occurrences in Dubai Canal taking in consideration the effects of currents on coastlines. Accordingly, develop mitigation strategies and propose sustainable maintenance schemes to reduce the impacts of sedimentations. The method of investigation was initiated by data collection and sourcing to be used for modelling and validation. Hence, MIKE 3 software was used for modelling the sedimentation occurrences in Dubai Canal based on the numerical solution of the three-dimensional incompressible Reynolds averaged Navier-Stokes equations to calculate both Bed Load Transport & Suspended Load Transport to predict the sediment behaviour in the canal. Based on the model’s findings identifying potential sedimentation in three different locations in Dubai Canal, the project’s outcome was to propose a comprehensive mitigation strategy is proposed, encompassing design changes like tidal flaps, gates, a pumping system, and fountains. Feasibility studies and modeling will validate these alterations. A preventive scheme, featuring real-time monitoring and regular surveys, ensures sustained canal functionality. In addition, future policy recommendations were driven, emphasizing a balance between technical feasibility and financial considerations to preserve Dubai Canal's significance amid evolving sedimentation challenges. The project undertakes a novel approach by using numerical modelling for the first time to solve the sedimentation problem in a man-made marine canal in the Gulf Region, identifying the problem causes and exploring sustainable and efficient maintenance and dredging methods that will result in improving the marine environment and ecotourism, and which are cost efficient.

1 Introduction

1.1 Background

During the past decade, Dubai has created several man-made coastal structures such as The Palm Islands and The World Islands, alongside the continuous reclamation of beaches and extension of ports. The need to enhance the coastline of Dubai as well as the desire to have state-of-the-art beaches and coastal developments was essential to maintain the growth of the city and boost tourism in Dubai. This led the city to invest in its coast taking into consideration the environmental need to maintain a healthy and pollution free environment for marine life and biodiversity.

Dubai is to be considered as one of the leading players in the marine development sector. Yet many challenges are currently facing Dubai's coastal projects as all had witnessed the continuous effect of unexpected build-up of sediment which affects the navigational channels, and results in the need for expensive ongoing maintenance. This project answers the main research question: "How could Dubai prevent and mitigate sedimentation problems within its man-made projects?"

The project was conducted from a numerical modelling perspective, not considering conducting field experiments or onsite surveys to obtain readings and results. The objective was to identify likely impacts due to sedimentation and provide preventative solutions that will either stop sedimentation occurrences or enable the use of planned maintenance methods and techniques. Planned maintenance normally being significantly less costly than remedial work to correct a problem. It is essential to understand the root cause of the sedimentation to drive a mitigation plan that could support the Dubai authorities and developers to perform the most feasible and convenient way to tackle this problem.

In this project, a literature survey was conducted to get an overview of the nature of sedimentation in water bodies in general and, in particular, man-made semi-closed channels. It investigated the water bodies' design elements and the natural characteristics of the area; also it explored approaches on how to mitigate the effects of sedimentation as well as maintenance reduction schemes. The literature survey showcased a variety of applications using numerical modelling to identify the impact of sedimentation and sand transfer, most were for natural water bodies. The applications concluded different approaches dealing with the modelling results including recommended mitigation and maintenance techniques. However, there is little evidence that these techniques have been considered or applied in the Gulf region and the coastlines of the UAE, especially for man-made harbours and channels.

This project studies the build-up of sediments in semi-enclosed channels linked to tidal basins in Dubai. Although the sedimentation problem is faced in several locations, the project uses, as a test case, a single man-made structure, the Dubai Water Canal. The Dubai Water Canal is the biggest and most recent man-made coastal structure in Dubai (completed November 2016). The canal is a 14 km long excavated channel which connects the natural Dubai Creek to the open sea. It has been projected that sedimentation will occur in the outlets and along the canal for the following reasons:

1) Tidal Force: Because the channel inlets are narrow compared to the open sea, tidal force is expected to create high speed currents which motivates sand transportation and sediment build-up in the inlets of the canal.
2) Channel Geometry: Variations in width along the channel can create internal currents which will cause erosion to some sections and sediment build-up in others.
3) Sediment Characteristics: Canal bed particles are likely not to be stable as they have undergone recent dredging and excavation processes.

A numerical model was developed that was used to study the hydrodynamics and sediment transport in the Dubai region using data from existing projects. The model was used to predict the build-up of sediment and to develop strategies to reduce sedimentation and maintenance. After validation, the model was capable of: (1) predicting sediment behaviours; (2) predicting the effects of currents (tidal and rotational) on the coastline and harbour/canal entrance; (3) assisting in the design of effective methods to manage the build-up of sediment and reduce or eliminate the need for dredging maintenance; and (4) assessing the impact of wave-induced coastal boundary currents resulting from seiche waves and storm surges on sedimentation patterns. Finally, the model outcomes were analysed and a government policy recommendation was suggested to mitigate and maintain the effects of sedimentation on the channel's hydrodynamic as well as the ongoing navigation activities taking place.

This project undertakes a novel approach by using numerical modelling for the first time to solve the sedimentation problem in a man-made marine canal in the Gulf Region, identifying the problem causes and exploring sustainable and efficient maintenance and dredging methods that will result in improving the marine environment and ecotourism, and which are cost efficient.

1.2 Research aims and objectives

Sedimentation occurrences and sand transfers cause disturbance to navigation channels (Sánchez and Wu 2011). The disturbance is more likely to occur in man-made water bodies due to the time required for sand beds to reach an equilibrium phase (Vilenica, et al. 2020).The impact had been witnessed many times in various water bodies in Dubai such as Palm Jumeira as well as The World Islands. Both projects are reclaimed lands including navigation channels surrounding the land areas for the purpose of transportation (Engineering 2014). Therefore, the aim of this project is to tackle the problem of sedimentation occurrences in open water channels (Dubai Canal) effecting the navigation routes, maritime activities, and tourism attractions in the canal with the most efficient cost and duration considering the following objectives:

- The model will be used to predict the build-up of sediment and identify likely impacts of sedimentation in the man-made projects in Dubai.
- To study the build-up of sediments in semi-enclosed channels linked to tidal basins to develop solutions which will eliminate or reduce the dredging maintenance required due to sedimentations.

1.3 Research contribution

The Dubai Canal is man-made; the canal was designed and constructed to enhance the circulation of water in Dubai Creek by the means of increased water flow in the canal. The canal is open directly to the sea which allows the tidal currents to drive the circulation process twice a day. Therefore, sediment transfer will occur within the flow process. As the canal is man-made, the bed and surrounding area is not yet stable and in equilibrium phase. This is due to the dredging and excavation that took place during construction. Hence, it is certain that sediments are not stable and will transfer along the canal. The canal functions as a navigational route to both leisure and public transportation vessels with a designed seabed of 5m only during low tide period. Therefore, any decrease in depth that might occur due to sedimentation will negatively impact the navigation route and cause vessels to get stuck on sand bumps.

This research project is the first investigation into the mitigation of sedimentation in a man-made water body (the Dubai Canal) in the Arabian Gulf region using numerical modelling to predict sedimentation occurrence and behaviour. Eventually, the canal will require continuous maintenance. However, the lack of research on the build-up of sedimentation has hindered the development of a formal strategy to mitigate it. This work will contribute to developing an effective maintenance strategy to reduce the cost of work and minimize the impact on marine traffic. The literature review confirmed the lack of previous work in applying numerical modelling to the study of sediment transfer in the Gulf Region. Differences in the characteristics of the region in terms of sedimentation, geometric parameters, temperature etc. prevent the direct application of existing studies from other regions. This research project benefits from the availability of accurate historical data collected over the last 15 years. The literature review confirms that based on this data set it will be possible to develop and validate a new numerical model for the region. An accurate model will make it possible for the first time to identify the causes of sedimentation problems and explore sustainable and efficient maintenance methods which will improve the marine environment, ecotourism, and cost efficiency.

1.4 Structure of the thesis

The literature review investigated sedimentation behaviour in coastal zones and around existing man-made marine bodies and structures such as islands, harbours and canals. It explores sedimentation behaviour i.e., the relationship between fluctuations of suspended sediment concentration, and turbulent sediment fluxes in open channel flow. The review concentrated on the application of experimental approaches with specially designed field experiments. It investigated various cases where numerical modelling was used to study sedimentation problems. It reviewed cases where numerical modelling was used in predicting the causes of sedimentation and resulted in mitigation plans, which reduced further maintenance. But there are no examples of where numerical methods have been applied to design entrance flow optimization systems (EFOS) to resolve problems of sediment ingress in harbours and basins. It is clear from previous work that Barenblatt's Theory of Sedimentation Laden flows gives a good approximation of experimental data. A wide range of numerical models capable of predicting water flows, sediment transfer, wave and tidal effects have been used in previous work including MIKE 3, Delft3D, SWAN and BOUSS-2D. Comparing between the models it has been concluded that MIKE 3 is the best fit to be used for this project. The MIKE 3 model has found extensive application in diverse areas, including oceans, coastal regions, estuaries, and lakes. It employs the incompressible Reynolds-averaged Navier–Stokes equations and incorporates the Boussinesq approximation and hydrostatic assumption (Yao et al. 2022). In addition, it is the software used by Dubai Municipality to model most of Dubai's coastlines.

2 Literature Review

2.1 Background

The importance of open channels reflects their multipurpose usage whether in navigation, development or economy. They also have a high environmental impact on the whole marine ecosystem (Walter R. Hill 1995). Sedimentation is an important factor affecting both natural and man-made open channels. From a hydraulic engineering perspective, discharges in and from the channel create movement of the channel's bed particles. Accordingly, the roughness may increase or decrease depending on the type of sediments occurring allowing a significant change in flow rates to take place in the channel. The stability of the bed will be affected especially in man-made channels which have not reached their equilibrium phase. Therefore, the amount and rate of sedimentation is the main factor determining the maintenance required for the channels to remain functional and especially if they are used for navigation. In many cases the type of sediment movement is the main cause of marine pollution: sediments may be contaminated with pollutants or particles unsafe to the new marine zone which the channel is connected to (Partheniades 2009). This literature review will consider sedimentation in open channels in detail and review mitigation methods, and numerical modelling to tackle sedimentation issues. Finally, a justification will be drawn to why this project was conducted and what are the main outcomes expected from tackling the problem.

2.2 Sedimentation

2.2.1 Sediment properties

The rapid development that has occurred in the Arabian Gulf region in the last twenty years, especially in the United Arab Emirates (UAE), has placed a heavy burden on coastal areas and negatively impacted coastal habitats. The high quantity of oil and other organic compounds in marine sediments is a result of the petroleum companies' presence in certain coastal areas. The Dubai coastal zone has undergone a number of developments in recent years pertaining to trade, fishing, and tourism, all of which have had an effect on the water and sediment quality (Darwish et al. 2005). The interaction of both marine and terrestrial processes results in the textural and compositional characteristics of sediments. The length and scope of these processes influence the major features of sedimentary deposits in part (Howari and El-Saiy 2008). Located in the United Arab Emirates on the southeast coast of the Arabian Gulf, Dubai is one of a chain of barrier islands. There is a lot of carbonate sedimentation in the Arabian Gulf, and most of the deposits on the seafloor and along the UAE's coastline are Pleistocene or Holocene in age. The Gulf's recent geological history, structural configuration, coastal orientation, and the dominant northwest Shamal winds all have an impact on the kind and distribution of sediments (Epps 2011).

The sediments found in the lagoonal channels are characterized as predominantly grey speckled sands, exhibiting varying quantities of coarse gravel-sized debris, lithoclasts of Miliolite Sandstone, and fragments of weakly cemented younger rock or sediment. Along the inner edge of the lagoons, the channel sediments consist of a blend of carbonate sand and carbonate mud. The sand fraction is comprised of skeletal debris, ooids (with higher abundance toward the tidal deltas), faecal pellets, and composite grains (Epps 2011).

Waves are the main force driving the natural sediment drift along the Dubai shoreline, which results in a net shift from southwest to northeast. Dubai's tides follow a semi-quadrupole pattern, ranging from 0.7 meters in neap tides to 1.8 meters in spring tides. With their 0.2 to 0.3 m/s pace, coastal tidal currents have little effect on the flow of sediment down the beach. As noted by Smit et al. (2008), wind-generated waves are the main cause of sediment movement instead. Dubai's wave climate is typified by calm spells punctuated by ferocious waves, especially during "shamal" festivals (Cavalcante et al. 2011).

2.2.2 Causes of sedimentation

The effects of human activity on soil erosion date back three millennia, and they corresponded with the expansion of the human population in select river basins. Around 1000 years ago, these impacts became more widespread and accelerated. Soil disturbance had grown widely by the sixteenth century when contemporary nations began implementing environmental engineering.

A global increase in sediment discharge in most major rivers was caused by a spike in mechanization that occurred in the early twentieth century and was associated with operations like mining, terracing, deforestation, and Earth removal. But by the 1950s, the widespread building of dams had reversed this pattern for many major rivers. Some deltas saw a change starting in the 1930s when subsidence outpaced sedimentation and took the lead as a signal for relative sea level. In many instances, the influence of global warming on the total rise in sea level has been surpassed by this trend. When taken as a whole, these effects of human activity have significantly changed the way that sediment and water travel across continents and eventually end up in the sea. Hyperpycnal flow events have increased in frequency for some rivers and decreased in frequency for others (Syvitski and Kettner 2011).

By accelerating erosion and intercepting sediment along hydrological channels, sometimes simultaneously and sometimes sequentially, humans have had two distinct effects on the landscape. The main processes that increase the amount of silt in a river include mining, deforestation, conversion of pastureland to crops, inappropriate farming practices, and road building. When low relief and widespread urbanization are present, land use becomes the primary factor affecting particle fluxes (Wasson 1996). Sediment yields in low-relief locations could be increased by more than ten times by clearing land. Roughly 75% of the elevated sediment yields found in Mediterranean headwater basins are caused by human activity. An annual volume of sediment carried by direct human activity is estimated to be around 15±0.5 billion metric tons, which is similar to the fluvial sediment load released into the world's coastline ocean. The basis for this estimate is the scaling up of particular technical projects for which thorough data are accessible (Syvitski and Kettner 2011).

2.2.3 Hydrodynamics

As a natural behaviour in open water channels, the opening known as the “inlet cross-section” will be in continuous changing phase until it reaches the equilibrium status. Depending on sediment type and characteristics entering the channel, the inlet will evolve to the suitable format to accommodate the status quo. However, man-made inlets behave differently. The geometry of the inlet canal is important for the sedimentation at the entrance and for navigational safety (Raiverman, Kunte and Mukherjea 1984). Additionally, the tidal flow in an inlet channel will be along the channel, hence, type of sediments, bathymetry of surrounding area and strength of local currents are other sedimentation influencing parameters. Local bathymetry and incoming waves will cause shoaling around channel entrance. Shoaling will stir the sand and create a sand-water mix. The strength of local current and type of sediments such as grain size and type will govern the critical velocity to move the sediments. The magnitude of tidal variation and extent of the creek are other parameters that govern the flow velocities at the inlet canal. The sediment will be eroded if the flow velocity increases beyond the critical shear stress, which will lead erosion in the banks. If the banks are protected or deep enough with large cross-sections, erosion may be prevented. The sediment will settle if the velocity falls below the critical shear stress, which leads to deposition of the sediments in the inlet canals, consequently decreasing the cross-section, and increasing the flow velocities. This process yields a dynamic equilibrium cross-section that is common to every inlet subject to ocean dynamics (D.S. van Maren 2013)(Ali, Zeeshan and Subhasish Dey 2016)

2.2.4 Flushing and discharge

The rate at which the net flow within open channels exchanges with the open sea directly affects the flushing time of the system. Flushing of a particular water body is often used as an indicator of water quality. It is well known that if a particular volume of water does not exchange with an external source of high-quality water, the resulting stagnating water may become degraded in terms of clarity, colour and odour. It is difficult to identify criteria for an acceptable flushing time of an open channel, or a consistent definition of what constitutes a flushed system. Therefore, most channels would require an individual study of their flushing scheme to identify the minimum flushing rate adequate to maintain the required water quality within the channel. Based on the flushing occurring in open channels, the incoming sediments are most likely to cause sedimentation in the channel beds. Yet, if the channel requires additional improvement to facilitate the flushing rate to improve the water quality, further sedimentation is most likely to occur within variant perimeters of the channel, based on the erosion occurring during flushing as well as settlements of sediments along the way of the channel (Shen 1999).

2.2.5 Sand Transport and erosion

Sand transportation in open water channels is directly affected by the channel's water flow and wave conditions. During outflow, current speeds and flow rate are considered as a concentrated water jet exiting the channel to the main water body. While during inflow, the velocity of the current varies depending on the depth of channel. Depth-averaged flow statistics for the tidal flow are generated from the flow field which includes only typical wind driven and tidal driven currents. Water flow varies according to its direction in the channel causing an asymmetric behaviour in the location of the flow. Outlet flows are more likely to have the characteristic of the lower magnitude of the main water body. While inlet flow will be more of high-speed currents especially during extreme events, where the depth-integrated flow speed may increase.

The presence of waves will increase the near-bed velocities due to the orbital motion they impose. However, the flow statistics are normally generated from the flow field which includes only typical wind driven and tidal driven currents (Haiyan Li 2013).

Wave conditions in open channels determining sand transportation are represented by 8 wave fields with a probability of exceeding 12 hours per year, considering various percentages of the wave heights including: 1, 5, 10, 20, 30 and 50 percent. Such waves enable the sediments to form and move along the channel which ultimately causes the sand transportation of the channel (Ole Secher Madsen 1976). Regarding the depth relation with sand transport in open channels, the gross transport decreases when water depth increase sand flow velocities decrease. The increase in net transport relative to the gross transport is caused by a change in the shape of the current profile at the outer cross-sections. Accordingly, the sand transport rates will determine the sediment budget accumulating in the seabed of the channel.

2.2.6 Sediment dispersal by delta plumes

The main stem's discharge is divided in part by distributary canals, which increases the hydraulic radius that river water can flow through. This lowers the effluent's velocity in distributary channels relative to the main stem flow, which lessens the effluent's inertial capacity to move sediment away from the coast. More suspended silt is maintained close to these river mouths as a result of the decreased velocity affecting the seaward-flowing plumes at distributary mouths. A more extensive dispersion of the fluvial-suspended load has resulted from human intervention's reduction of the number of distributary channels. Dam activities, however, have lessened the size of seasonal flood waves, which has limited the amount of river material that can disperse. More material avoids the delta and enters the coastal ocean when there is a decrease in sediment retention on deltas, which indicates lower rates of aggradation. When considering this from the perspective of the coastal ocean, it could make up for the reduced amount of material transported to the delta as a result of the silt being sequestered upstream in reservoirs. At the very least, the effects of human activity on the distribution of sediments are complex (Hetland and Hsu 2013).

Due to the substantial density barrier that prevents freshwater entry into the coastal ocean, most rivers transport their sediment load through momentum-driven surface plumes (hypopycnal). The characteristics of a river plume and its sedimentation are influenced by factors like the discharge magnitude, the rate of particle flocculation, floc settling velocities, ambient currents, and the density structure, which includes bottom boundary-layer dynamics. The critical concentration of suspended sediment required to generate a hyperpycnal plume in seawater is 35–45 kg m−3 or possibly higher. Rivers that are able to carry the necessary sediment concentration for hyperpycnal activity are usually smaller mountainous rivers that discharge directly into the ocean without an intervening floodplain.

In contrast to surface plumes, hyperpycnal flows hug the seafloor; bathymetry and ambient bottom currents affected by coastal upwelling or downwelling are key factors in determining the flow pattern. Compared to the riverbed, the bathymetry of shelves frequently offers a greater gradient, and as a hyperpycnal current descends into the coastal ocean, it is usual for it to accelerate and become erosive. On the other hand, coastal winds, ambient surface currents, river momentum, and buoyancy have a greater influence on surface plumes. The process by which hypopycnal versus hyperpycnal plumes disperse will determine the differences in the offshore sedimentary record (Bentley 2003).

Humans have altered these mechanisms of sediment dispersal in contrasting ways:

- elevated suspended-sediment concentrations to such an extent that hyperpycnal currents are generated and
- reduced a river's sediment concentration so as to reduce or eliminate its ability to produce a hyperpycnal current.

2.2.7 Controlling Sedimentation

The nature of open water channels such as rivers and canals allow the flow to occur in various ways and forms. Depending on the flow characteristics, erosion within water body edges will occur. The eroded particles consisting of rocks, sand and other natural material will then be transported along the flow until they are settled somewhere as sediments in the water body beds. Sedimentation in open water channels is a dynamic characteristic. Its negative impact will be clearly noticed in water bodies with human interference such as rivers and canals within cities. However, sedimentation could be controlled using various tools such as sediment budget; a tool that helps to understand the behaviour of the water bodies and looks deeply into what is likely to occur underwater. Some of the benefits of drawing-up a sediment budget to control sedimentation could be considered as having in place a full set of relevant and organised data, identifying morphological problems and finding solutions to problems likely to occur, besides optimising maintenance required that includes dredging and excavation. Moreover, sediment budget aims to assess the impact of human interference and provides an effective management plan to any named water body (Frings and Brinke 2018).

