WATER QUALITY MODELING OF DUBAI CREEK USING HEC-RAS

by

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Approval Signatures

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Dedicated to my inspiring parents

Abstract

The quality of the water resources is facing threats because of the continuous urbanization. This increase in human activities around the coastal areas changed the water quality, affecting the aquatic ecosystem. Eutrophication occurs when high levels of nutrients cause algal bloom. The water quality modeling can be a useful tool for assessing water bodies. Dubai Creek can be defined as a tidal marine water body located in Dubai, UAE. As Dubai witnessed a rapid urbanization in recent years, the creek has been detrimentally affected. The objective of this study was to develop a hydrodynamic model coupled with water quality model for the Dubai Creek to assess and understand the processes affecting the creek. A 1D hydrodynamic model of the Dubai Creek was constructed using the HEC-RAS software, and it was coupled with a water quality model to evaluate the amount, source and distribution of algae, dissolved oxygen, nitrate and orthophosphate. The hydrodynamic model was calibrated using historical water levels along the creek, and the water quality model was calibrated and validated for the targeted parameters by comparing them with the available data. The model results showed an increase in the algae from the Creek Mouth station to Sanctuary station, and the nutrients showed high concentrations in the STP Outfall station. However, dissolved oxygen had the highest concentration recorded in the Creek Mouth station and the lowest in Wharfage station. The different scenarios were also investigated, and the result showed that changing the algae concentration in Sanctuary station didn't impact the creek stations except STP Outfall recorded 0.0024 mg/L of algae. On the other hand, utilizing nitrate at 2 mg/L in STP Outfall showed a reduction the nitrate concentration along the creek.

Search Terms: HEC-RAS; 1D model; Hydrodynamic modeling; Water quality modeling; Dubai Creek

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Chapter 1: Introduction

1.1. Background

Surface waters such as rivers, lakes and oceans provide humans with food, transportation and recreation; however, they are also critical recipients for the waste. Around 77% of pollution in the ecosystems comes from the human activities [1]. Spuriously there are $6500x10^6$ tons of waste dumped into the different surface waters worldwide each year [1]. There are two types of chemical contaminations that enter the ecosystems; inorganic (phosphates, nitrates and metals) and organic (pesticides and hydrocarbons). Understanding the water quality pattern is necessary to identify the distribution, growth and physiological function of aquatic ecosystems [1].

The Arabian Gulf has been contaminated with various pollutants affecting the biological life. During the Gulf War, oil disposal in addition to the untreated waste water discharge in Kuwait shores caused the water quality degradation in the region [2]. The eutrophication has been recorded as a result of the high levels of nutrient in the coastal regions, causing high risk to the aquatic life and the recreational facilities [3]. Therefore, the evaluation of the nutrient levels, such as the phosphate, nitrate, nitrite and ammonia, to assess the water quality degradation is a necessity. The marine coastline of United Arab Emirates (UAE) includes Abu Dhabi, Sharjah, Dubai, Ajman, Ras Al Khaimah and Fujairah, located near to the Straits of Harmouz at the lower part of the Arabian Gulf, and the eastern coast is located on the sideways of the Gulf of Oman. The water bodies of Dubai, Sharjah and Ajman were examined for chosen nutrients and bacterial communities, however, the results were similar to the pre-war data [3]. Dubai Creek has recorded high nutrient levels with some variations due to anthropogenic activities [3]. During spring and summer seasons, the presence of microorganisms was at a higher level than the winter session [3]. However, the study did not identify any significant problems with the water bodies in the UAE in terms of nutrients and microbial communities [3].

1.2. Problem Statement

In recent years, UAE had an increase in its population due to a massive urbanization. Dubai Creek is a salt water creek in Dubai which has been impacted by the urbanization. The anthropogenic activities including disposal of treated municipal wastewater, storm water, industrial shipping and agricultural activities can have significant impact on the water quality of the creek. The water quality degradation in Dubai Creek is a serious concern which needs to be investigated to preserve the aquatic life and the tourism activities of Dubai. Hydrodynamic model coupled with water quality model are necessary to investigate the impact of anthropogenic activities on the Dubai Creek. There was no previous study conducted on the Dubai Creek to develop these types of models. Therefore, development of such a model can contribute significantly to the analysis of water quality in Dubai Creek.

1.3. Research Objectives

The overall objective of this study was to examine the water quality degradation in Dubai Creek. The specific objectives of the study were to:

- Develop a 1D hydrodynamic model integrated with a water quality model for Dubai Creek.
- Study and assess the factors (algae, dissolved oxygen, nitrate and orthophosphate) affecting the pollution in Dubai Creek.