2.2.8 Mitigation Strategies

Controlling sedimentation is not a process or an action that can be implemented easily in any open water channel. The characteristics of sediments and the dynamics of sediment behaviour vary from one water body to another. The impact of sedimentation may vary in different locations of a channel due to the shape, size, and geometry difference within it. Hence, it is essential to consider placing effective and adequate mitigation strategies to maximise the controlling procedure of sedimentation.

In general, the mitigation strategies will combine both design change applications as well as conducting a preventive maintenance scheme measures as following:

1) **Design changes:**

The objective of applying a design change is to enhance the water flow in the open channel to minimize the likelihood of sediment occurrence. This could be achieved by:

- Introducing flow enhancement tools such tidal flaps and tidal gates.
- Adding on pumping system or fountains to facilitate water movement locations where sediments are likely to occur.

2) **Preventative scheme**

Although design changes will result in reducing sedimentation in open channels, it is likely that sediments will yet occur. therefore, a preventive maintenance scheme will be essential as following:

- Apply a real-time monitoring system to the bed-level changes.
- Scheduled underwater surface levelling activities to proact on immediate sediment occurrences.

To identify the most suitable mitigation strategy it is necessary to gather data on the sediment characteristics and behaviour in the waterbody. Obtaining relevant information will conclude the full understanding of the negative impact likely to occur and the cost of such occurrence. Therefore, by building up a complete database of the canal’s behaviour, sediment characteristics and hydrodynamic features in the water body, it will be possible to predict, monitor and control sedimentation during the planning, operation and maintaining phases.

The second element to be considered in placing mitigation strategies is to completely understand the problem and its impact. By identifying the problem, it will be possible to set a course of action to tackle the impacts considering cost, time and quality of service expected from the waterbody. In the case of a navigable water channel, the cost does not lie only in maintenance fees as other costs are taken into consideration such as stopping of vessels' operations as well as the disturbance of maritime public transportation routes within the canals.

Finally, it is vital that mitigation strategies consider a monitoring process and a follow up scheme. This phase could be conducted in collaboration with academic facilities and research centres. Dynamic changes are likely to occur in structures exposed to nature, therefore, initial studies may not be as relevant in time (National Research Council 1987).

2.2.9 Maintaining Sedimentation

It is a common practice to mobilise a dredger for maintenance work in open water channels causing blockage and disturbance to all navigation routes. Alternatively, barges carrying long boom excavators could be shipped to certain location in the canal for maintenance works required. Similarly, navigation is most likely to be held upon completion of required works. Hence, it was essential for alternative solutions to be considered for the sake of reducing maintenance cost and effect.

Part of the alternative solution is to conduct preventive maintenance with low impact equipment based on a pre-set schedule. Another part is to implement advanced maintenance scheme using modern techniques and innovative approaches with low-cost impact (National Research Council 1987).

2.2.10 Dredging

Dredging is the conventional way to tackle sedimentation and maintain bed levels of water bodies. It is common to witness dredging activities taking place frequently in ports and dry docks as it is essential to assure the depth can accommodate large cargo vessels at all times. However, due to common dredging practice in maintaining water bodies bed levels, dredging became a widely used technique in maintaining open water channels such as canals and rivers even though dredging activities cause enormous disturbance in the functionality of the channels.

Although dredging is used as a maintenance tool to tackle excess sedimentation in the waterbody bed levels, further sediment particles and sand transfer is generated in the dredging process. The impact of the dredging process and behaviour of sediments post dredging is dependent on the dredging mode used and varies according to the dredger type. Mechanical dredger work is by excavation of the ground material and crushing the material prior to pumping it away. This type generates larger sediments with a heavier density like the bed particles. Hydraulic dredgers mix the excavated material with water before pumping it away and produce finer particles in silt format. Such product is exposed to extensive sand transfer and may cause sedimentation in various locations.

Besides the impact of sediment distribution and sand transfer post-dredging, there are many environmental considerations in the dredging process dependent on the type and location of the dredging process. Additionally, disposing of the dredged material negatively impacts the environment considering the natural habitat available in the disposal area. (National Research Council 1987). The impact of dredging does not affect the exact dredged location only, as its effects extend to the surrounding areas in which natural habitats might exist. Therefore, the government entity responsible for environment and wildlife normally takes extreme precautionary measures for dredging and requires an extensive number of studies and environmental impact assessments before the dredging process takes place in open canals and rivers. Eventually, such processes add further complication to the procedure and require certain specialities to conduct.

Eventually, environmental considerations within the dredging process translate to additional cost to the maintenance procedure. Therefore, the cost-impact study should always be taken into consideration. Hence, the maintenance mode and method to be conducted should always take the hidden costs into consideration prior to taking the decision to conduct the maintenance required (National Research Council 1987).

2.2.11 Excavation

Excavation is the process of removing the accumulated earth material of sand, rocks, soil and dirt. In case of underwater excavation, a similar process is applied to remove the material accumulated in the waterbody bed for the purpose of creating a change in the depth. Marine excavation includes within its procedure the process of mapping and surveying the location prior excavation as well as identifying the expected behavior of the site after excavation is conducted (Alexander J. Gatch 2021).

Underwater excavation is executed by one of two methods. The first is where the intended area to be excavated is adjacent to the water edge. In this case, a long-boom excavator could be mobilised to the water edge. Hence, the reach of the excavator could easily conduct the excavation required. However, in most cases the excavation takes place within waterbodies away from the land. In such cases, the excavators are mobilised on a barge that transports the long-boom excavator to the intended location for excavation to take place. The barges used to carry out excavation operations are designed to accommodate the weight of barges, the weight of excavator, the weight of excavated material as well as the load generated from the excavator long reach. In some cases, a jack-up barge is used to form a better stable ground for excavation. A jack-up barge is a barge equipped with four long piles that act as a foundation to raise or lower the barge according to the tidal level besides providing the required stability (J. L.R. Manoj Kumara 2017).

However, underwater excavation will cause many implications in the waterbody and its bed level. As the excavation process takes place, the general bed level within the water body undergoes significant topographical change due to improper excavation procedures. Underwater excavation in open water channels will significantly cause reduction of water levels because of the inconsistency of changing the bed structure and layout. This will cause a gradual decrease in water depth in general and will eventually affect navigation with the channel (Shuai-shuai Zhang 2022). Another implication of underwater excavation is the change in the uplift force occurring to the bed within the waterbody. During the excavation process, the uplift deformation will be subjected to a gradual increase causing the disturbance of particles and sediments within the seabed that will be transformed and settled in various locations within the waterbody (Guoquan 2021).

2.2.12 Sediment retention in reservoirs

Retaining sediment in reservoirs is the main technique for reducing the amount of river sediment that is transferred to the shore. Large reservoirs often have entrapment efficiency of about 80%. With an average height of 31 meters and an average reservoir area of 23 square kilometers, there are more than 48,000 major dams in the world, which are classified as structures with a height greater than 15 meters. Furthermore, more than 2000 sizable dams are presently under construction.

Every reservoir has some effect on the movement of silt into the coastal region. In contrast to the early dams that were built in high areas mainly to produce hydroelectric power, contemporary reservoirs are typically located on floodplains. This location fulfills several needs, such as flood management, recreational use, and water diversion for irrigation needs. As the Indus River demonstrates, one effective way to reduce a river's silt burden is to reroute it into agricultural canals. Furthermore, it has been shown that strengthening riverbanks using materials like concrete and rafts reduces the amount of silt that is carried downstream (Liang et al. 2021).

2.2.13 Modern waterway management techniques

Waterway management systems have incorporated many enhanced maintenance techniques relying on advanced technologies with the aid of software, numerical modelling and computerised procedures that take place during maintenance.

Observation and monitoring schemes are widely used as precautionary measures to tackle incidents before they occur. Some waterways and rivers have installed advanced information systems using remote sensors, advanced underwater visual instruments, with underwater vibrators to help distribute sediment to lower the impact of accumulation on certain locations in the waterbed. (Lee, et al. 2021)

Other techniques have used piping systems laid on the bottom of the channels to pump water to facilitate sand transfer and direct it to areas and locations with minimal impact on the seabed level. Such techniques use GIS mapping systems to incorporate the piping layouts, and visual monitoring appliances aid the pumping operations (Kim and Moon 2017).

Further technologies are globally tested to determine their effectiveness. However, most are designed to accommodate certain cases with definite projected problems to impact the specific waterway. Moreover, it is suggested that academic institutions as well as research and development centres are encouraged to capitalise on advanced underwater maintenance technologies including three main criteria: Governance, Monitoring, and advanced maintenance technologies. These measures include (Lee, et al. 2021):

- Establishing a government supported technical procedure and a legal framework to determine the safety and impact of traditional underwater maintenance.
- Create a comprehensive database and information centre that will allow decision makers to analyse and assess the impact of maintenance conducted in waterways beds.
- Advance in monitoring schemes and measures to incorporate real time monitoring systems and apply real time data for analysis and decision-making processes.
- Advance technologies aiming to stabilise waterway beds and increase particle densities by eliminating erosions from the waterways edges hence resulting in reducing fine particles from transferring to settle as sediments.

2.3 Previous Work

2.3.1 Methods of modeling sediment transport in open water channels

The methods used to study sediment transport in open water channels vary based on the nature of the channel, the characteristics of water, sediments, and the geometry of the water body. Although, all studies share the same aim, to identify the problems caused by sedimentation, they vary by method, model, and the way results are demonstrated.

Some studies have used the two-fluid model (K.Jha and A.Bombardelli 2011). This estimates the total volume of sedimentation via two models. The first is the "Partial two-fluid model for uniform sediments (PTFMU)" (K.Jha and A.Bombardelli 2011) that works by considering the sediment particles as a single unit. The second is the "Partial two-fluid model for non-uniform sediments (PTFMNU)" that differentiates between sediments taking into consideration, sizes of the grades and their classes. The total velocities of every particle size and grade are considered as a main function in the modelling process. The two-fluid model approach couples both models for the consideration of drag force, water velocity and sediment concentration within a water sample (K.Jha and A.Bombardelli 2011).

In some cases, where the open channel is affected by an outlet discharged to the channel, a 3-dimensional model is used to provide a complete assessment of the channel behaviour and the impact of the outflow on sedimentation. 3-Dimensional numerical modelling works by validating the overall system in two cases: one considering the outfall, and the other without. This enables the model to quantitatively predict the increase of flow generated by the outfall. In addition, 3-dimensional modelling schemes enable prediction of the energy losses taking into consideration the discharged water into the channel, and the energy enabling sediment transfer and settlement (C.W.Li and C.Zeng 2009).

In cases when the problem involves curved channels, with various degrees and turns, two-dimensional models are used. 2-Dimensional models average the vertical components in the channel, while distributing the horizontal components linearly. However, this model is not applicable for all types of open water channels. Therefore, selection to use this model should be made carefully considering the significance of horizontal components in the study, for example strongly curved channels where flow is significantly increased in the curves and turns (Ghamry and Steffler 2010).

2.4 Review of applications of modelling

Many studies have investigated problems occurring as result of sedimentation in various specific water bodies worldwide, both natural and man-made. Some used numerical modelling to predict alternative behaviours within the water body such as water quality and water flow impacts on the water edges and erosion.

This section provides an overview of relevant studies in both natural and artificial water bodies that have been reviewed, highlighting their effectiveness in relation to the research topic. Most studies indicated lack of sedimentation modelling for waterways within the water bodies, lack of Mitigation plan driven from studies, in addition, maintenance scheme design was not driven from the studies to prevent sedimentation. The studies include:

1) Natural Water Bodies:
    - Eel River, Northern California
    - Dubai Coast
2) Artificial Water Bodies
    - Songdo City artificial urban canal, South Korea
    - Jabel Ali Port, Dubai
    - Palm Jumeira

2.4.1 Natural Water Bodies

Eel River, Northern California: Rivers are considered one of the most common water bodies where sediment can present a problem. This is due to the nature of water flow and the amount of erosion occurring in them. Therefore, many studies have been conducted on rivers to tackle such problems. For example, the Eel River in northern California undergoes frequent floods that result in severe sedimentation problems (Courtney K. Harris 2005). A study was undertaken using 3-dimensional numerical modelling to predict future occurrences of sedimentation in the riverbed. The model studied the flood impact in transferring fine sediments, thick mud layers, as well as the flood dispersals. The objective of the study was to compare the relevance of the predicted sedimentation and their impact on future floods. The model was used to evaluate the extend of sediment transportation during floods. The study calculated the sedimentation occurrence frequency and the factors enabling sedimentation to occur during flooding season. However, the study did not propose any mechanism to mitigate sedimentation nor to maintain it.

Dubai Coast: A number of studies tried to understand the dynamics of water systems in the region as a whole taking into account the interference in various water bodies in a specific region for example a study of the Dubai coast (Gunaratna and Gunaratna 2012). This work used a MIKE3 HD 3D hydrodynamic numerical model that included Dubai Creek, The Palm Islands projects as well as the World Island Project. The objectives were to forecast water levels (considering water quality, currents, flow rates, temperature, and salinity), and to predict the behaviour of wave patterns and tidal levels. The results obtained were used as guidance for the coastal defence system that included breakwater designs, beach design as well as the waterways of Dubai. However, this study did not include the prediction of sedimentation behaviour or the mitigation and maintenance strategies to overcome any problems foreseen by the results obtained from the model.

2.4.2 Artificial Water Bodies

Songdo City artificial urban canal, South Korea: Artificial man-made water bodies are commonly studied using numerical models because artificial bodies cause a significant change to the nature of the geography. Besides, no matter how detailed the designs were prior construction, the hydrodynamic effects within the man-made water bodies and their surroundings are unpredictable. Therefore, numerical models help to understand the behaviour using initial data obtained from the initial stage after completion. Similarly, to the Dubai Canal that is studied in this paper, Songdo City in South Korea built an artificial canal within the city for tourism purposes. The canal was filled with filtered sea water and has in operation a water circulating system to prevent contamination. However, due to the geometry of the canal as well as the extreme nutrients content from the sea water, the canal is exposed to water quality risks. Therefore, a study was conducted using MIKE 3 FM and ECO-lab to forecast the water quality behaviour in time, taking into consideration the existing water quality obtained from samples taken from the canal and concluded a gradual impact on the water quality over time. However, the model didn't tackle sedimentation nor suggest any mitigation or maintenance plan aside from the recommendation to alter the source of water used to fill in the canal (Ahn, Na and Park 2019).

Jabel Ali Port, Dubai: Ports are considered one of the best man-made water bodies to undergo numerical modelling studies to predict sedimentation. This is due to the nature of business and necessity to always have the required bed depth to accommodate large vessels and cargo ships. Jabel Ali Port in Dubai is considered one of the largest ports worldwide, hence it undergoes continuous studies conducted by reliable consultants to assure the suitability and effectiveness of operations in the ports. One of the studies was conducted during the design phase of the port's expansion back in 2004. The study's objective was to apply the numerical modelling method to predict the sedimentation occurrence within the port's basin. The study aimed to count for possible sedimentation occurrence and redesign the port to reduce sedimentation occurrence and minimize the dredging process in the port. By utilizing the results obtained from the model, the port expansion was designed, yet ongoing monitoring and modelling is being conducted to improve operation and maintenance measures (Padron, et al. 2010).

Palm Jumeira: At the time of completion, Palm Jumeira Island in Dubai was the largest man-made waterbody structure in the world with an overall footprint of 23 km^2 in which 7.9 $km^2$is land. Due to its geometry and structure, the projects witnessed several consequences relative to water quality. Hence, a hydrodynamic numerical modelling study was conducted that aimed to analyse the implication causing the water circulation challenges. The study considered the water flow variables such as water flows, tidal range, sand transfer and water resident time. Although the study struggled with obtaining relevant baseline data for the model due to the variability of readings on both sides of the project, the numbers were averaged for the sake of the model and the final outcomes were obtained. The results indicated that the water quality problems within the island basin were due to the non-sufficient water circulation, and it was recommended to apply a design change by introducing additional openings that allow the water to leave the island and fresh water to enter during the tidal currents. Although the study's objective was met and the results were utilized to apply the design change by introducing additional openings in the breakwater of the Palm Island, like other studies, the study did not take sedimentation into account, additionally, no mitigation strategy was developed in the study's conclusion (Cavalcante, et al. 2011).

2.5 Conclusion

By surveying the literature and looking into previous studies conducted that used numerical modelling to solve problems occurring in water bodies both natural and artificial, several gaps in literature were identified:

1. Lack of sedimentation modelling for waterways in Dubai and the Middle East: Although many studies tackled the sedimentation problem occurring in water bodies, no studies were found that investigated sedimentation problems in any water body in Dubai specifically and in the Middle East in General. This may be justified as the Middle East region is not known for waterways and urban navigation. Dubai introduced Maritime Public Transportation systems in 2008 when the water bus service was launched, followed by several cities in the ME. However, all systems used deep navigable routes where no risk of sedimentation could interfere with the operation. Additionally, mega man-made water body structures with shallower beds were only introduced in the Middle east back in 2008 when Palm Jumeira Island was complete.
2. Lack of Mitigation plan driven from study results: Most studies surveyed presented their outcomes and driven policies to control the problem that the study was looking into. It was

not found that any study’s objective was to drive a mitigation strategy to prevent the main problem from occurring. Although some studies investigated sedimentation or water quality problems, however, the conclusion did not put in place a strategy to either prevent the problem from reoccurring in the future nor to tackle it in a systematical and cost-effective way.

3. Lack of maintenance scheme design based on the obtained study outcomes: While the studies looked deep into the problem, it was noticed that the study did not recommend a series of measures that aim to solve the problem for any decision maker to consider. It is certain that water bodies undergo an ongoing problematic incident due to the nature of water that includes forces, salinity, humidity, and erosion. Therefore, it was necessary to put in place a maintenance plan that would tackle the problem in the most effective and efficient way possible.

3 Methodology

3.1 Summary

This thesis project studied the area of “Dubai Canal”, a man-made extension to the upstream end natural Creek in Dubai which was constructed in 2016 as shown in Figure 1. The canal was designed to follow a route through various areas in Dubai introducing a new connection to the Arabian Gulf. The purpose of executing the canal was to introduce a unique leisure navigation route into the heart of the city to enhance maritime tourism and boating activities. Moreover, this project increased the total length of Dubai’s waterfronts by approximately 30KM.

Figure 1: Layout of “Dubai Canal”, the Project’s studied area

Similar to any man-made water body, it is projected that the unstable canal bed will generate sediment accumulation in various areas along the canal. Accordingly, the sedimentations will result in disturbing the navigation route, boating and tourist activities. Therefore, the purpose of this project was to develop a numerical model to predict the sedimentation size and location that is projected to occur during the next 30 years. The research study was delivered in three phases:

1. Data sourcing for modelling and validation: Data gathering of historical reading and applying test models to compare results from the model with real data.
2. Modelling and simulation: Running of the model to simulate the behaviour of sedimentation through time, gather and analyse predicting readings. The validation of the model was for the creek area where the data was only available for that area. It covered the period from January to December 2012 and was considered as the baseline, including:
   - Elevation and surface and bottom current speed
   - Surface and bottom salinity/temperature
   - Mean of surface current speed
   - Net flow speed
   - Accumulated discharge volume through Creek mouth
   - Mean surface salinity

   The simulation modelling took place after the model was validated. The canal extension was inserted in the model for simulation. The modelling consisted of 2 models: a hydrodynamics model and a coastal model.

   - Hydrodynamics model: simulates the same components above for both the creek and canal combined, allowing the simulation of tracer flushing, and total suspended solids time series.
   - Coastal modelling: uses the coastline of the canal to simulate the sediment transportation prediction likely to occur over time. The model includes the following:
     i) Wave Agitation: wave penetration into the Canal (Using Wave and Wind conditions):
        - Wave Transformation Simulations
        - Wave Disturbance Simulations

ii) Channel Stability Assessment

   - Sand Transport model, STP

Combining both wave agitation and channel Stability outcomes, the sedimentation likely to occur in the entrance of the canal can be predicted.

3. Development of mitigation and maintenance strategies: Based on the results, further investigation to be done on the causes of the sedimentation and techniques that can eliminate or reduce the ongoing required maintenance.

3.2 Data sourcing for modeling and validation

The collection of the data is required to enable the modelling process. The data will allow the model to analyse the current behaviour of sediment in order to forecast the expected settlements overtime. It included developing a test model to study current flow and sedimentation transportation rates. The results obtained from running the models are compared to the available data for comparison and validation purpose.

The data collection was required to understand the current situation of sediment behaviour, and to initiate the suitable model to forecast the expected settlements and sedimentation over time. At this stage all the relevant and readily available existing data including site investigation information, meteorological, oceanographic and information from previous studies was gathered and reviewed. Once the data was gathered, a gap analysis was carried out to highlight any shortcomings and issues to enable alternative data to be sourced or suitable assumptions to be made.

The primary source of data was from Dubai Municipality as it is responsible for monitoring the behaviour of the coastal zone in Dubai. This is required in order maintain the man-made beaches in Dubai Water as these beaches are relatively unstable and need regular excavation and sand movement. The Dubai Coastal Zone Monitoring & Forecasting Programme (Environmental Department, Dubai Municipality 2010) has a vast store of Oceanographic data about the Dubai region. Oceanographic field data is required to establish the site conditions. The numerical models required this data for the initial and boundary conditions, as well as providing a means of calibrating the models which are used to provide design basis details.

Dubai Creek has been studied previously to understand its physical (water levels, currents, and net flow) as well as chemical and biological behaviour resulting from the combination of tidal variations, wind, and atmospheric conditions, treated sewage inflow, overflow and irrigation drainage inputs. The Creek together with the special circumstances posed by all sections including developments surrounding the creek has been the subject of an extensive study by Dubai Municipality. It is this study that is most relevant to the present study, the studies examined the hydrodynamics and water quality for now superseded layouts of various sections of the creek.

Dubai Coastal Zone Monitoring Program was started in 1997 by measuring Bathymetric and Topographic Survey conducted. Part of the monitoring program consists of:

- Remote Video monitoring
- Sediment sampling and Analysis
- Near Shore directional wave measuring
- Current measurements for selected locations (using ADCP)
- Bathy survey each year (using dual frequency eco sounder combined with GPS)
- Topo Survey each year (using RTK GPS)
- Further to the above data, modelling study data of the Canal Design stage also available such as
- Wind and Wave data of four offshore points (PERGOS Wind and wave hindcast from 1983 to 31 December 20009)

The data gathering was conducted by collecting historical data of water surfaces alongside the Dubai Canal (Dubai Creek and Dubai shoreline). It included: bathymetric data, current flows, tidal levels, and sediment characteristics. The data collected was measured since 2004 using tide gauges measuring water level variation, Acoustic Doppler Current Profilers (ADCPs) to measure currents and wave parameters, and data from a Meteorological Station which measures the wind speed and direction, local air temperature, relative humidity, and barometric pressure. A bathymetric LIDAR survey of the area was taken to include the latest layout of the Dubai Creek and Coastal Zone. A gap analysis was carried out after the data gathering and it was concluded that the data sets were sufficiently complete to support the modelling phase of project.

3.3 Modelling and simulation

A set of preliminary evaluation models of outlet areas of the Dubai Creek and Coastal Zone were created using the available data and MIKE3 modelling software. The objectives were to predict: (1) water flow, (2) sedimentation transportation rates in out-let area and the coastline, and (3) compare the predicted results with the measurements taken over a specific year. Prior to the first release of MIKE 21 & MIKE 3 Flow Model FM the model has successfully been applied to several idealized situations for which the results can be compared with analytical solutions or information from the literature (DHI Notes 2004). The flow model has also been applied and tested in numerous natural geophysical conditions; ocean scale, inner shelves, estuaries, lakes and overland (French, Kerper 2004) which are more realistic and complicated than academic and laboratory tests.

3.3.1 Hydrodynamic Modelling

The hydrodynamic modelling has been carried out using MIKE 3 FM developed by DHI Water & Environment. MIKE 3 Flow Model FM is a modelling system based on a flexible mesh approach. The modelling has been developed for applications within oceanographic, coastal and estuarine environments.

The system is based on the numerical solution of the three-dimensional incompressible Reynolds averaged Navier-Stokes equations invoking the assumptions of Boussinesq and of hydrostatic pressure (Alfonsi 2009). Thus, the model consists of continuity, momentum, temperature, salinity, and density equations and is closed by a turbulent closure scheme. In the horizontal domain both Cartesian and spherical coordinates can be used. The free surface is considered using a sigma-coordinate transformation approach.

For the 3D model, the free surface is taken into account using a sigma-coordinate transformation approach or using a combination of a sigma and z-level coordinate system. Below the governing equations are presented using Cartesian coordinates. The local continuity equation is written as

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=S \tag{1}$$

and the two horizontal momentum equations for the x- and y-component, respectively

$$\frac{\partial u}{\partial t}+\frac{\partial u^2}{\partial x}+\frac{\partial vu}{\partial y}+\frac{\partial wu}{\partial z}=fv-g\frac{\partial \eta}{\partial x}- \\ \frac{1}{\rho_0}\frac{\partial p_a}{\partial x}-\frac{g}{\rho_0}\int_z^\eta \frac{\partial \rho}{\partial x}dz+F_u+\frac{\partial}{\partial z}\left(\nu_t\frac{\partial u}{\partial z}\right)+u_s S \tag{2}$$

$$\frac{\partial v}{\partial t}+\frac{\partial v^2}{\partial y}+\frac{\partial uv}{\partial x}+\frac{\partial wv}{\partial z}=-fu-g\frac{\partial \eta}{\partial y}- \\ \frac{1}{\rho_0}\frac{\partial p_a}{\partial y}-\frac{g}{\rho_0}\int_z^\eta \frac{\partial \rho}{\partial y}dz+F_v+\frac{\partial}{\partial z}\left(\nu_t\frac{\partial v}{\partial z}\right)+v_s S \tag{3}$$

The spatial discretization of the primitive equations is performed using a cell-centered finite volume method. The spatial domain is discretized by subdivision of the continuum into non-overlapping elements/cells. In the horizontal plane an unstructured grid is used while in the vertical domain a structured discretization is used. The elements can be prisms or bricks whose horizontal faces are triangles and quadrilateral elements, respectively. An approximate Riemann solver is used for computation of the convective fluxes, which makes it possible to handle discontinuous solutions.

For the time integration a semi-implicit approach is used where the horizontal terms are treated explicitly, and the vertical terms are treated implicitly.

3.3.2 Sediment transport modelling

Sedimentation conditions are estimated by use of MIKE 3 FM Sand Transport Module. The model system comprises of a 3D flow model and a sand transport model which calculates sand transport from the combined effect of waves and currents. The Sand Transport Module calculates the resulting transport of non-cohesive materials based on the mean horizontal flow conditions found in the hydrodynamic calculations and, if included wave conditions from wave calculations. Apart from the sediment transport components, the initial rates of bed level change associated with the time-averaged over the user defined simulation period transport field are also obtained as output from the Sediment Transport simulation.

The Sand Transport Module can be applied to a wide range of sediment-transport related phenomena, including modelling of sediment transport fields in the littoral zone, in the vicinity of coastal structures, in tidal inlets, and under the sole or combined effects of tidal, wind and wave driven currents in estuaries or coastal areas. The Module calculates non-cohesive sediment transport. Two modes of sediment transport are described (Elfrink, Berry, and Baldock 2002):

1. Bed Load Transport
2. Suspended Load Transport

A third category is normally referred to as wash load and it is not included in ST module.

There are two different model types in the sediment transport model as follows:

- Pure Current:
    - For pure current model type, the bed load and suspended load is calculated separately.
- Waves and Current
    - For combined waves and currents model, the total load will be calculated.

The flow model results provide the input to Sediment Transport and drive the sediment transport in the Dubai Canal. From the previous experiences in the project vicinity, it is evident that waves inside the canal are less than 0.5m. Due to the mild nature of wave conditions, the effect of waves on sediment transport is considered insignificant and waves are excluded from this study.

In numerical simulations, the sediment transport total load can be numerically estimated by two approaches: Either jointly as bed-material load (equilibrium sediment transport model); Or separately as bed-load and suspended-load considering the effect of sediment entrainment and deposition from the bed layer (non-equilibrium sediment transport model). For the pure currents model, both the equilibrium and non-equilibrium models are possible. If equilibrium is selected, then the transport rates are calculated assuming equilibrium conditions. If the non-equilibrium option is selected, then the transport rates are calculated considering the conditions at the previous time steps. Currently, only one category of sediment can be simulated in the model.

There are four sediment theories presently available in the model and they are listed below (Papanicolaou et al. 2008):

- Engelund and Hansen (Total Load) (BaoshengWU, MAREN and LingyunLI 2008)– Scheme1
- Van Rijn (Bed Load + Suspended Load) (Van Rijn 2007)– Scheme 2
- Engelund and Fredsoe (Bed Load + Suspended Load) (Lu, et al. 2020)– Scheme 3
- Meyer-Peter and Muller (Bed Load) (WR WHITE 1975)– Scheme 4

The morphological part of the sediment transport model uses the computed hydrodynamics result obtained in the hydrodynamic model, since the water depth and the velocity components are known. The sediment transport module carries out iterations of the bed surface evolution and sediment volume exchange between computational mesh elements. The overall sediment transport is governed by the sediment mass-balance equation and depends on porosity of the movable bed material and total sediment load transport rate.

3.3.3 Evaluation models

Based on the Canal's geometry and current flow data, the model will run to predict the flow conditions in Dubai Creek taking into consideration the treated wastewater discharged in the creek, which affects the flow rate, and the shipping activities that increase turbulence in the channel. The evaluation models use the general parameters pre-set in prior modelling as well as the data collected to predict total water flow discharge in two opening locations where sediment is likely to occur more often. A comparison will be driven between the flow velocities in both openings. As the difference may have a minor impact on local scour potential but in most cases will not disturb navigation.

For the sedimentation test model, additional information on sediment characteristics must be included in the model set-up using boreholes sampling tests. With these readings and the required perimeters, the test model will indicate an annual net transport rates showing the direction of transportation likely to happen.

3.3.4 Calibration and Validation of the Evaluation Models

Following the set-up, the domain of the required area is to be created by the grid mesh using the bathymetric data available. This allows calibrating the model by presenting a repetitive process of establishing a relationship between measured data and modelled results. The calibration is assessed either by visual comparison of the model output against measured data: the shape, trend, range and limits of model output and measured data or a statistical compliance analysis between measured data and model results, although it is strongly recommended using both while calibrating a model.

To qualify the level of calibration, and allow comparison between sites, a qualitative scale of model to data fit is adopted. This comparative scale is based on the frequency with which tolerance criteria are achieved:

- **Excellent Fit** Calibration tolerances are achieved >90% of the time
- **Very Good Fit** Calibration tolerances are achieved >80% of the time

- **Good Fit** Calibration tolerances are achieved >70% of the time
- **Reasonable Fit** Calibration tolerances are achieved >60% of the time
- **Poor Fit** Calibration tolerances are achieved <60% of the time

These qualitative terms are also like those that might be used when describing fit based on visual assessment criteria, and therefore allow an objective comparison between visual and statistical evaluation to be made. Under certain conditions, models can meet statistical calibration standards, but, on visual inspection, appear to perform poorly. Conversely, seemingly accurate models can fall short of the guidelines. Also, with the described limitations of the specified tolerances under specific situations in mind, it is pertinent to recognize that guidelines alone cannot be used when assessing the performance of the model. It is necessary for experienced modellers / oceanographers to offer a critical assessment of model performance taking all the available information into account to ensure model performance is suitable for the intended purpose of the study. After the model is calibrated, it must be run during a period for which the data exists to create a comparison between the model results and actual data gathered in the past.

The validation process involves dividing the data into two distinct sets: a training set and a test set. The model undergoes training on the designated training set, and subsequently, its performance is assessed using the test set. The validation step is crucial for ensuring that the model's performance extends effectively to new, unseen data, while also highlighting potential concerns like overfitting or underfitting. This validation process is indispensable for evaluating the dependability and precision of a machine learning model.

3.4 Mitigation and maintenance strategies

Based on the model outcome, a closer study of the status was conducted to verify the possible reasons and what is likely to happen, therefore this work-package explored sustainable and efficient maintenance and dredging methods as an alternative sustainable maintenance regime to the high-cost and non-efficient maintenance currently being used in Dubai.

4 Results

4.1 Overview

The numerical hydrodynamic modelling was carried out in two stages:

- **Stage 1 – Regional Hydrodynamic Model**. A large scale two-dimensional (2-D) tidal hydrodynamic model of the Arabian Gulf was used to establish general regional circulation patterns and to provide boundary conditions for the Local Hydrodynamic Model.
- **Stage 2 – Local Hydrodynamic Model**. A local scale 3-D model of the Dubai coast was used to evaluate tidal hydrodynamics in the vicinity of the project site, using boundary condition input supplied from the Regional Model.

The flowcharts in Figure 2 and Figure 3 provide an overview of how the regional and local hydrodynamic modelling is carried out. For carrying out a reliable model, all the information to be provided as input to the model should be of good quality. During the data collection stage, all the information is collected and reviewed for the quality of data. If there is any data gap, it will be complemented by literature review and research. Once data collection is satisfactory, all the required input for carrying out the model (bathymetry, boundary conditions, initial conditions, etc.) are prepared and model is run to cover the full spring-neap tidal cycle. The model results are post-processed, and results are compared with the measured data. The model calibration and validation procedures are detailed in Model Calibration and Validation Section below. The regional model provides the boundary conditions for the local model.

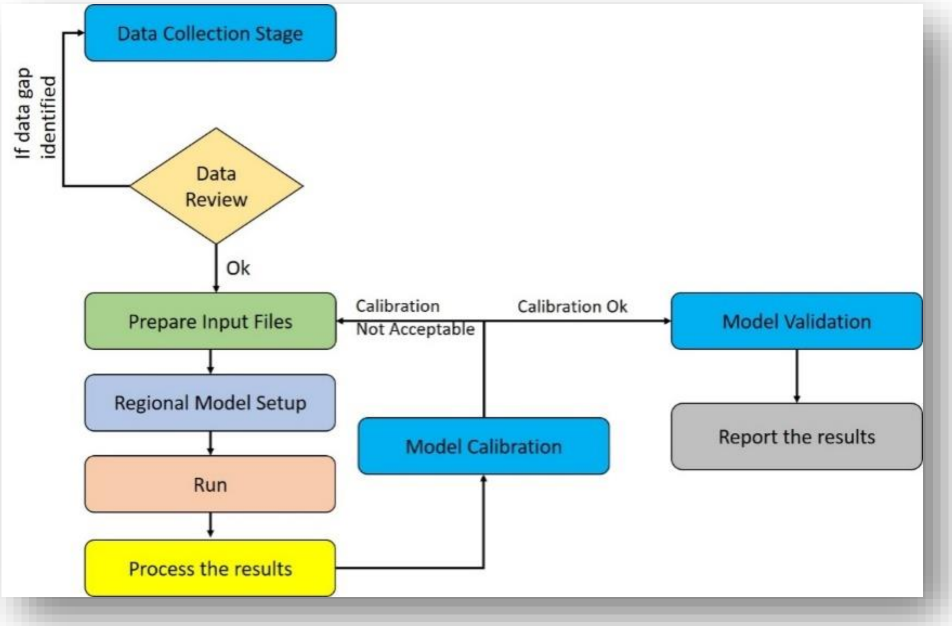


Figure 2: Modelling regional hydrodynamic flow

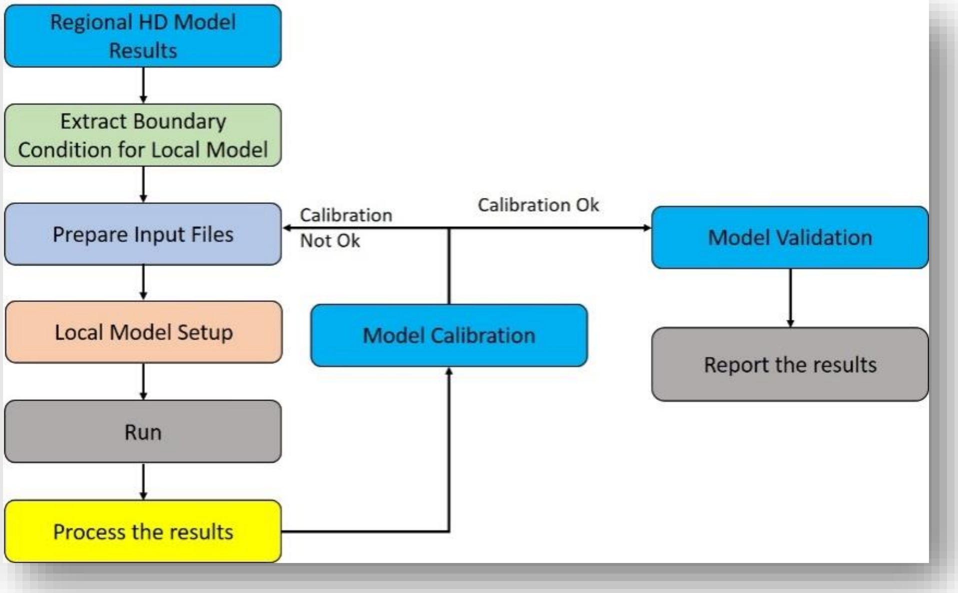


Figure 3: Modelling local hydrodynamic flow

4.2 Regional Hydrodynamic Model (Arabian Gulf)

A 3-dimensional MIKE model of the Arabian Gulf was developed and calibrated / validated against tidal constituents and measurements at various locations throughout the region. The Regional Model establishes general circulation patterns around the Gulf, including the Dubai coastal zone, and provides boundary condition input to the Local Hydrodynamic Model.

4.2.1 Regional Model Setup

The computational domain of the Regional Hydrodynamic Model covers the entire Arabian Gulf to the open sea boundary between Khawr Fakkan (United Arab Emirates) and Ras al Kuh (Iran). The model bathymetry and computational mesh are shown in Figure 4. The mesh consists of more than 30,000 triangular elements. The coastline and bathymetry of the model were generated from:

- World Vector Shoreline data downloaded from the National Oceanic and Atmospheric Administration (NOAA) website (National Oceanic and Atmospheric Administration 2016);
- Digitized Admiralty charts (ADMIRALTY Vector Chart Service (AVCS) 2024);
- The GEBCO_08 Grid (The British Oceanographic Data Centre (BODC) 2023), a global continuous terrain (land and sea) model with a spatial resolution of 30 arc-seconds; and
- Bathymetric survey data for various sites around the region.

The open boundary between Khawr Fakkan and Ras al Kuh was forced using the Admiralty tide predictions (ADMIRALTY Vector Chart Service (AVCS) 2024) using MIKE 21 Toolbox.

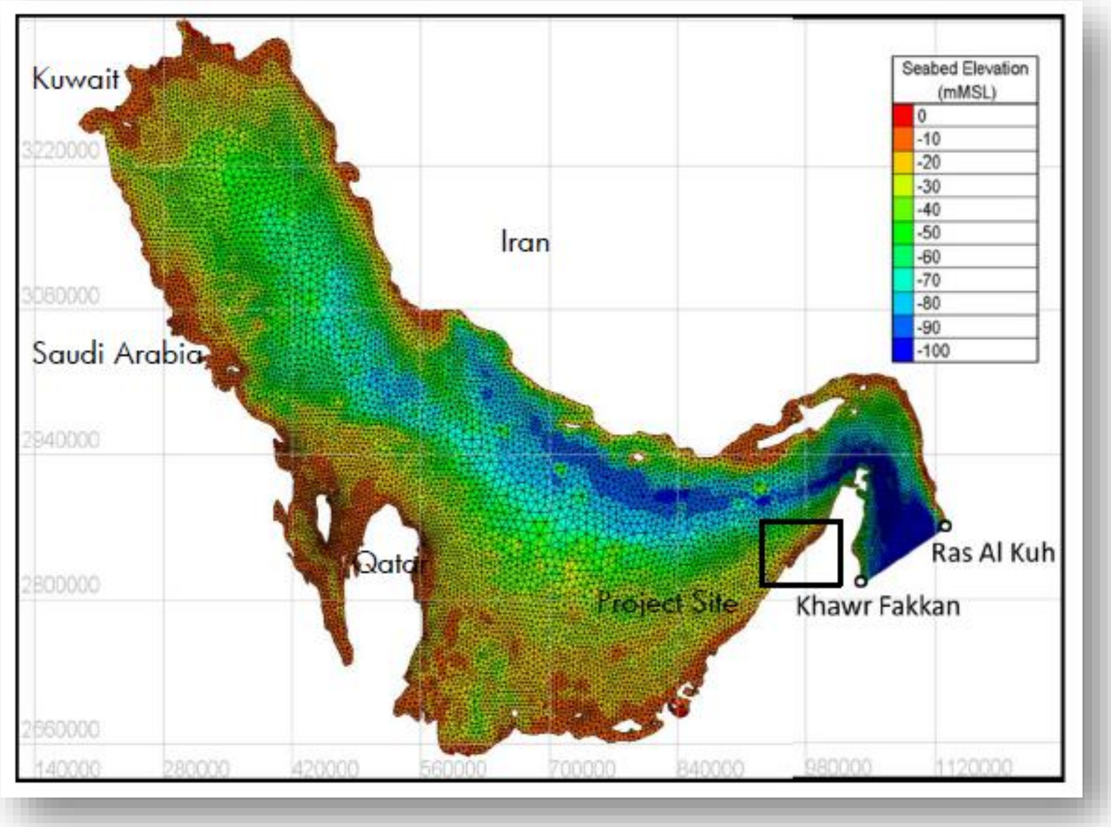


Figure 4: Regional Arabian Gulf Model domain, bathymetry contours and computational mesh

4.2.2 Regional Model Calibration and Validation

Model calibration and validation are necessary and critical steps to ensure confidence in model predictions. Calibration is an iterative procedure of parameter and boundary condition evaluation and refinement: comparing simulated with observed values of interest. Model validation generally follows the calibration process. Its purpose is to assure that the calibrated model properly assesses all the variables and conditions which can affect model results, and to demonstrate the ability of the model to accurately characterise tidal hydrodynamics based on parameters identified through calibration.