1.4. Study Area

Dubai Creek divides Dubai city into two halves; Deira and Bur Dubai [4] (Figure1). Dubai Creek is a tidal marine intrusion with an extension of 14 km from its opening at the Arabian Gulf to Ras Al Khor Wildlife Sanctuary [5]. The narrow section leads to a lagoon in the upper part station; however, the Creek did not record any remarkable natural water input [5]. The creek width varies from 100 m in the lower part (Creek Mouth) to 1.2 km in the upper part (Sanctuary) with a depth variation of 5.5-8 m, and a maximum flow velocity 1.5 m/s in the lower part [5]. It passes through Port Saeed and Dubai Creek Park from the south eastward, links four bridges (Al Maktoum Bridge, Al Garhoud Bridge, Business Bay Crossing and Floating Bridge) and one tunnel (Al Shindagha Tunnel) [4]. Dubai is an attractive city for all people locally and internationally. It became a perfect destination for commercial, recreational and industrial purposes [6]; and Dubai Creek is a critical part of the city. Al Aweer wastewater treatment plant discharges part of their treated effluent in the creek. There are many international hotels located by the side of the creek. Green spaces for tourist attraction are also observed by the side of the creek.

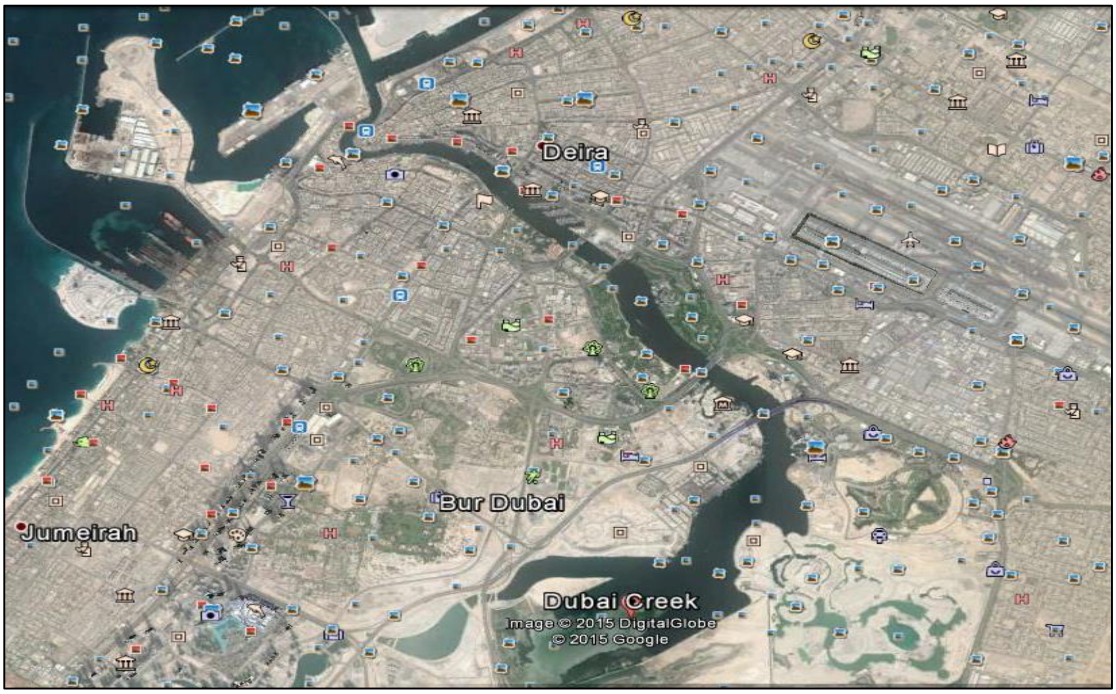

Figure 1: Dubai Creek Map in Google Earth

Chapter 2: Literature Review

2.1. Water Quality

Because water is a critical resource for life on earth, the changes in the water quality and distribution system have a huge environmental influence [7]. Fresh water demand is continuously increasing due to the population growth, economic development and land use, yet climate change threats its availability in the coming decades [8]. All living organisms need water for their survival; therefore, securing the required water supply is essential. Earth is often referred to as the Blue Planet; however, rising water levels is a serious issue. Nonetheless, those water bodies are connected directly; surface and land waters are treated as individual systems in terms of rules and regulations [7]. Approximately 2.5% is fresh water that is hand reachable in earth, and the rest is stored as glaciers or groundwater [9]. Despite the hydrological cycle that gives the needed balance, water pollution plays the role of reducing the water quality globally.