The Regional Hydrodynamic Model of the Arabian Gulf has been extensively calibrated and validated against field data (water levels and currents) and tidal harmonic predictions throughout the region as shown in Figure 5 below.

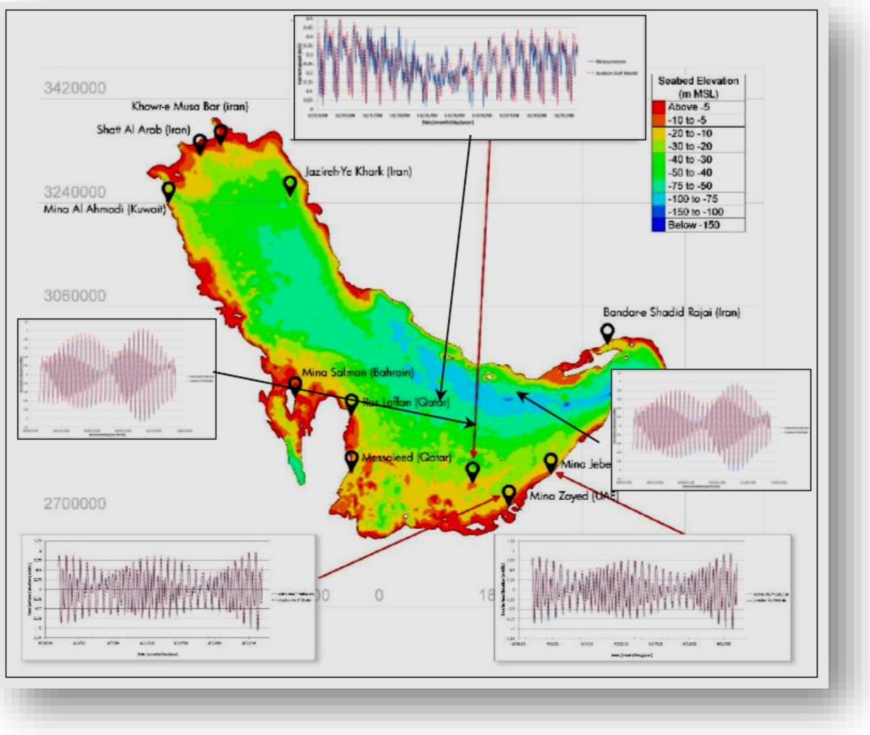


Figure 5: Calibration stations for the Arabian Gulf model and sample calibration/validation plots

For the purpose of investigating tidal hydrodynamics at the Dubai Canal site, and to facilitate investigation of post-development scenarios, a local scale MIKE 3 FM model was developed and driven (forced) by boundary conditions extracted from the Regional Hydrodynamic Model.

The local model domain is designed in such a way to ensure that the key features to hydrodynamics within Dubai Canal are suitably represented. The computational domain of the MIKE 3 FM Local Hydrodynamic Model was set up to encompass the full Dubai Canal as shown in Figure 6. The computational mesh and bathymetry are shown in Figure 7. The mesh consists of approximately 7500 triangular elements, with increased resolution at the new Dubai canal side where characteristic element edge length is in the range 15-20 m. The time step used for the hydrodynamic model is 30 seconds. For the bed friction, a roughness height with a constant value of 0.01m was selected. A series of sensitivity tests were carried out using different roughness height values such as 0.02, 0.03 and 0.05. The coastline and bathymetry of the model were generated from the following data set collected from Dubai Municipality (Coastal Section of Dubai Municipality 2017):

- Detailed bathymetric/topographic surveys of the site and surrounding areas;
- Digitized navigational charts;
- LiDAR survey data (2013).

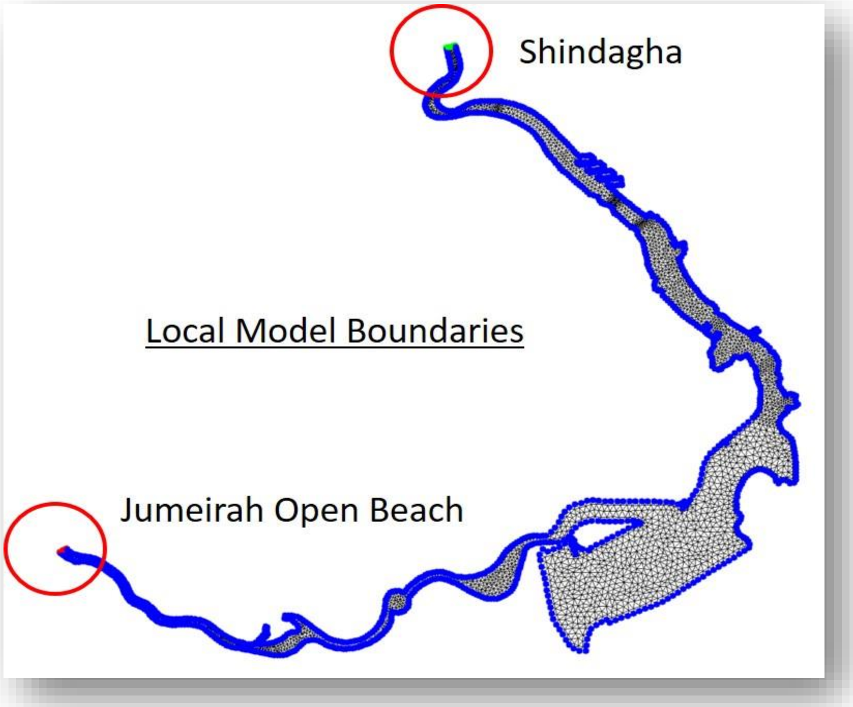


Figure 6: Local Model Water Level Boundaries

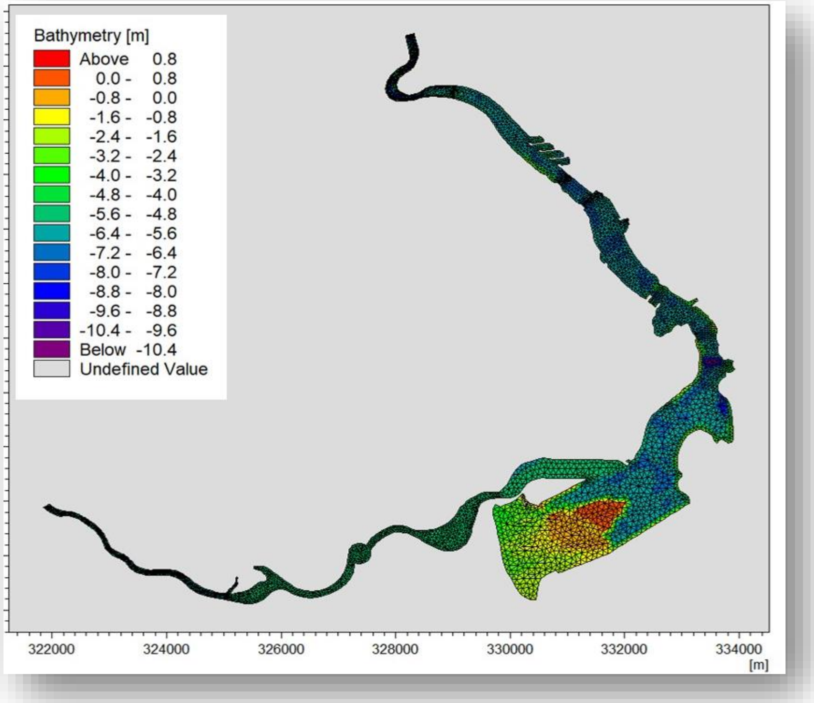


Figure 7: Computational mesh and bathymetry of the Local Hydrodynamic Model

4.2.3 Hydrodynamic Model Calibration and Validation

The data sets used for the calibration and validation for the Hydrodynamic Model are the following:

- Shindagha (2015 & 2016): Water levels, current speeds and current direction;
- Dubai Festival City (2015 & 2016): Water levels;
- Jumeirah Open Beach (2015 & 2016): Water levels; and
- Business Bay (2015 & 2016): Water levels, current speeds and current direction.

The model was run from 5th to 22nd July 2016, for a total of 17 days including 2 days warm-up time was made to ensure accurate simulation, stability, comprehensive data collection including both Neap and Spring Tides during the run period to represent complex hydrodynamic processes within the system. The time step 30 seconds is used. For a local model, the parameters available for adjustment are the friction coefficient, and the representation of the eddy diffusivity for momentum representing turbulent processes.

As stated above a roughness height value of 0.01m has been specified, after a series of sensitivity tests were carried out using different roughness height values. Smaller values of roughness height correspond to the low friction and vice versa. The Smagorinsky formulation is used for eddy viscosity and no wind forcing is used in the model. Tidal forcing at Shindagha in the north and Jumeirah open beach in the south are used as the boundary conditions for the local model. The water level and currents are assessed at four locations along the canal and are shown in Figure 8.

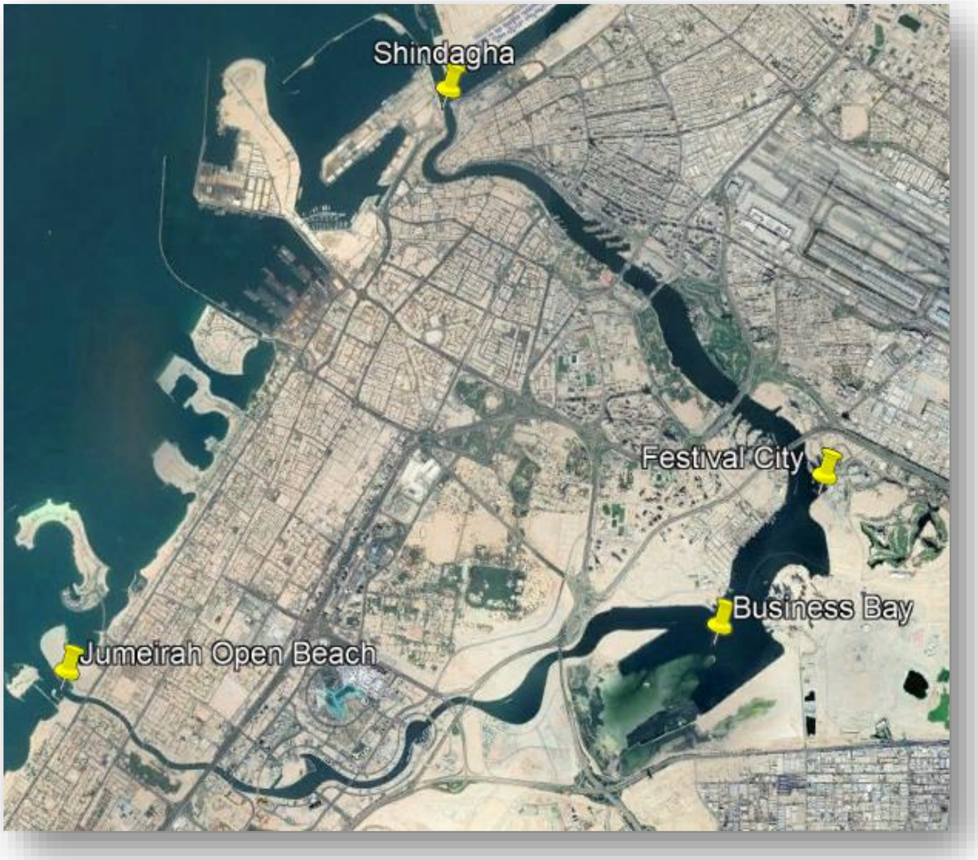


Figure 8: Extraction locations for calibration and validation

Calibration is achieved by comparing the model output against observed data. The best model 'fit' was then achieved by verifying the calibration coefficients (bed resistance). The degree of fit between model and observation determines the level of model calibration: poor fit suggests poor calibration, good fit suggests good calibration. The degree of fit will vary from location to location depending on local conditions and how well these can be represented in the model. The quality of the observed data is also a significant factor in determining calibration, and is a function of instrument type, accuracy, resolution, deployment location and environmental conditions. Model fit to field data can be assessed in two ways:

- Visual comparison of the model output against the measured data: the shape, trend, range and limits of model output and observed data.
- Statistical comparison of the differences between observations and the model to determine the frequency with which the model fits observation within defined limits, e.g. 90% of the model predictions are within 0.1 units or 10% of the observed value.

In practice, both methods should be used, as no single method provides a full assessment of model performance. The model performance in this study has been assessed following the guidelines set out in the Foundation for Water Research (FWR) (The Water Research Foundation 2010). The FWR tolerances used in this study for calibration and validation are presented in Table 1.

Table 1: FWR Guidelines of Hydrodynamic Model Performance Criteria (Evans 1993)

Parameter	**Tolerance Applied**			
	Coastal		**Estuarine**	
	Absolute	**Relative**	**Absolute**	**Relative**
Water Level	**+/- 0.1 m**	**10% of Spring tidal ranges** **15% of Neap tidal ranges**	**+/- 0.1m at mouth** **+/- 0.3m at head**	**15% of Spring tidal ranges** **20% of Neap tidal ranges**
Current Speed	**+/- 0.1 m/s**	**+/- 10-20% of observed speed**	**+/- 0.2 m/s**	**+/- 10-20% of observed speed**
Current Direction	**+/- 20 degrees**	**N/A**	**+/- 20 degrees**	**N/A**
High Water Phase	**+/- 15 mins at mouth** **+/- 15 mins at head**	**N/A**	**+/- 15mins at mouth** **+/- 25mins at head**	**N/A**

These criteria maybe too testing for all regions of the modelled area. Therefore, it is recommended that these conditions should be satisfied for “90% of position/time combinations evaluated” and this requirement has been applied as the target standard in this study. Absolute and relative tolerances are presented, and it should be noted that relative and absolute tolerances can be used interchangeably when undertaking calibration analysis and the most appropriate should be used for each comparison case.

It is unlikely that these tolerances will be achieved throughout the calibration period as there will inevitably be some factors that cannot be fully accounted for in the model numerical scheme, input data and calibration coefficients, particularly in shallow coastal and estuarine waters. However, model calibration should seek to achieve these tolerances over most of the position/time combinations evaluated.

To qualify the level of calibration, and allow comparison between sites, a qualitative scale of model to data fit is adopted. This comparative scale is based on the frequency with which tolerance criteria are achieved:

- **Excellent Fit** Calibration tolerances are achieved >90% of the time
- **Very Good Fit** Calibration tolerances are achieved >80% of the time
- **Good Fit** Calibration tolerances are achieved >70% of the time
- **Reasonable Fit** Calibration tolerances are achieved >60% of the time
- **Poor Fit** Calibration tolerances are achieved <60% of the time

These qualitative terms are also like those that might be used when describing fit based on visual assessment criteria, and therefore allow an objective comparison between visual and statistical evaluation to be made. Under certain conditions, models can meet statistical calibration standards, but, on visual inspection, appear to perform poorly. Conversely, seemingly accurate models can fall short of the guidelines. Also, with the described limitations of the specified tolerances under specific situations in mind, it is pertinent to recognize that guidelines alone cannot be used when assessing the performance of the model. It is necessary for experienced modellers / oceanographers to offer a critical assessment of model performance taking all the available information into account to ensure model performance is suitable for the intended purpose of the study.

Figure 9 to 12 show the visual comparison between modelled and measured water level at Shindagha, Dubai Festival City, Jumeirah Open Beach, and Business Bay locations. The model result matches well with the measured/predicted water levels at all the locations, and difference in water level is less than 0.05m. A summary of the statistical analysis of model fit and visual analysis of the calibration plots is provided in Table 2. At all the locations, the simulated results agree well with the measurements and comply fully with the FWR guideline. For both spring and neap tides, the fit of simulation could be classified as full compliance or excellent fit.

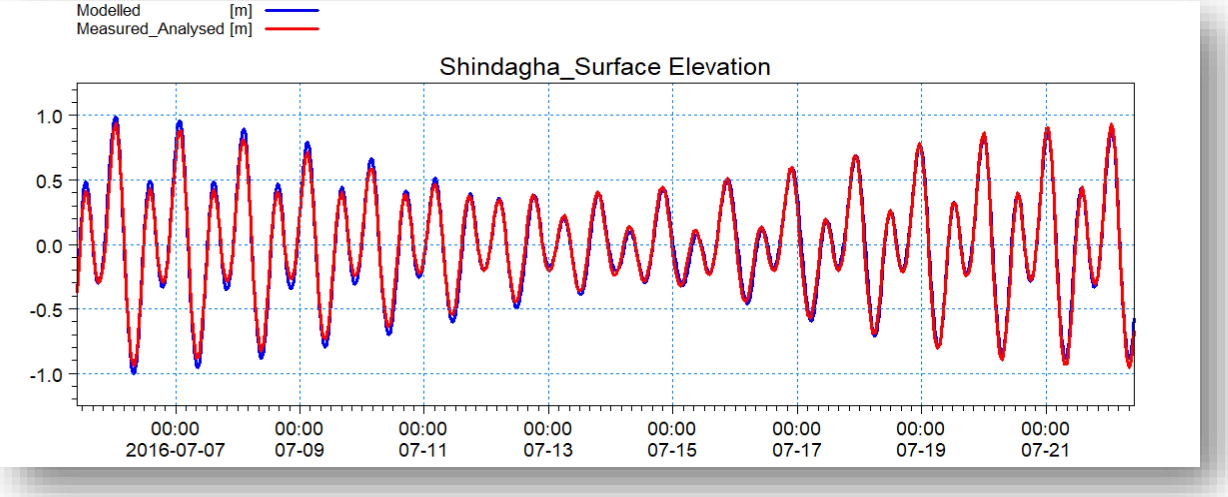


Figure 9: Comparison of measured (in red) and modelled (in blue) water level at Shindagha for calibration

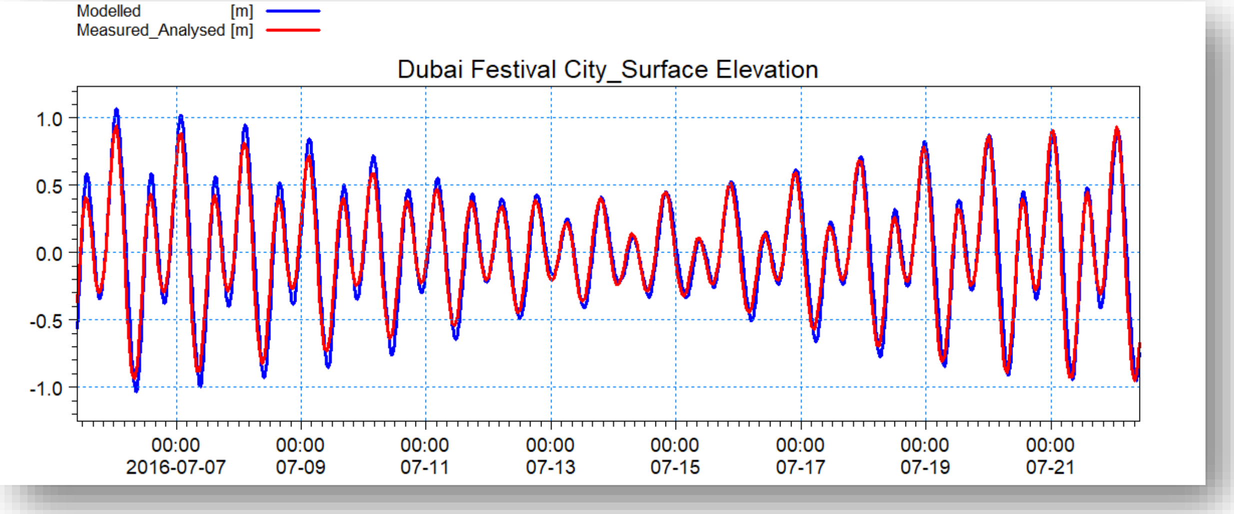


Figure 10: Comparison of measured (in red) and modelled (in blue) water level at Dubai Festival City for calibration

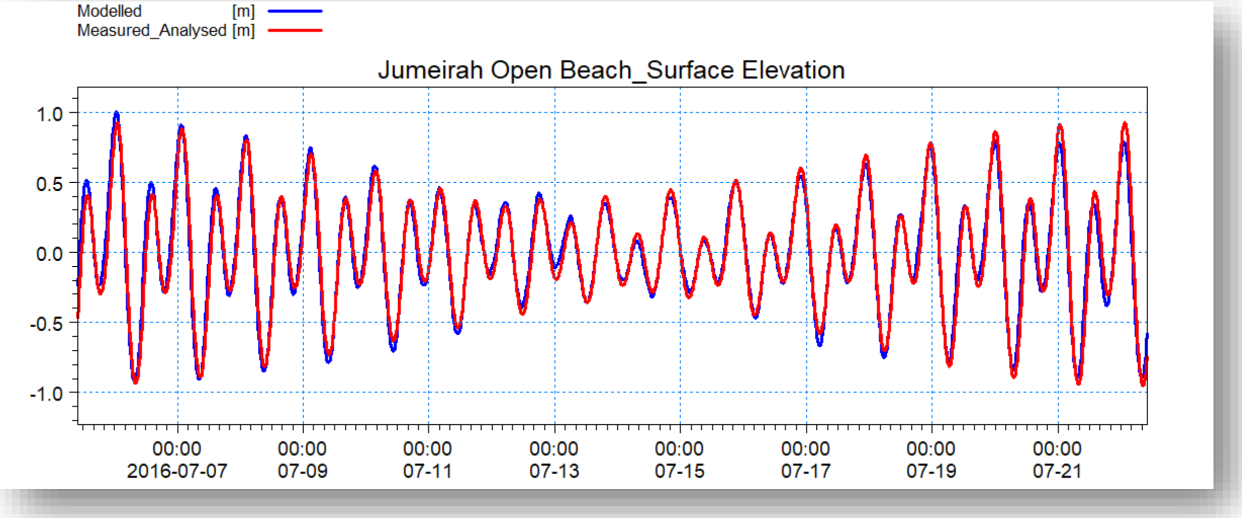


Figure 11: Comparison of measured (in red) and modelled (in blue) water level at Jumeirah Open Beach for calibration

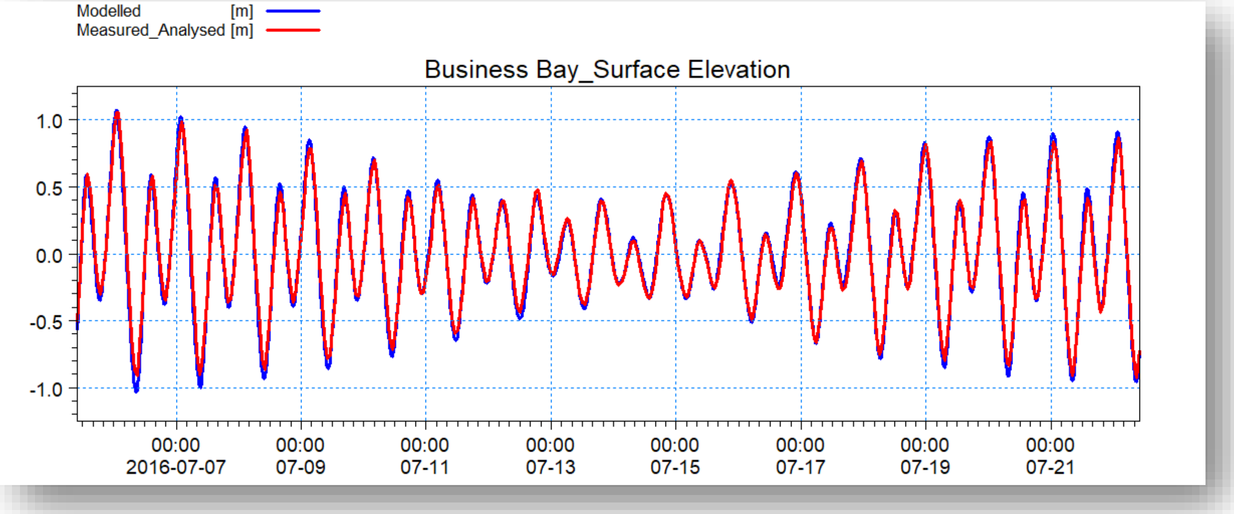


Figure 12: Comparison of measured (in red) and modelled (in blue) water level at Business Bay for calibration.

Table 2: Summary of Model Calibration for Water Levels (7/12/2016 20:00 –7/4/2016 20:00)

Location	**Time Period**	**Parameter**	**% Fit**	**Phase (min)**	**Comment**
Shindagha Tide Gauge	Spring Tide	Elevation	100%	0	Full compliance with FWR coastal criteria in both spring and neap tide
	Neap Tide	Elevation	100%	-1	
Business Bay Tide Gauge	Spring Tide	Elevation	99%	0	Full compliance with FWR coastal criteria in both spring and neap tide
	Neap Tide	Elevation	100%	-2	

Modelled currents at the Shindagha and Business Bay locations are compared with the measurements and are presented in Figures 13 to Figure 16. At Shindagha, modelled current speed matches well with the measurements during the ebb tide. Whereas, during the flood tide the model slightly over predicts the currents. However, the differences between the modeled results and actual measurements remain within the limits.

With regards to the current's directions, most of the modelled results perform a perfect match with the actual measured directions. However, a deviation of currents direction was noticed on few occasions as demonstrated in Figure 14 below. This might be due to irregularities in the actual measurements.

The current speed in the Business Bay location is relatively slow in the range 0.1m/s. The model slightly under predicts the current speed at Business Bay but the difference is less than 0.05m/s. Modelled current direction agrees well with the measurements for the majority of the simulation duration. The instances of underprediction and overprediction identified at distinct locations can be ascribed to diverse factors such as the intricate characteristics of tidal patterns, local hydrodynamic conditions, and potential irregularities in measurement data. The variances between the model predictions and the actual measurements are relatively negligible and fall within acceptable limits, signifying that, on the whole, the model demonstrates effective performance. The statistical analysis of currents at Shindagha and Business Bay locations are provided in Table3. A very good fit is observed in terms of current speed at both the locations for both spring and neap tides and a good fit is observed in terms of current directions.

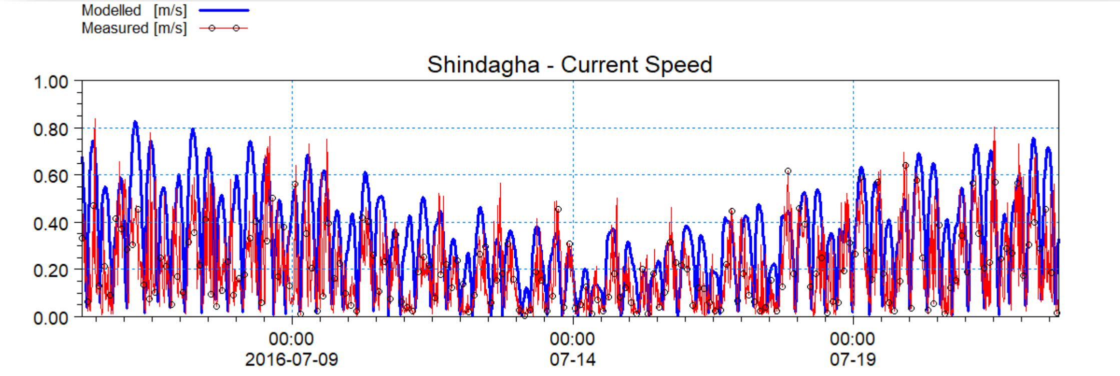


Figure 13: Comparison of measured (in red) and modelled (in blue) current speed at Shindagha

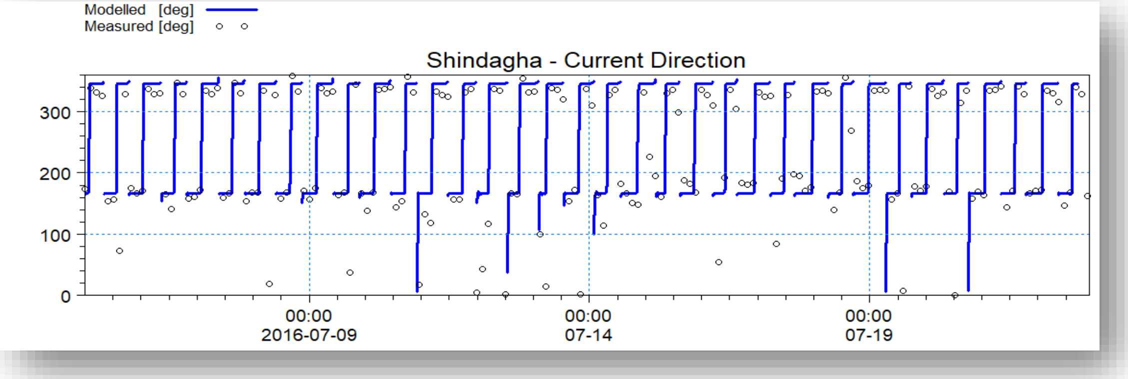


Figure 14: Comparison of measured (in red) and modelled (in blue) current direction at Shindagha

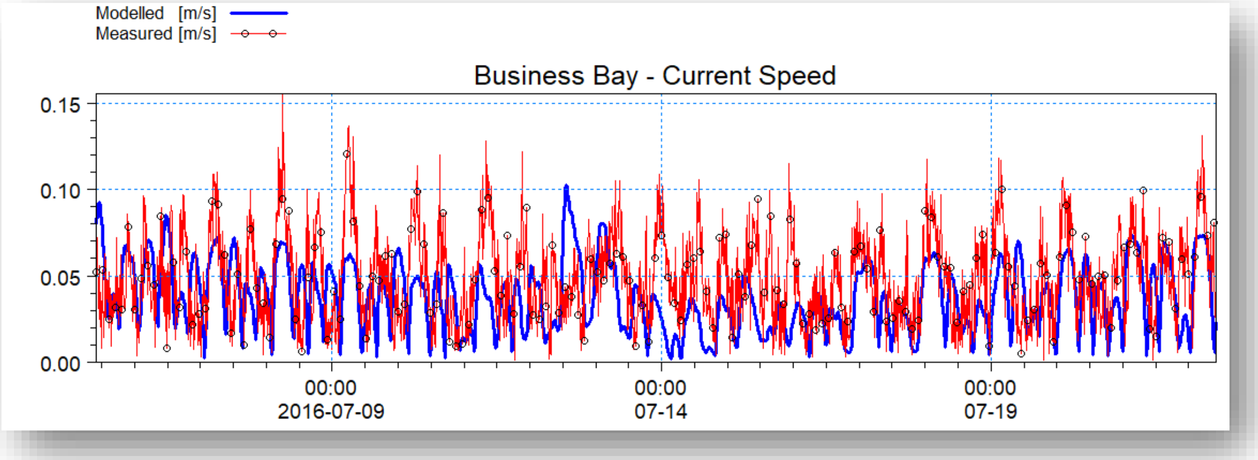


Figure 15: Comparison of measured (in red) and modelled (in blue) current speed at Business Bay

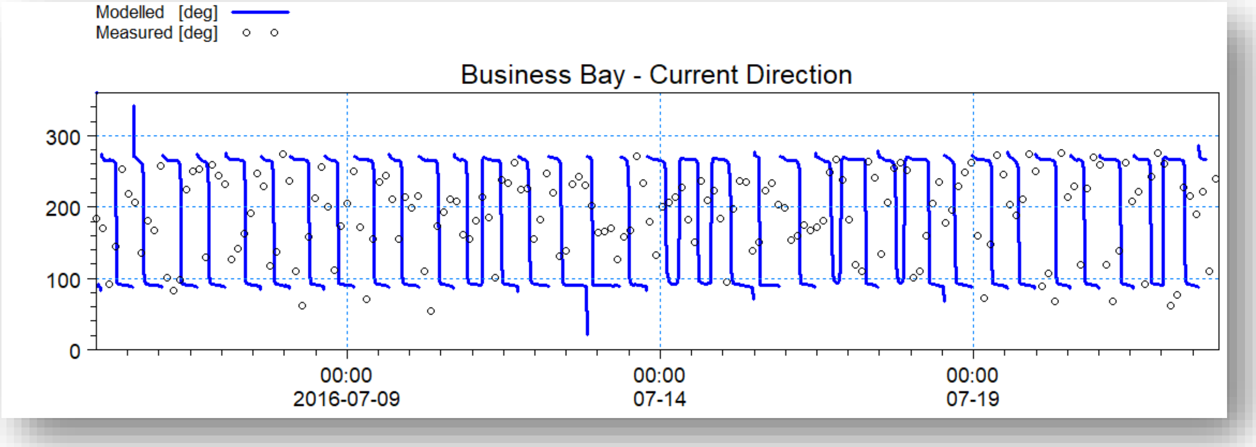


Figure 16: Comparison of measured (in red) and modelled (in blue) current direction at Business Bay

Table 3: Summary of Model Calibration for Currents

Location	**Time**	**Parameter**	**% Fit**	**Phase (min)**	**Comment**
Shindagha **Acoustic Doppler Current Profiler** **(ADCP)**	Spring Tide	Speed	86%	-2	Very good fit in terms of current speed in both spring and neap tides
		Direction	76%	-1	
	Neap Tide	Speed	84%	-4	Good fit in terms of current direction
		Direction	73%	-6	
Business Bay **Acoustic Doppler Current Profiler** **(ADCP)**	Spring Tide	Speed	85%	-3	Very good fit in terms of current speed in both spring and neap tides
		Direction	75%	-5	
	Neap Tide	Speed	75%	3	Good fit in terms of current direction
		Direction	71%	-5	

Model validation is undertaken by using the model set-up and parameters demonstrated to produce the best model 'fit' during calibration and then run for a past condition in 2015 (1st July to 16th July 2015) in which period water level and current data are available for Shindagha and Business Bay locations.

Figure 17 to Figure 20 show the visual comparison between modelled and measured water level at Shindagha, Dubai Festival City, Jumeirah Open Beach and Business Bay. The model result matches well with the measured/predicted water level at all the locations and difference in water level is less than 0.05m. A summary of the statistical analysis of model fit and visual analysis of the validation plots is provided in Table 4.

At all the locations except Business Bay, the simulated results agree well with the measurements and comply fully with the FWR guideline. For both spring and neap tides, the fit of simulation could be classified as full compliance or excellent fit. At Business Bay, the model slightly overpredicts the water level during neap tide but provides an excellent fit over the simulation duration.

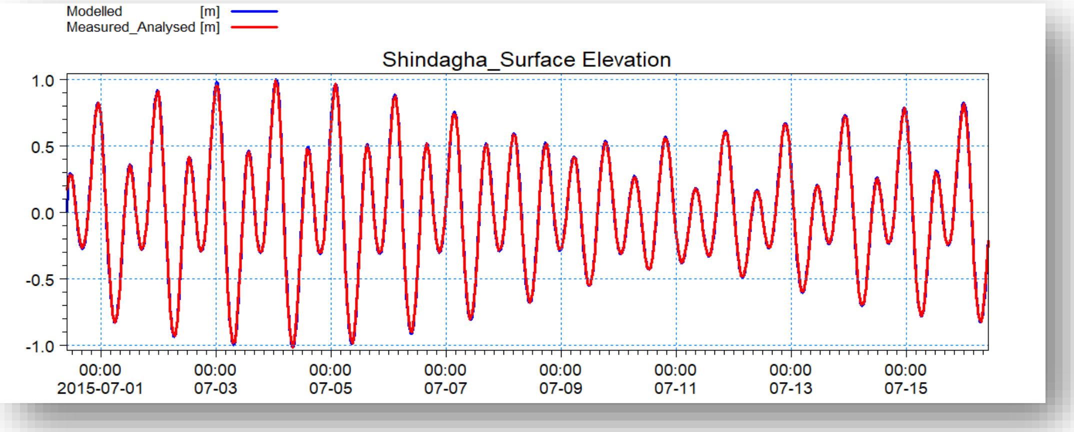


Figure 17: Comparison of measured (in red) and modelled (in blue) water level at Shindagha

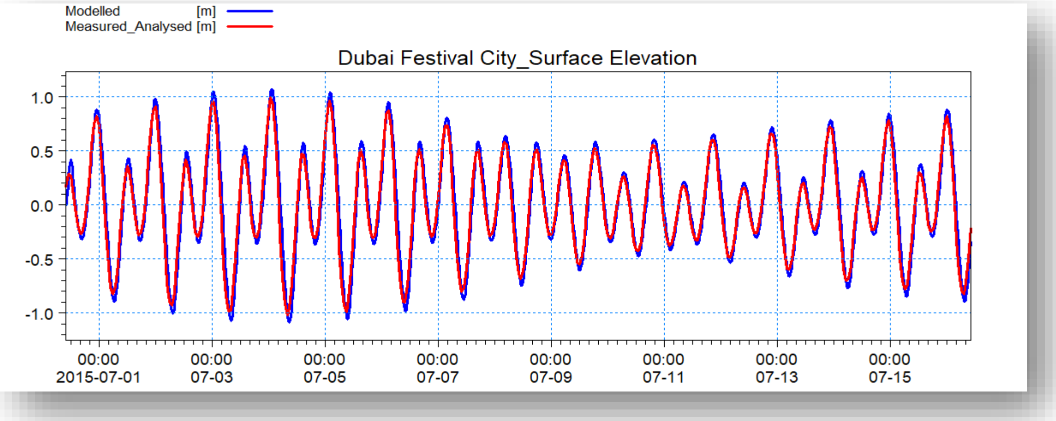


Figure 18: Comparison of measured (in red) and modelled (in blue) water level at Dubai Festival City

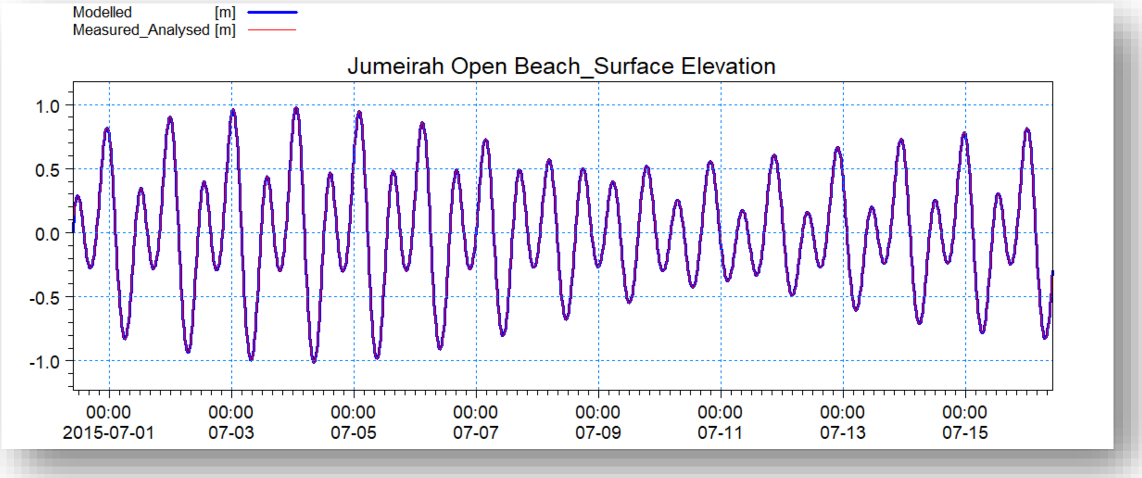


Figure 19: Comparison of measured (in red) and modelled (in blue) water level at Jumeirah Open Beach

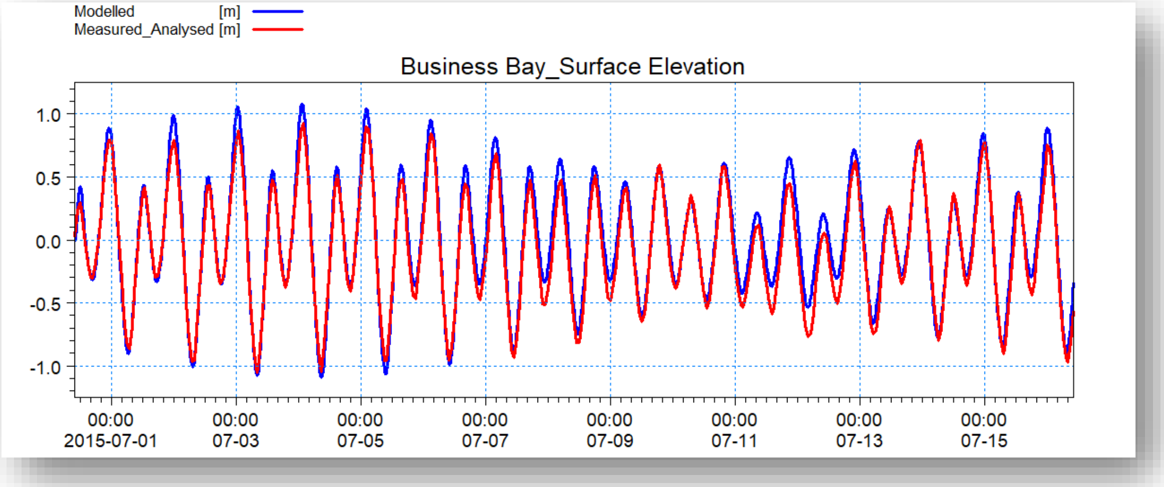


Figure 20: Comparison of measured (in red) and modelled (in blue) water level at Business Bay

Table 4: Summary of Model Validation for Water Levels

Location	Time Period	Parameter	% Fit	Phase (min)	Comment
Shindagha Tide Gauge	Spring Tide (7/4/2015 02:00 –7/6/2015 02:00)	Elevation	100%	0	Full compliance with FWR coastal criteria in both spring and neap tide
	Neap Tide (7/11/2015 20:00 –713/2015 20:00)	Elevation	100%	0	
Business Bay Tide Gauge	Spring Tide	Elevation	94%	1	Full compliance with FWR coastal criteria in both spring and neap tide
	Neap Tide	Elevation	91%	1	

Modelled currents at Shindagha and Business Bay are compared with the measurements and are presented in Figures 21 to Figure 24. Similarly to the model calibration explained above, the validation results demonstrated a perfect match between the modelled results and the actual measured current speeds during the ebb tide. Whereas during the flood tide, the model slightly overpredicts the currents. However, the differences between the modeled results and actual measurements remain within the limits. Similarly, the modelled current direction agrees well with the actual measurements for most the simulations. Yet, the deviation in current's directions was still noticed in few occurrences as demonstrated in Figure 22 below. This might be due to irregularities in the measurements.