Watershed is the highest topographic point around the water body that allows every surface run off within the watershed to run into water body [7]. Therefore, water surface bodies are considered the main receivers of the contaminations through the surface run off from all directions within the area of the watershed. In ground water surface, the land use controls the pollution of land surface water bodies [7]. Two types of pollutions are considered; natural and man-made. However, it is clear that the presence of different pollution matter is increasing. Natural contaminations occurring into environment are not intensive compared to man-made type [10]. Human-induced activities are causing the water pollution that is changing the chemical, physical, biological and radiological quality of water. There are two types of pollution sources which are point and non-point sources. Nutrients or toxins, which are being produced by the organisms in wildlife, are not considered as pollutant [11]:

- Point-source in which the discharge of the containments is being disposed from a discrete site that includes industrial and domestic wastewater, septic tanks and hazardous spills.

- Non-point source in which the discharge of the containments is being disposed direct to the water body in a wide areas' range or a combination of point sources discharging.

The water quality of surface-water bodies is acceptable depending on the present time and future uses. Water bodies 'quality should preserve the human health and aquatic ecosystem, should serve the recreational human purposes such as swimming and fishing, and should also be sight pleased. Water quality term usually refers to the water suitability to sustain various users or operations. Experiments in terms of dose and response relationships along with risk levels concentration are conducted to measure the water quality impact on human. On the other hand, exposing organisms to different level of contamination within period of time is conducted to measure water quality for aquatic life [7]. Water quality has improved through the environmental management in the last decade due to the lack of the environmental resources, which are forcing the authorized decision makers to apply the most cost-effective techniques available, and the development of water quality modeling tools [12].

However, monitoring water quality requires the physical, chemical and biological water parameters to be available in order to estimate the transformation for the multiple constituents. Accordingly, the impact of the water system on the human health and aquatic life is investigated [13]. To understand and manage the surface water quality, the authorized environmental managers should consider the use of the various available tools for analyzing, designing, implementing, and monitoring sustainable water quality management programs [3].

The ecosystem in the Arabian Gulf region is facing various stresses because of its location in an area that is rich with oil. Arabian Gulf countries host 67% of the worldwide oil [14]. The activities that are related to oil impact the ecosystem significantly, such as algal mats and mangrove. Moreover, many other coastal activities in the Gulf marine region bring critical pollution issues into the water surfaces. Because of this, close investigations should be carried on [14]. The governments and the people of the Arabian Gulf are facing major challenges because of the limited availability of freshwater [15]. The rare rainfall with the high evaporation rate is leading to deficit in the water budgets of the Arabian Gulf countries [15].

2.1.1. Water Quality Parameters

The physical, chemical and biological parameters define the water quality statuses in the surface-water. The classification of the marina pollution depends on whether the nature of the contamination source is generated from human or anthropogenic activities. Moreover, each type of pollutants imposes different forms of pollution. The physical pollution, for instance, has an adverse impact on the chemical and ecological environments while chemical contamination has a bad impact on the biological and chemical environments [14].

Physical pollution is usually referred to the elevated temperature-salinity levels and also to the increase in the sediments in the saltwater. Chemical pollution exists in the water, sediments and/or aquatics. Oil spills contain chemicals and are considered one of the most hazardous sources in the Arabian Gulf. The biological pollution is referred to the pollution that is generated from biological loads. The biological discharges include organic loads that can be found partially in organisms or nutrients, which boosts the growth of the present organisms. Such biological contamination comes from the domestic and industrial sewage treatment plants, the dumped solid waste, and the ships discharges [14].

2.1.1.1. Algae

Algae are varied groups of simple organisms that belong to Protista kingdom; they are not plant, yet most of the algae make their food through the photosynthesis process. The algae do not have the structure of plant like roots and leaves. However, they are found in many water bodies. High concentration can be harmful to them. The blue green algae, Anabaena flos-aqua, Microcystis aeruginosa and Aphanizomenonflos-aqua produce toxicity. On the other hand, the existence of nutrients with high levels in coastal water causes red tides (algal blooms where the water body is discolored). The related coloration might be red, white or brown [16].

2.1.1.2. Dissolved Oxygen (DO)

Dissolved Oxygen is the amount of molecular oxygen dissolved in water; DO is a very critical parameter in water quality as it impacts the aquatic life, fish mortality and others. The discharges of organic substances result in consuming the DO in water bodies which leads to the depletion of DO concentrations. The reduction in the DO levels affects fish reproductive process, and yet it can cause death. If the depletion of DO occurs in the low depths, that will solubilize iron and manganese. Unacceptable odor and taste due to resulted production of the anoxic and/or anaerobic will decay. DO levels decrease with the high temperatures, though; usually 5mg/L will be sufficient to serve different ecosystem life [16].