The current speed in Business Bay is very mild in the range 0.1m/s. The model slightly underpredicts the current speed at Business Bay during neap tide but the difference is less than 0.05m/s. Modelled current direction agrees well with the measurements for the majority of the simulation duration.

A very good fit is observed in terms of current speed at both the locations for both spring and neap tides and a good fit is observed in terms of current directions. A summary of the statistical analysis of model fit and visual analysis of the validation plots is provided in Table 5.

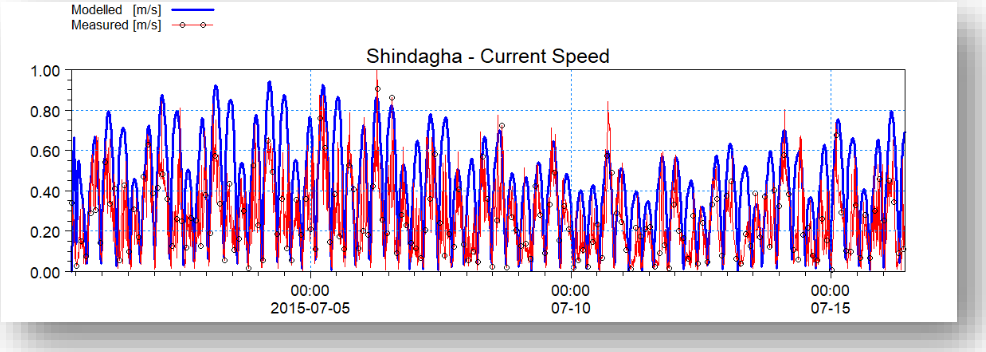


Figure 21: Comparison of measured (in red) and modelled (in blue) current speed at Shindagha

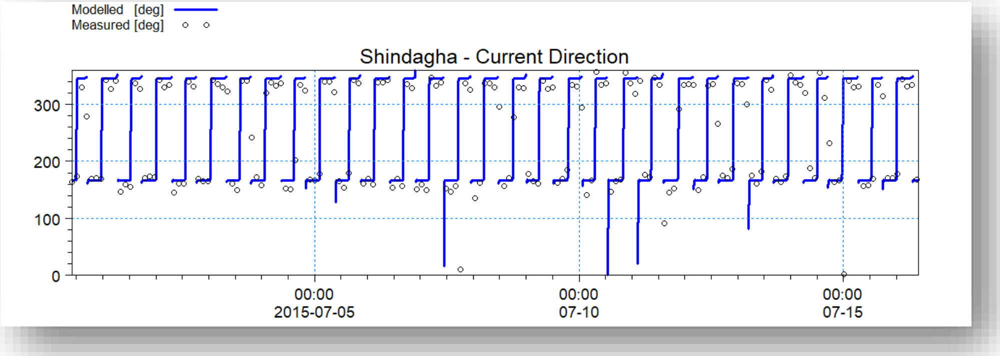


Figure 22: Comparison of measured (in red) and modelled (in blue) current direction at Shindagha

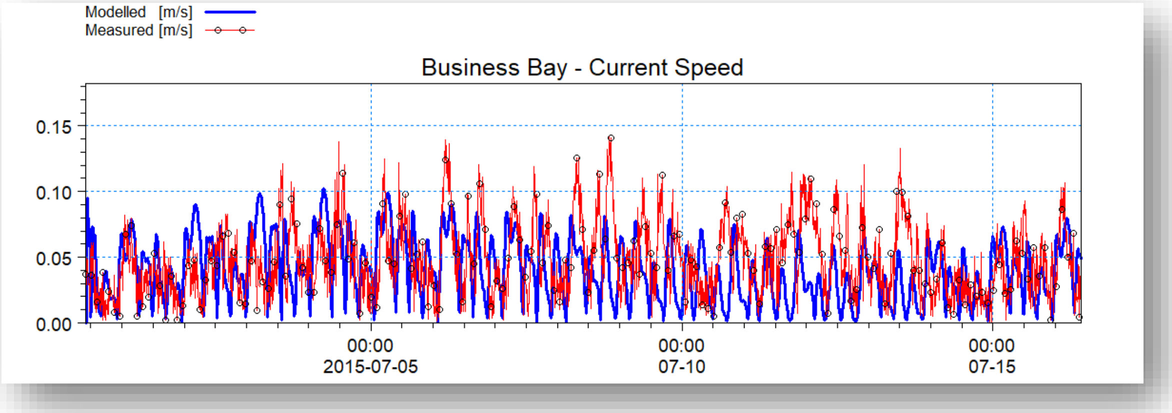


Figure 23: Comparison of measured (in red) and modelled (in blue) current speed at Business Bay

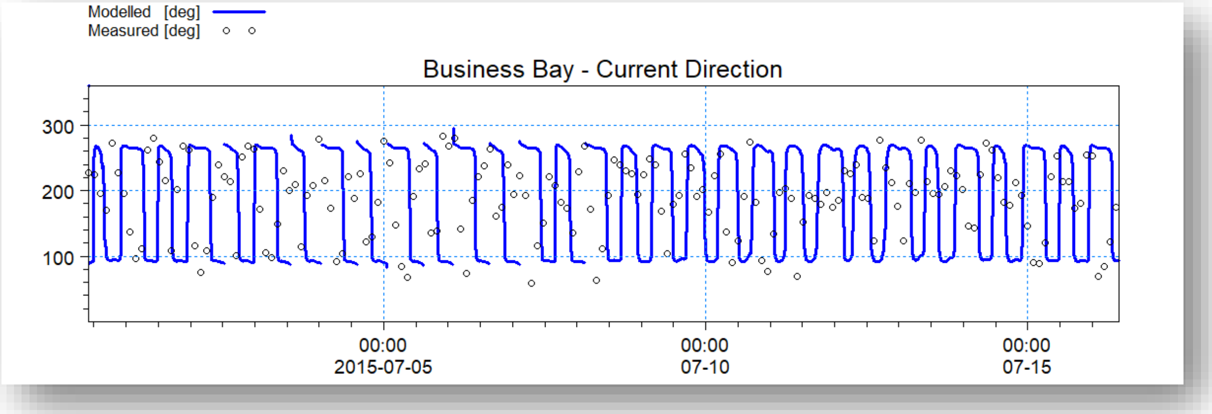


Figure 24: Comparison of measured (in red) and modelled (in blue) current speed at Business Bay

Table 5: Summary of Model Validation for Currents

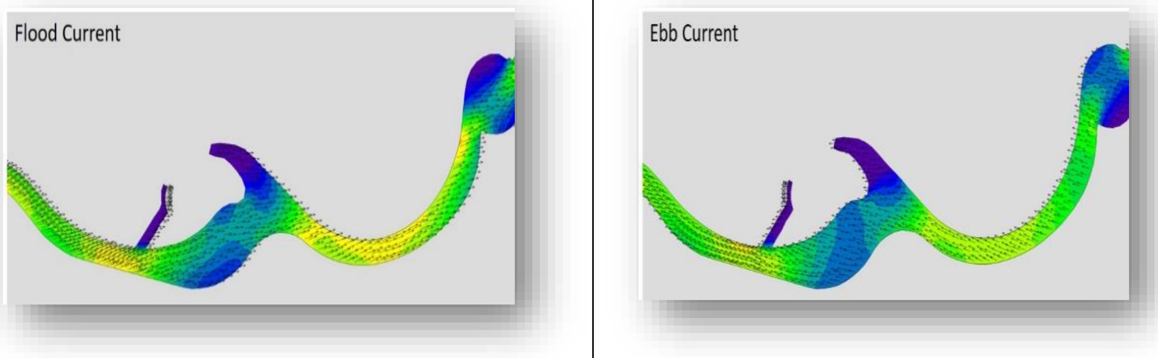
Location	**Time Period**	**Parameter**	**% Fit**	**Phase (min)**	
Shindagha Acoustic Doppler Current Profiler **(ADCP)**	Spring Tide	Speed	83%	-2	Very good fit in terms of current speed in both spring and neap tides
		Direction	81%	-6	
	Neap Tide	Speed	82%	-4	
		Direction	78%	-6	Very good fit in terms of current direction during spring tide and good fit during neap tide
Business Bay Acoustic Doppler Current Profiler **(ADCP)**	Spring Tide	Speed	85%	-3	A very good fit in terms of current speed in both spring and neap tides
		Direction	76%	-5	
	Neap Tide	Speed	83%	-4	
		Neap	75%	-5	Good fit in terms of current direction

4.2.4 Summary of Hydrodynamic Model

Hydrodynamic modelling is carried out in two steps. At first, a regional Arabian Gulf model is developed using MIKE software forced with Admiralty tidal predictions and is calibrated for water levels at various locations around the Gulf. A local model is developed covering the entire Dubai Creek and new Dubai Canal using MIKE 3 FM. The tidal boundary conditions for the local model at Shindagha and Jumeirah Open Beach are extracted from the regional model. The local model is calibrated and validated for water levels and currents at four locations along the canal.

Typical flood currents are characterized by water from the sea entering the canal from both north and south; boundary and ebb currents are characterized by water from canal area entering the sea. The flood and current in the new Dubai Canal are more or less similar and are in the range of 0.15 to 0.25m/s. The flood current in Dubai Creek is less when compared to the reversing ebb current. The flood current is in the range of 0.15 to 0.25m/s whereas strong ebb current of 0.4m/s is noticed in Creek area. The typical flood and ebb currents in the new Dubai Canal and Creek are shown in Figure 25 below.

New Dubai Canal



Creek

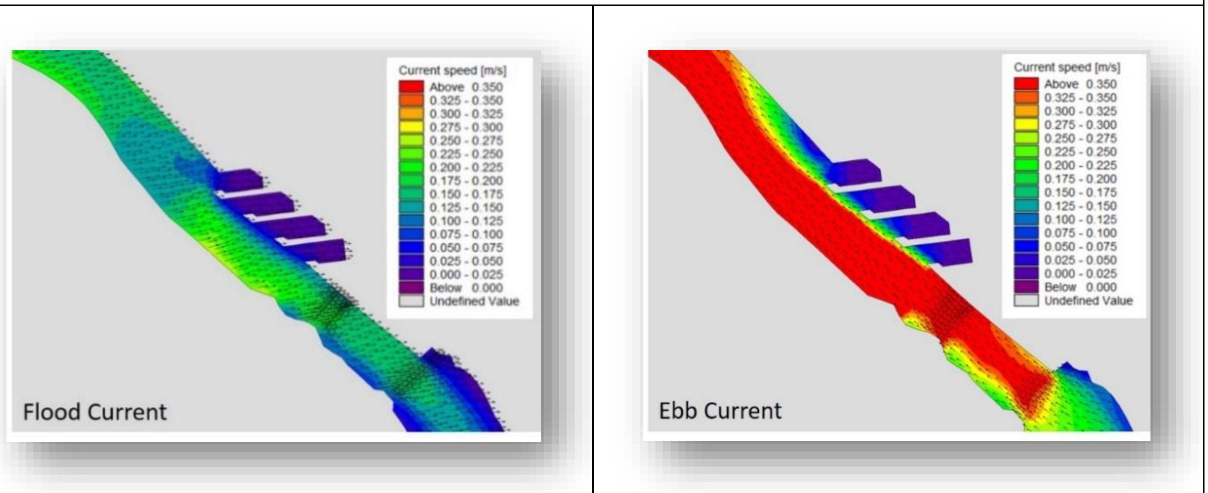


Figure 25: Typical flood and ebb currents in New Dubai canal and Creek area

The maximum current speed of more than 1m/s is noticed at both the entrances along Dubai Creek side and new Dubai Canal. The peak current speed inside the creek close to Business Bay and Dubai Festival City are in the range of 0.1 to 0.5m/s as demonstrated in Figure 26.

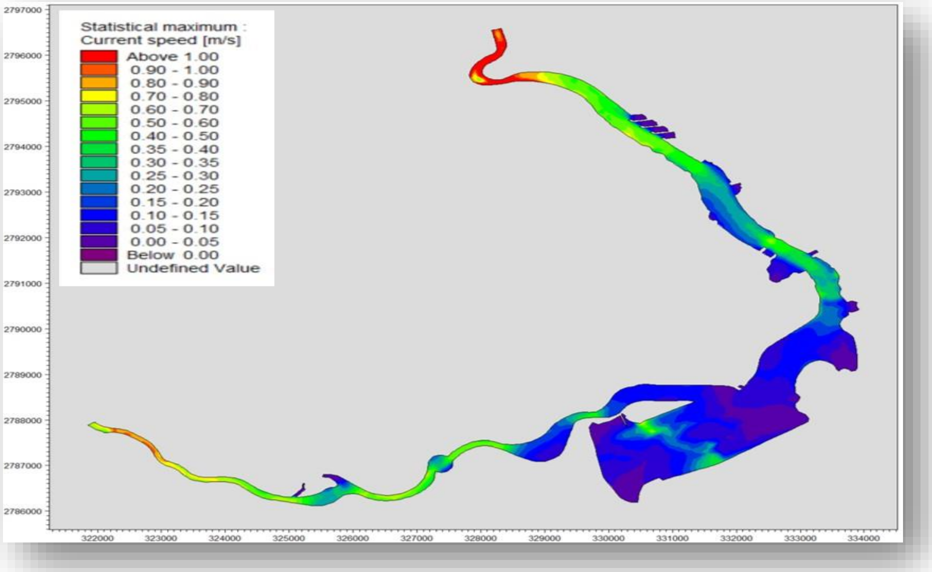


Figure 26: Statistical Maximum Current Speed over the simulation duration

To summarize, model validation demonstrates that the numerical model fully complies with the FWR water level guidelines. The modelled currents replicate the amplitude, phasing and mean flow axis with a high degree of accuracy. It can be concluded that the hydrodynamic model established a solid foundation for non-cohesive sediment transport assessment in the Dubai Canal.

4.3 Sediment Transport Modelling

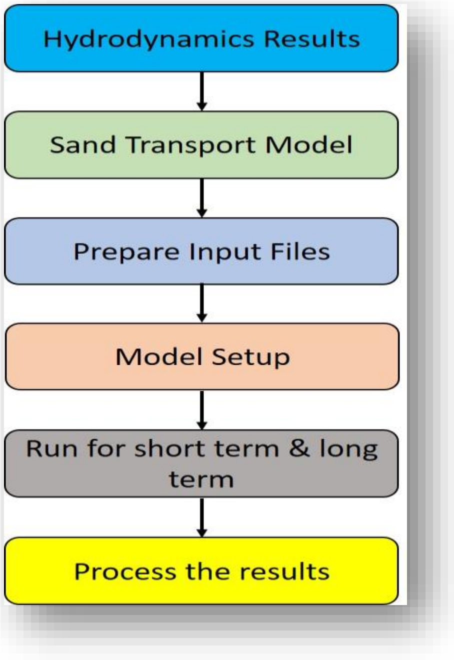


Figure 27: Sediment Transport Model Flowchart

Model type (pure current, and current plus waves) determines the necessary forcing to calculate the sediment transport. As the pure current model type is selected, only flow field is required which is provided by hydrodynamics (Figure 27). The dispersion usually describes transport due to non-resolved processes. In coastal areas it can be transport due to non-resolved turbulence or eddies. Especially in the horizontal directions the effects of non-resolved processes can be significant, and the dispersion coefficient depends on the resolution of mesh elements. The Smagorinsky formulation was selected as the eddy viscosity model for this study (Bing-Chen Wang 2005). The dispersion coefficient is usually one of the key calibration parameters for the Transport Module and in this study order of 1 is selected for scaled eddy viscosity formulation.

Initially the model is run for a short duration (i.e. 15 days) using Engelund and Hansen and Van Rijn theories to assess the short-term sediment transport along the canal and at the entrances. This study will be extended for 1 year by carrying out hydrodynamics for 1 year and sediment transport will be assessed for a long duration. The seasonality will be covered in yearly simulation, and it can be extrapolated for longer durations such as 5, 10 and 25 years.

4.3.1 Sedimentation Model Parameters

The parameters considered in the sand transport model are presented in Table 6 below (Jure Srše 2023):

Table 6: parameters considered in the sand transport model

Category	Parameters
Model definition	• Model Type – Pure current • Transport Description – Non-equilibrium • Forcing parameters – Depth-averaged velocity from hydrodynamics
Fraction Definition	• Bed and Suspended Load – Engelund and Hansen theory • Bed and suspended load Factor – 1
Sediment Properties	• Porosity – 0.4 (which is typical for sand) • D_{50} – 0.14mm • Relative density – 2.65
Bed Resistance	• Resistance Type – Taken from HD simulation
Dispersion	• Formulation – Scaled eddy viscosity formulation • Scaling factor – 1

Two schemes are currently considered for sand transport in the Dubai Canal and they are Engelund and Hansen (Total Load) and Van Rijn (Bed Load + Suspended Load).

4.3.2 Sedimentation model results

The model was run for 15 days for Scheme 1 and 2 and the results are extracted at five locations each at the new Dubai Canal and along the Creek for the whole duration of the simulation. The extraction locations along Dubai Canal and Creek are shown in Figure 28 and Figure 30 respectively. The bed change level plots for Dubai Canal and Creek are shown in Figure 29 and Figure 31 respectively. It must be noted that both in the new Dubai Canal and Creek area, slight sedimentation is noticed at the entrance and very low erosion is noticed in the inner edges of the canal. The high current speed at the entrance suddenly drops down resulting in sedimentation. The current speed is very weak inside the canal and very minor bed level change is noticed.

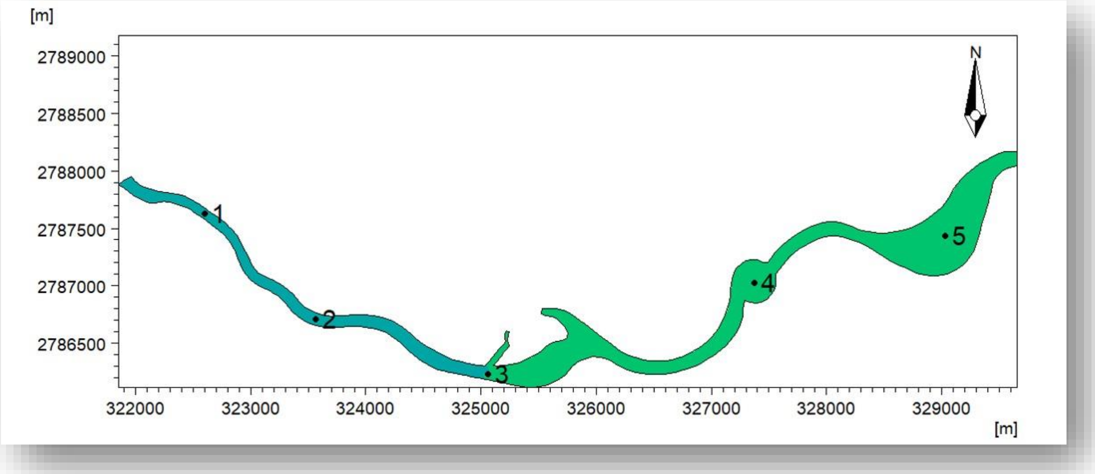


Figure 28: Extraction location for Bed Level Change along new Dubai Canal

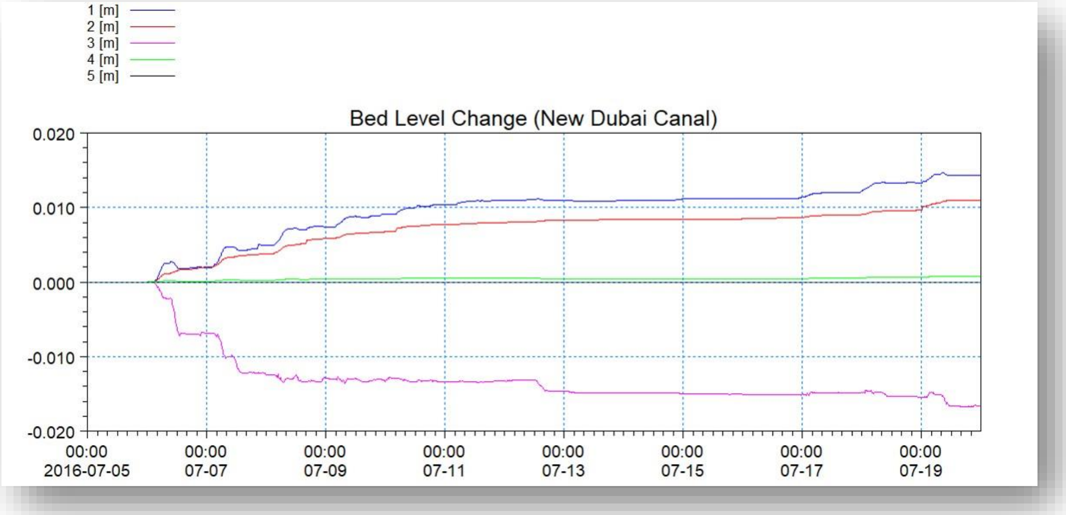


Figure 29: Time Series of Bed Level Change Along New Dubai Canal

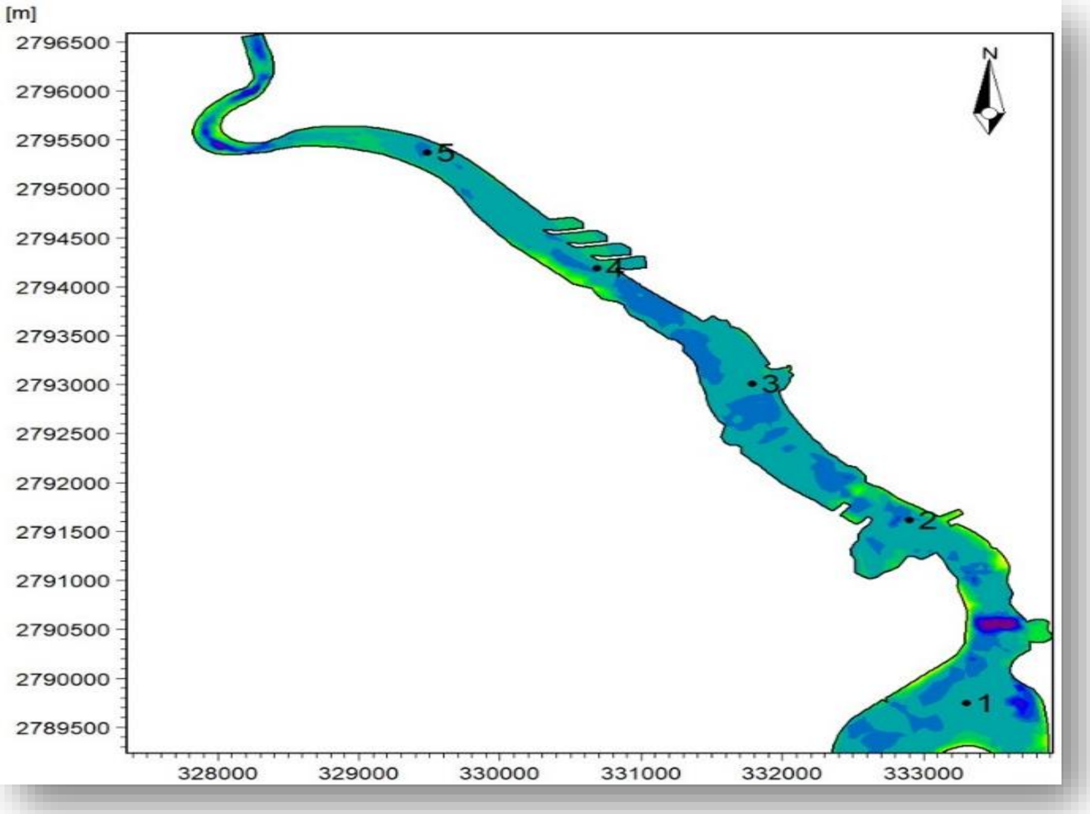


Figure 30: Extraction location for Bed Level Change along the Creek

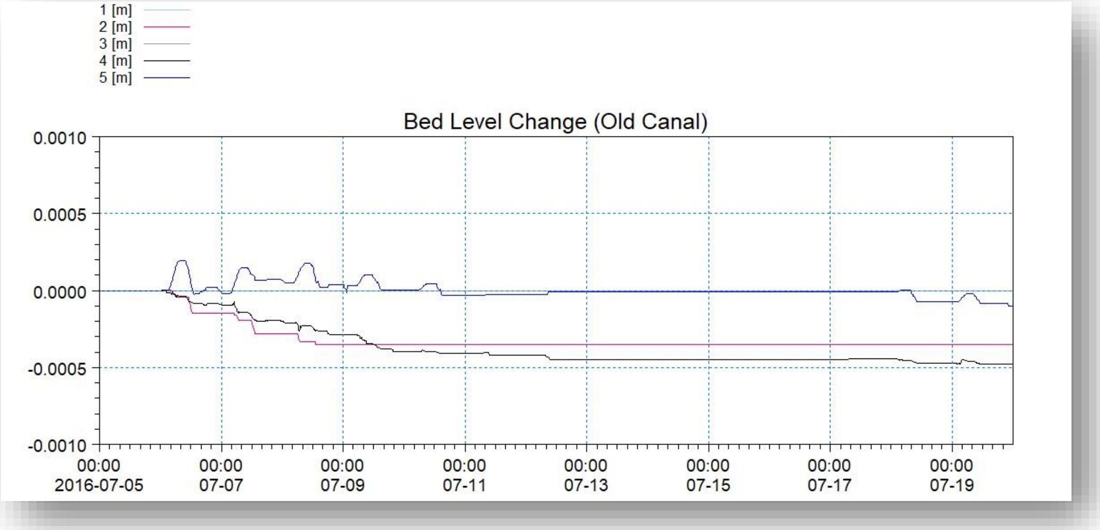


Figure 31: Time Series of Bed Level Change along Creek

As explained in Section 4.1, Engelund and Hansen (Scheme 1) and Van Rijn (Scheme 2) were simulated for 15 days to assess the bed level change and to carry out a comparison between two schemes. Figure 32 shows the bed level changes of both the schemes after 15 days of simulation. A slight difference is noticed in Scheme 2 where more positive bed level change is noticed compared to Scheme 1. However, the changes are very low in the order 1cm.

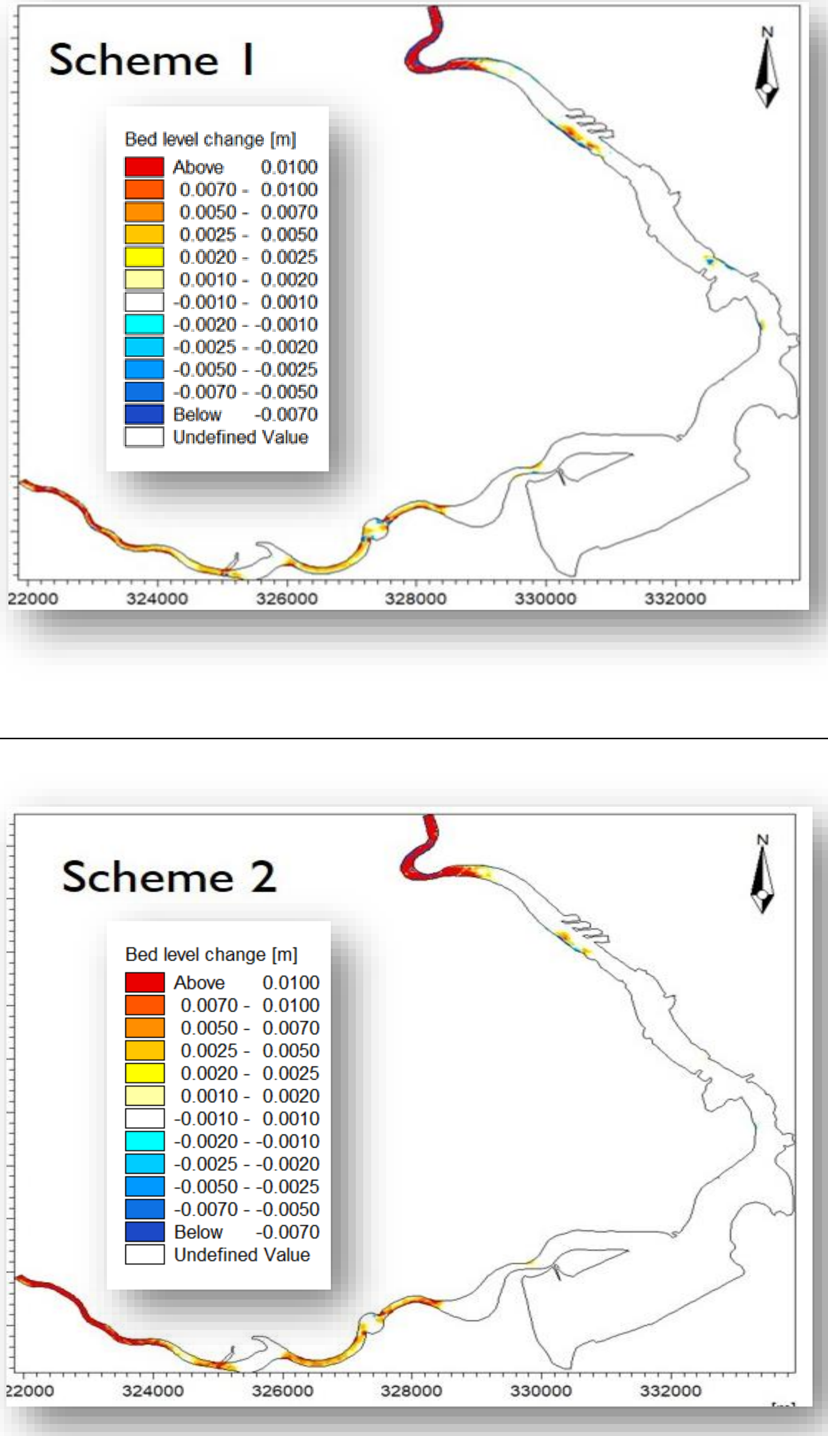


Figure 32: Comparison of bed level change between Scheme 1 and Scheme 2 after 15 days of simulation

The net transport is directed seawards and the net transport is lowest at the innermost portion of the canal and increases towards the entrances. The magnitude of the net transport when compared to the gross transport is close to zero along the inner part of the canal and increases in the outer parts. The low net transport in the innermost canal section is since the flow is evenly distributed across the canal for both inflow and outflow conditions. The bed level changes are assessed in three different locations along the canal (T1, T2 and T3 indicated in Figure 33). As the new Dubai Canal is our area of interest, the time series of bed level changes extracted from both the schemes is presented in Figure 34.

After 15 days of simulation, sedimentation of approximately 2mm (Figure 33) is identified at the entrances. If linearly extrapolated, sedimentation of 5cm and 50cm are predicted for 1 and 10 years respectively. It must be noted that sedimentation occurs only at the canal entrances and hardly any change in the seabed is noticed along the inner portion of the canal. This can be explained by low current speeds in the inner portion of the canal.

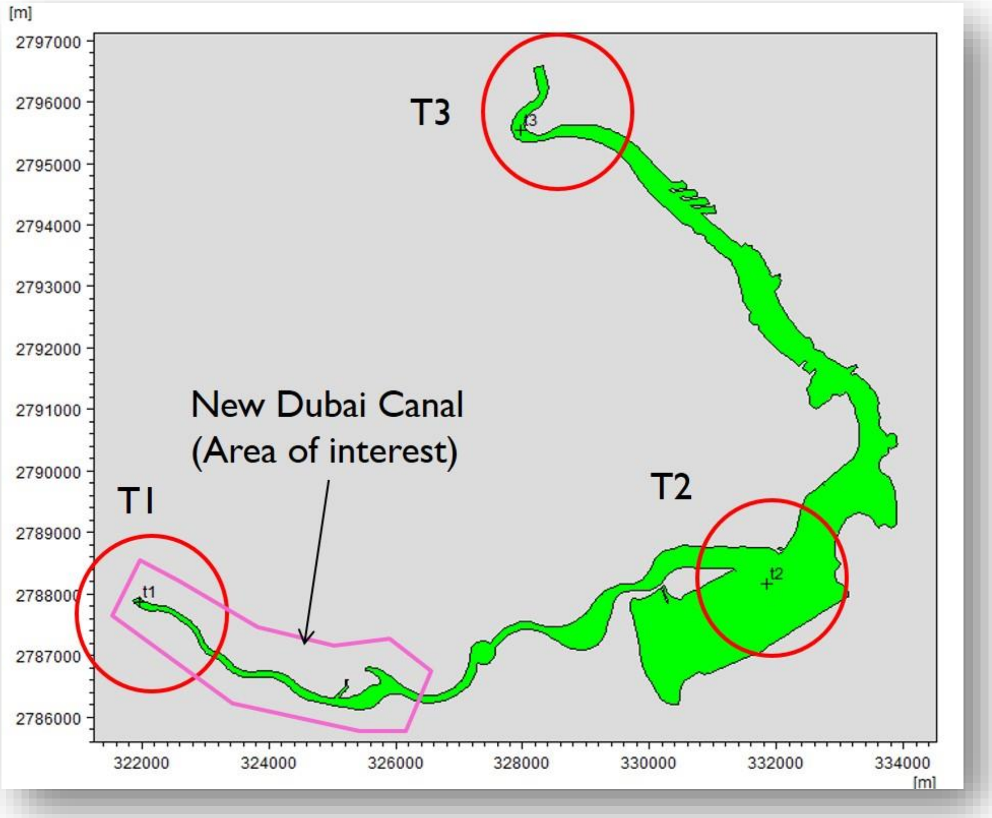


Figure 33: Extraction locations for assessing bed level change

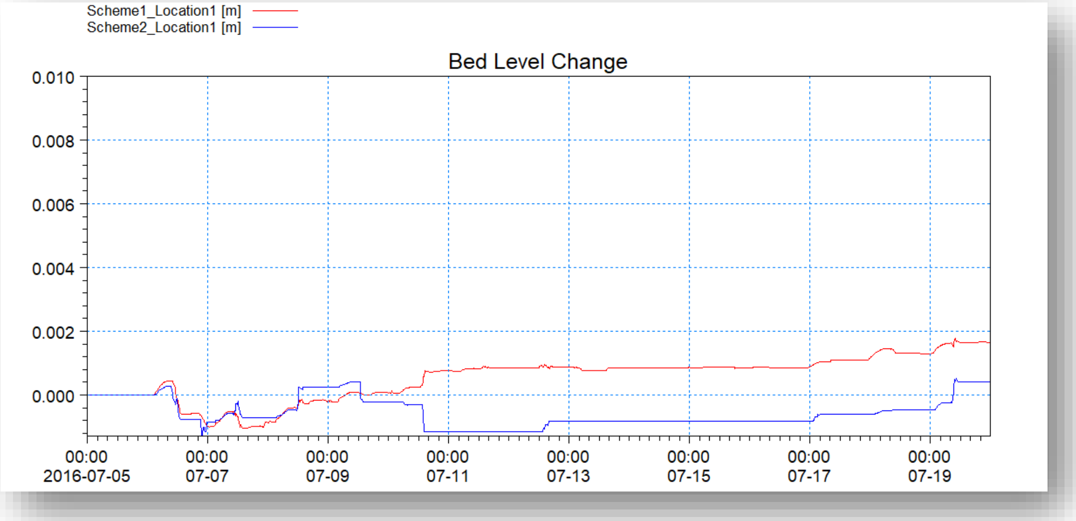


Figure 34: Bed Level Change

5 Discussion and Application

This Chapter is considered the transition from the results obtained in Chapter 4 towards the policy recommendation of the thesis illustrated in Section 6.1. A discussion will be delivered to create a link between the model's results outcomes and the problem that is likely to occur within the time span of the project. Furthermore, the relation between the model and the mitigation strategy will be discussed leading to clarifying how the model was used to solve the problem and deliver the strategy. Finally, the mitigation strategy will be explained and discussed highlighting the means and ways to achieve the desired goal including both design changes recommendations as well as the required maintenance scheme to be implemented.

5.1 Model prediction of sedimentation

As an outcome to the model and results explained in the previous chapter, it was witnessed that the model predicted accumulation of sediments in various locations such as the entrance of the canal, alongside the extended portions out of the canal as well bending parts of the canal (Figure 35).

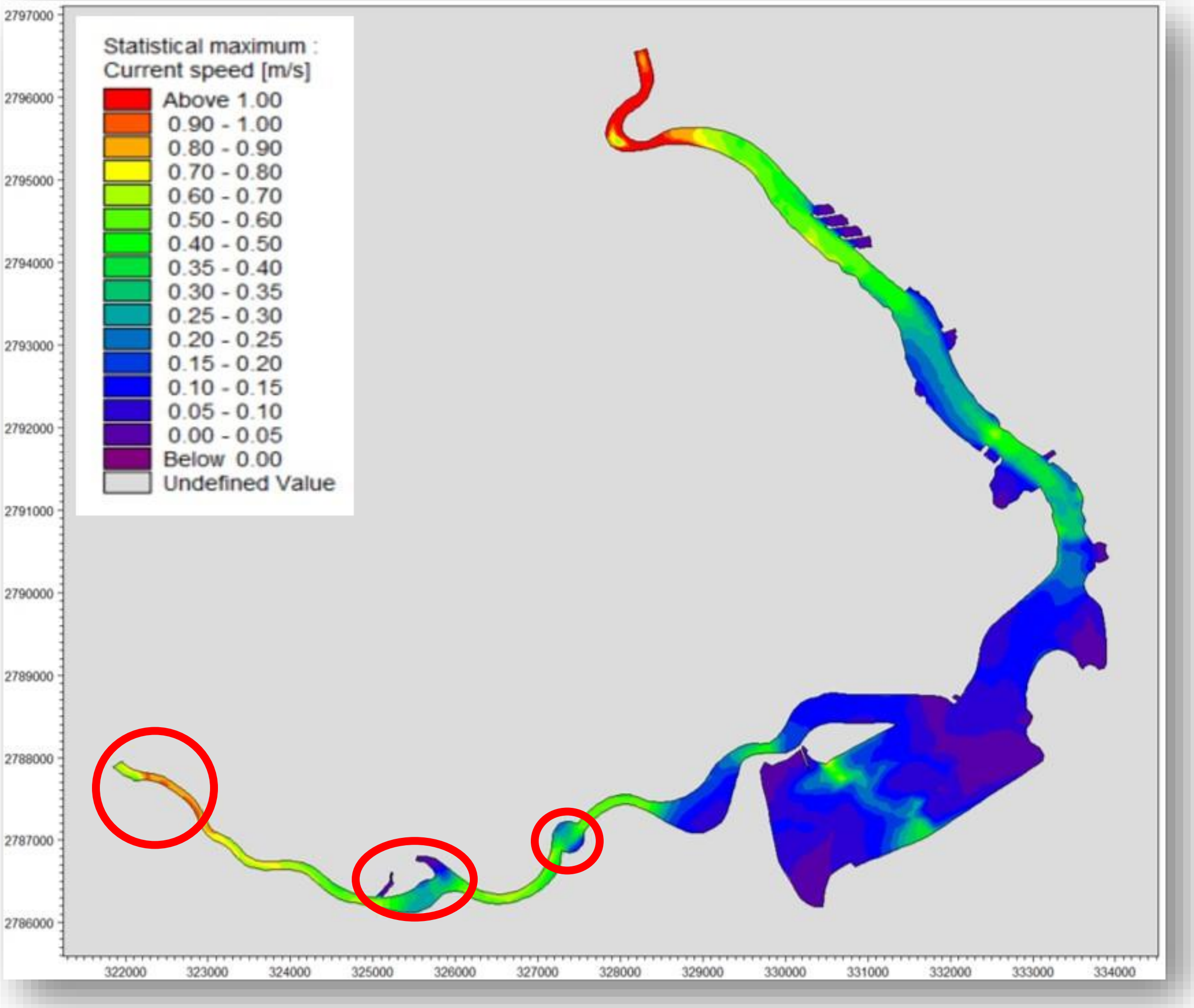


Figure 35: Location of sediment accumulation

The model used the algorithms to assess the area modelled in terms of hydrodynamics as well as sand transfer due to the nature of sand and the way they are affected by the water flow, and wave movement generated in the coastline adjacent to the canal's entrance.

Meanwhile, the canal's geometric features that consist of a 100m opening to the sea that decreases to the 80m wide canal stretching for 4 km into the mainland followed by unevenly distributed dimensions of a man-made water body, were a major driver for the model in the process of predicting the sedimentation that is likely to occur in the canal.

Therefore, the results, indicating that the major sedimentation would occur at the entrance of the canal are clearly justified by two major factors. The first is the turbulence caused by the tidal wave. The current will facilitate the sand movement and will keep the canal entrance section unstable allowing the sedimentation to occur in the location where the waterflow decreases its velocity. The second factor is the turbulence occurring due to wave reflection and diffraction while entering the canal from the sea. As the sediments transferred by the currents settle at the edges of canal, the waves facilitate its movement towards the centre of the entrance allowing the accumulation in the area. Besides, the waves play a major role in causing the disturbance of the water body during the low current period of the day.

5.2 Application of results to reduce sedimentation

As a result, the sedimentation likely to occur will cause a problem that will affect the usage of the canal. The first problem is related to the navigation as the canal entrance is considered the navigational gateway in and out of the canal for transportation and leisure vessels. Hence, the accumulative sedimentation will form an underwater sand bump that will result in decreasing the depth of the navigation channels causing vessels to get stuck while sailing.

The formation of sand bumps within the navigational channel occurs gradually over time. Normally, it is only noticed when a vessel gets stuck and needs a tugboat to pull it out. A corrective maintenance procedure then takes place by dredging the accumulated sediment and bringing the navigational channel back to its normal depth. In the case of this project, the model predicted the location and duration of sediment occurrence.

The model will provide clarity to the relevant authorities managing the waterways in Dubai in terms of the future behaviour of the water body. This will allow convenient management and handling of maintenance. Therefore, the model will play a major role in solving both navigation and maintenance problems caused by accumulating sediments in Dubai Canal.

5.3 Sedimentation mitigation strategies

The results clearly identify that there will be a problem and when is it likely to occur. Furthermore, to understand the significance of the results to the mitigation strategy, an assessment should be conducted of the effects of this problem to set out a proper strategy tackling the problem and limiting the likelihood of its reoccurrence.

By reviewing the results and witnessing the sediment occurrence in the locations identified, a further look into the geometric design of the canal is required. The changes of widths along the canal played a major role in the flow speeds and velocities which ended up in sediments collecting in these locations. Also, the curves and bends along the canal helped in channelling the sand transportation to accumulate the sediments and cause the increase in the bed levels. Therefore, the mitigation strategy will have to consider action measures to overcome the existing geometric design of the canal.

Additionally, the change in bed levels that is likely to occur will have an impact on the navigation route in the canal, for both private and public vessels. As a sub-bed change could occur, this might cause vessels to hit sand bumps during navigation causing disturbance and delays of vessels. To prevent this problem from occurring, the mitigation strategy should consider, besides mitigate the problem, precaution measures aiming to eliminate any dredging requirements and avoiding stopping navigation activities.

Overall, these indications could be taken forward by putting in place a complete mitigation strategy including taking corrective measures to slow the sedimentation as well as putting in place a preventive maintenance plan tackling the problem before it occurs.

5.4 Mitigation strategy

The model developed in this project provided an insight on how the canal bed will look during the upcoming 30-year period. The model showcased the significant change that is likely to take place and the increase in bed level that will occur. Although the results were expected, it was not known when and where the sediment will occur. Therefore, the model clarified the vision of what will happen compared to what is needed or wanted by the canal operators as well as the entities responsible for navigation.

The model specified areas of concern according to a time frame set for the span of 50 years. Additionally, the model provided the illustration via images, graphs, and videos of how the gradual sediment accumulation will take place during the time frame. This provides clear insights on the frequency of corrective measures and preventive actions that should be considered within the mitigation strategy.

Based on these outcomes, the results obtained from the model will be used as a basis for this project outcome. The strategy will be driven from the major problems that the model identified within the results generated. Hence, the strategy will consist of two main elements: the mitigation strategy and the preventive action plan. The areas and location where sedimentation is likely to accumulate will be investigated from a prospective of change design that aims to eliminate or reduce the sedimentation occurrence. Following this approach, the sedimentation occurrence by itself will be investigated from a prospective of preventing the sand bumps from reaching the limit in which it will impact negatively on the navigation channel and vessels' draft. Therefore, the mitigation strategy will completely rely on the outcomes of the results generated by the model in putting in place a mitigation strategy and a future policy recommendation for sustaining the canal flow, water quality, and most importantly the navigation in the canal.

Based on the discussion above, it will be essential to drive a mitigation strategy to overcome the problems identified from the model results. The strategy will aim to use all available means, tools and resources within the capacity of the government of Dubai and utilize them in the best possible way to achieve the desired goals and end results. Keeping in mind, the strategy will have to take into consideration the financial feasibility of the approach beside the technical capability of the resources available in Dubai. Accordingly, the recommendation will balance between maintaining the existing features, both visual and functional, of the Dubai Canal and the required alterations that should take place to overcome the expected setbacks due to sedimentation occurrence and disturbance to water flow and navigation. Mainly the strategy will focus on conducting minor alterations that will aim to eliminate or reduce the sedimentation in the canal bed as well as put in place the required preventive maintenance needed for the continuity of the canal’s navigational functions.

Mitigation Strategy: Eliminating and reducing sedimentation occurrence, plus preventive maintenance.

5.4.1 Design changes

The two steps identified in the mitigation strategy described above kick off by tackling the origin of the main problem of sedimentation aiming to eliminate the occurrence or to reduce the pace of its development. To do so, certain changes will be required to affect the water flow and sand transportation within the canal. Taking into consideration the enormous cost of construction, besides the difficulty of conducting major design changes that will require major construction works, it will be more appropriate for the design change scheme to take the path of add-ons into the existing structure rather than demolishing sections or widening parts of the canal. This approach will require further studying and modelling in order to test the efficiency and effectiveness of the suggested alteration. However, the preliminary concept of the design change will be discussed below.

The first approach will be to consider the addition of tidal flaps between the three locations where the sediments are likely to occur. Tidal flaps are mechanical structures that are reducing and widening the width of any water canal structure according to the required flow rate at a given point in time. Hence, the tidal flaps will be wide open during high tides working as boosters for the water flow going out of the canal during this period. This will act as a natural flush to the unsettled sediments and will support the sand transportation to flow out of the canal. On the other hand, during low tide, the flaps will close allowing the normal canal width to take place to reduce the flow rate from the sea into the canal. In order to go through with this approach, the parameters of the tidal flaps should be incorporated in both hydrodynamic and sand transportation numerical models used in this project to provide a better understanding on the significance of this change.

The second approach that might be investigated is the addition of tidal gates in the canal. The tidal gates have similar functionality to the tidal flaps described above with a higher effectiveness and impact on flow rates within canals. However, the cost of installing a tidal gate is enormous and might not be feasible to tackle the sedimentation problem.

The third possible change to be considered is the addition of a pumping system to facilitate flow rate in the canal. The system will generate current allowing the flow velocity to increase from the canal towards the open sea. The flow will help in transferring the sediments out of the canal. The benefits of using a pumping system to generate the current is the ability to control the time of the flow, while in comparison with tidal flaps and tidal gates, the time is identified according to the tidal time during the day. However, the downside of this approach is the large operational expenses generated from fuelling and maintaining the pumps. Overall, this approach will require further modelling beside the feasibility study.

The fourth and final change design suggested is the installation of fountains in several locations in the canal. Although fountains will not facilitate the flow rate or affect the flow velocity in the canal, the fountains will prevent the settlement of sediments due to the water circulation disturbance occurring when operating fountains in a certain area. The unsettled sediments will be likely to exit the canal along the normal tidal current generated by high and low tides on a daily basis. Additionally, having fountains in the canal - away from the navigation route - will create a visual enhancement in the canal and help improve and maintain the required water quality.

Overall, as a next step, the design change approach within the strategy will require an intensive feasibility study followed by incorporating the options in the numerical model and testing the change in sedimentation occurrence if the option was applied.

5.4.2 Preventative scheme

The second step in the mitigation strategy is to put in place a preventive scheme that will capture the sedimentation which is likely to occur after implementing the design change scheme. The preventive measure will aim to tackle any sediment occurrence during the accumulation phase before it reaches a limit which might cause a disturbance to the navigation channel and be quite difficult to solve.

The preventive scheme should include a proper real-time monitoring system in the expected locations where sediments may accumulate. The monitoring could be a scheduled bathymetric survey conducted regularly or by visual monitoring using divers or underwater imaging that will clearly demonstrate any change in the bed level. Additionally, a preventive maintenance plan will be put in place that will include regular scheduled underwater surface levelling. This method is conducted by sinking a levelling lever and tugging it along the navigational channel in the canal. This approach will substitute the dredging solution as it (the dredging solution) is more expensive and causes huge disturbance to the ongoing activities in the canal.

Moreover, the preventive maintenance scheme is essential to secure the business continuity in the canal, prevent sudden major works from taking place in the canal and preserve the Dubai Canal as a navigational and tourist attraction in Dubai.

6 Conclusion

The model predictions revealed sediment accumulation at the canal entrance, attributed to tidal turbulence and wave dynamics. This sedimentation poses challenges to navigation, forming sand bumps that impede vessel movement. The model offers insights for effective waterway management, playing a crucial role in addressing navigation and maintenance issues. Considering the geometric design's influence on sedimentation, the mitigation strategy encompasses design alterations and preventive measures.

The proposed mitigation strategy relies on the model outcomes, emphasizing a balance between maintaining existing features and necessary alterations to counter sedimentation impacts. The strategy suggests minor alterations and a preventive maintenance plan to ensure continued canal functionality. Design changes involve the addition of tidal flaps, gates, a pumping system, and fountains to manage water flow and sediment transportation. These changes aim to mitigate sedimentation occurrence and reduce the need for corrective measures, incorporating feasibility studies and modeling for validation.

6.1 Drive policy recommendation

As an outcome to the discussion conducted in this chapter, a set of recommendations was proposed. The recommendations which are aligned with the mitigation strategy explained above aim to tackle the problems likely to occur in the Dubai Canal maintain all navigational activities taking place in Dubai canal and preserve the Dubai Canal as a desired tourist and leisure destination. In order to achieve the maximum gain from the available resources, it was essential to leverage on the capabilities of both technical and human capital available in Dubai. Additionally, it is vital that Dubai preserve its image as a maritime and tourism destination. Finally consider the economic impact on any further activities likely to occur. Accordingly, the following policy recommendations were listed:

- It is recommended that the government of Dubai partners with both Academic entities and Technical Laboratory firms to conduct the further required studies
- The Government of Dubai should take this project further and investigate the change design options.
- It will be essential for Dubai Municipality to carry on the regular monitoring scheme, especially in the locations identified in the model as potential for sediment occurrence.
- The responsibility for maintaining the Dubai Canal should be assigned to a reliable authority (Dubai Municipality or Roads and Transport Authority) tasked to put in place and conduct a comprehensive preventive maintenance plan.

6.2 Limitations

The study on sedimentation in Dubai Canal acknowledges several potential limitations that may influence its findings and proposed mitigation strategies. The first limitation with regards to the accuracy of predictions is contingent on the modeling method (MIKE 3) including uncertainties arise from model resolution, parameterization, boundary conditions, and the complexity of coastal processes and the quality of input data, introducing uncertainties if proves inaccurate. Moreover, the limitations of reliance on assumptions and input data quality, leading to errors in model predictions. Assumptions made regarding sedimentation behavior, canal dynamics, and environmental factors may be sensitive and impact the reliability of outcomes. Natural environmental variability, changes in human activities, budget constraints, evolving regulations, societal and political factors, and technological constraints are all potential limitations that could influence the successful implementation of the proposed strategies. Recognizing and addressing these limitations is crucial for ensuring the study's outcomes align with the dynamic and multifaceted nature of the Dubai Canal and its surrounding environment. Additionally, numerical modeling allows a range of error up to 10% that could be accepted. Therefore, the results will always be subjected to the allowed error percentage.

6.3 Contribution to Knowledge

In summary, this project contributed to knowledge by the following means:

1) Application of numerical modeling to identify the causes and provide solutions to sedimentation problems in Man-made Marine Canals for the first time in the UAE and Gulf Region
2) Exploring the use of Numerical Modelling for sustainable designing, building and maintenance of man-made water bodies in the Gulf Region

7 References

ADMIRALTY Vector Chart Service (AVCS). 2024. *ADMIRALTY Maritime Data Solutions.* https://www.admiralty.co.uk/charts/digital-charts/admiralty-vector-chart-service.

Ahn, Jungkyu, Yeji Na, and Sung Won Park. 2019. "Assessment of water quality in an artificial urban canal: A case study of Songdo City in South Korea." *Environmental Engineering Research* 24 (4): 582-590. doi:https://doi.org/10.4491/eer.2018.286.

Alexander J. Gatch, Scott T. Koenigbauer, Edward F. Roseman, Tomas O. Höök,. 2021. "Assessment of Two Techniques for Remediation of Lacustrine Rocky Reef Spawning Habitat." *North American Journal of Fisheries Management* (484-497). doi:10.1002/nafm.10557.

Alfonsi, Giancarlo. 2009. "Reynolds-Averaged Navier-Stokes Equations for Turbulence Modeling." *Applied Mechanics Reviews*, July: 040802-20. doi:10.1115/1.3124648.

BaoshengWU, D.S.van MAREN, and LingyunLI. 2008. "Predictability of sediment transport in the Yellow River using selected transport formulas." *International Journal of Sediment Research* 23 (4): 283-298. doi:https://doi.org/10.1016/S1001-6279(09)60001-9.

Bing-Chen Wang, Donald J. Bergstrom. 2005. "A general optimal formulation for the dynamic Smagorinsky subgrid-scale stress model." *International Journal for Numerical Methods in Fluids* 49 (12): 1359-1389. https://doi.org/10.1002/fld.1031.

C.W.Li, and C.Zeng. 2009. "3D Numerical modelling of flow divisions at open channel junctions with or without vegetation." *Advances in Water Resources* 32 (1): 49-60. doi:https://doi.org/10.1016/j.advwatres.2008.09.005.

Cavalcante, Geórgenes H., Björn Kjerfve, David A. Feary, Andrew G. Bauman, and Paolo Usseglio. 2011. "Water Currents and Water Budget in a Coastal Megastructure, Palm Jumeirah Lagoon, Dubai, UAE." *Journal of Coastal Research* 384–393.

Coastal Section of Dubai Municipality. 2017. "Dubai Coast Marine Data Set." *Dubai Coast Marine Data Set.* Dubai: Dubai Municipality.

Courtney K. Harris, Peter A. Traykovski,W. Rockwell Geyer. 2005. "Flood dispersal and deposition by near-bed gravitational sediment flows and oceanographic transport: A numerical modeling study of the Eel River shelf, northern California." *Journal of Geophysical Research: Oceans* 110 (C9): 1883-1891. doi:https://doi.org/10.1029/2004JC002727.

D.S. van Maren, J.C. Winterwerp. 2013. "The role of flow asymmetry and mud properties on tidal flat sedimentation." *Continental Shelf Research* (Elsevier) 60: S71-S84. doi:https://doi.org/10.1016/j.csr.2012.07.010.

Engineering, Nakheel Marine. 2014. *Incident Report 8.* record, Dubai: Nakheel.

Environmental Department, Dubai Municipality. 2010. *Coastal Development Guidelines for Dubai Coast.* Dubai: Dubai Municipality.

Frings, Roy M., and Wilfried B. M. Ten Brinke. 2018. "Ten reasons to set up sediment budgets for river management." *International Journal of River Basin Management* 16 (1): 35 - 40. https://doi.org/10.1080/15715124.2017.1345916.

Ghamry, Haitham K., and Peter M. Steffler. 2010. "Two-dimensional depth-averaged modeling of flow in curved open channels." *Journal of Hydraulic Research* 44-45. doi:https://doi.org/10.1080/00221680509500110.

Gunaratna, Priyantha, and Thamali Gunaratna. 2012. "3D Numerical Modeling of Hydrodynamics in the Dubai." *Journal of Shipping and Ocean Engineering* 283-292.

Guoquan, WANG. 2021. "Impact Analysis of River Excavation on the Deformation of an Underlying Shielded Tunnel." *Soil Engineering and Foundation* 290-296.

Haiyan Li, Anbang Shi, Mingyi Li, Xiaoran Zhang. 2013. "Effect of pH, Temperature, Dissolved Oxygen, and Flow Rate of Overlying Water on Heavy Metals Release from Storm Sewer Sediments." *Journal of Chemistry* 2013. doi:https://doi.org/10.1155/2013/434012.

J. L.R. Manoj Kumara, H. S. LakmalPerera. 2017. "DESIGN OF A BARGE FOR SMALL SCALE EXCAVATOR IN NARROW CANAL." *International Research Journal of Mathematics, Engineering and IT* 4 (10).

Jure Srše, Marko Perkovič, Aleksander Grm. 2023. "Sediment Resuspension Distribution Modelling Using a Ship Handling Simulation along with the MIKE 3 Application." *Journal of Marine Schience and Engineering* 11(8). https://doi.org/10.3390/jmse11081619.

K.Jha, Sanjeev, and Fabián A.Bombardelli. 2011. "Theoretical/numerical model for the transport of non-uniform suspended sediment in open channels." *Advances in Water Resources* 34 (5): 577-591. doi:https://doi.org/10.1016/j.advwatres.2011.02.001.

Kim, Jin-Man, and In-Jong Moon. 2017. "Evaluation System of River Levee Safety Map for Improving River Levee Maintenance Technology." *Journal of the Korea Academia-Industrial cooperation Society* 18 (12): 768-777. doi:https://doi.org/10.5762/KAIS.2017.18.12.768.

Lee, Sangeuna, Jin-Won Park, Dong Sop Rhee, Du Han Lee, Dong Hyun Kim, and Seung Oh Lee. 2021. "Building technical and institutional capacities towards new river maintenance." *Journal of Korea Water Resources Association* 54 (11): 849-862. doi:10.3741/JKWRA.2021.54.11.849.

Lu, Xiaorong, Xuelei Wang, Xuan Ban, and Vijay P.Singh. 2020. "Transport characteristics of non-cohesive sediment with different hydrological durations and sediment transport formulas." *Journal of Hydrology* 591: 125489. doi:https://doi.org/10.1016/j.jhydrol.2020.125489.

National Oceanic and Atmospheric Administration. 2016. *National Oceanic and Atmospheric Administration.* May 9. Accessed 2022. https://shoreline.noaa.gov/data/datasheets/wvs.html.

National Research Council. 1987. *Sedimentation Control to Reduce Maintenance Dredging of Navigational Facilities in Estuaries.* Washington DC: National Academy Press.

Ole Secher Madsen, M.ASCE and William D. Grant , A.M.ASCE. 1976. "Quantitative Description of Sediment Transport by Waves." *Coastal Engineering 1976* 1092 - 1112. doi:https://doi.org/10.1061/9780872620834.065.

Padron, Dennis V., Shubhra Misra, Peter Rasch, Daoxian Shen, Andrew Driscoll, Ehab Tanagho, and William Allsop. 2010. "No AccessExpansion of Jebel Ali Port." *essential engineering knowledge.*

Partheniades, Emmanuel. 2009. *Cohesive Sediments in Open Channels: Properties, Transport, and Applications.* Oxford: Butterworth-Heinemann. doi:https://doi.org/10.1016/B978-1-85617-556-2.X0001-7.

Raiverman, V, S V Kunte, and A Mukherjea. 1984. "Basin geometry, Cenozoic sedimentation and hydrocarbon prospects in north western Himalaya and Indo-Gangetic Plains." *Petroleum Asia* (ETDEWEB) 6 (4): 67-92.

Sánchez, Alejandro, and Weiming Wu. 2011. "A Non-Equilibrium Sediment Transport Model for Coastal Inlets and Navigation Channels." *Journal of Coastal Research* 39–48. doi:https://doi.org/10.2112/SI59-005.1.

Shen, Hsieh Wen. 1999. "Flushing sediment through reservoirs." *Journal of Hydraulic Research* 37 (6): 743-757 . doi:https://doi.org/10.1080/00221689909498509.

Shuai-shuai Zhang, Sheng-fa Yang, Shi-yu Zeng & Xin-yu Liu. 2022. "Analysis of the effect of unsteady reservoir flow and sand excavation on the channel conditions of the Yangtze River (Yibin-Chongqing)." *SN Applied Sciences.* doi:https://doi.org/10.1007/s42452-022-05032-w.

The British Oceanographic Data Centre (BODC). 2023. *General Bathymetric Chart of the Oceans GEBCO.* https://www.gebco.net/data_and_products/gridded_bathymetry_data/version_20100927/.

The Water Research Foundation. 2010. "Guidelines for Developing, Calibrating, and Using Hydraulic Models." *The Water Research Foundation.* Accessed 2017. https://www.waterrf.org/research/projects/guidelines-developing-calibrating-and-using-hydraulic-models.

Van Rijn, Leo C. 2007. "Unified view of sediment transport by currents and waves. II: Suspended transport." *Journal of Hydraulic Engineering* 133: 668-689.

Vilenica, Marina, Ivana Pozojević, Natalija Vučković, and Zlatko Mihaljević. 2020. "How suitable are man-made water bodies as habitats for Odonata?" *Knowledge and Management of Aquatic Ecosystems.* doi:https://doi.org/10.1051/kmae/2020008.

Walter R. Hill, Michael G. Ryon,Elizabeth M. Schilling. 1995. "Light Limitation in a Stream Ecosystem: Responses by Primary Producers and Consumers." *Ecology* 76 (4): 1297-1309. doi:https://doi.org/10.2307/1940936.

WR WHITE, E MEYER PETER, J ROTTNER, ENGELUND, F, P ACKERS, H MILLI, R MULLER, AA BISHOP, E HANSEN, AD CRABBE, HA EINSTEIN, RA BANGOLD, FB TOFFALETIS. 1975. "SEDIMENT TRANSPORT THEORIES." *Proceedings of the Institution of Civil Engineers* 59 (2): 265-292. doi:https://doi.org/10.1680/iicep.1975.3740.