2.1.1.3. Nitrogen

Nitrogen stimulates the algal growth and consumes a lot of oxygen for oxidation. Different forms of nitrogen exist in water. Nitrogen includes organic nitrogen, ionized non- ionized ammonia ($NH_4^+$and NH_3), nitrite (NO_2^-), nitrate (NO_3) and dissolved nitrogen gas N_2. Moreover, the organic nitrogen is broken down by decomposer to release $NH_3$by the process of ammonification or deamination. The ammonia then is transferred to NO_3in the process of nitrification as shown in the below equation [16] .

$$\text{Organic nitrogen} + O_2 \rightarrow NH_3 \text{ nitrogen} + O_2 \rightarrow NO_2 \text{ nitrogen} + O_2 \rightarrow NO_3 \text{ nitrogen} \quad (1)$$

Ammonification occurs in water, soils and sediments; however, pH controls the existence of NH_4^+ and NH_3 according to the below equation [16].

$$NH_4^+ + OH^- \leftrightarrow NH_3 + H_2O \quad (2)$$

The ionized ammonium NH_4^+ are formed if pH is equal or lower than 7, and if pH is greater than 9 non ionized ammonia NH_3 is formed. Non ionized ammonia is a toxic form of nitrogen to fish while ionized ammonium is a nutrient to aquatic plants [16].

2.1.1.4. Phosphorus

Phosphorus has a low solubility. For this reason, it exists in most water surfaces with small concentration. It is usually found in the forms of phosphates or organophosphates. Orthophosphates are salts of phosphoric acid (H_3PO_4) where the soluble reactive inorganic orthophosphates types (H_2PO^{-4}, HPO_2^{-4}, PO_3^{-4}) are available to algae and plants [16].

2.2. Water Quality Modeling

As the awareness of water scarcity increased, it resulted/or led to more attention towards water quality modeling [8]. A model is a representation of a system that is used to investigate the properties of a system, to classify existing conditions, to evaluate proposed conditions and to estimate potential impacts [13]. The variability of water quality parameters requires a general complex model, though; it needs well trained expert controllers. [10]. Water quality management includes two major areas of investigation which are hydrology and ecology. Hydrology is related to the studying and observation of the existence and the movement of water, while ecology focuses on the connections among living things and their non-living surrounding. Hydrologic connectivity is the description that is used to relate both fields [7]. The estimations of the receiving water quality in the surfaces 'water can be predicted by using water quality models. The predication is a result of the available data of the non-point and point discharges for different receiving water bodies. The hydrodynamic and water quality parameters of the receiving waters vary with time and location. Moreover, water quality models are very appropriate to integrate different parameters such as water levels, flows and biochemical water. Overall, the models aim to predict the transport and dispersion operations to be followed by the results input to the water quality element model [10].

Water quality modeling is used to describe the surface water characteristics in terms of chemical, physical, radiological and biological conditions. In addition, the goal of using water quality models should be defined well in order to conclude the required outcome. However, decision makers and regulations should interact to draw the objectives of any proposed issues. In most cases, water quality parameters and the effluent discharge to water bodies have been the targeted objectives. The processes of water quality modeling are costly. For example in early 1980s United States spent US $ 50 million per year on the numerical modeling [10]. Therefore, the cost of modeling has to be part of the governmental budget. Due Diligence is a used term which shows/ means the water modeling will not affect the existence of water users regardless of the modeling objective. Water quality modeling has been the much useable tool to study and to analyze the status water resources. Some of the water quality applications are [10]:

- The approval processes for new discharges outfall or capacity.
- The processes of constructing dams and their operations.
- Resolving waters conflicts.
- The distributions of water to different water users.
- Irrigation processes.
- Oil spill management.

2.3. Water Quality Case Studies

Many case studies were conducted by using different water quality model approaches in order to evaluate the water body's statuses. In this section some were mentioned.

Keelung is an important river in the Taipei area of Taiwan. The population is increasing remarkably around the river with major developments in urban and economic sectors in the last few years [17]. As a result, the river was receiving contaminated loads and sewage discharges. As water quality modeling has been named to be a good tool for water quality management, an innovative utilizing of QUAL2K and HEC-RAS was used in this case. QUAL2K was selected because of its easy use and the popularity of the software for modeling. The model can stimulate different elements such as biological oxygen demand (BOD), ammonia nitrogen (NH_3-N), and total phosphorus (TP) and sediment oxygen demand (SOD). On the other hand, HEC-RAS was used to investigate the impact of tidal influence on the river. The model showed that BOD is most impacted pollution source which is also compatible with the observed data [17].

Another case is Yamuna's river, which is a famous water surface resource for drinking water in Delhi, India. The river is serving and providing water to the cities surrounding it [18]. The water witnessed degradation in its quality in the last few decades because of the discharges of treated and untreated wastewater [18]. Yamuna Action Plan was started in 1993 by the Ministry of Environment and Forests of the Indian Government [18]. The plan aimed to find a solution for reviving the river's water quality. QUAL2E was used as computer software for modeling in order to evaluate water flow quality; and it has been applied into various settings of different parameters. The study was divided into four approaches which were: (1) to apply the use of QUAL2E to the river among Wazirabab and Okhala, cities surrounding Yamuna, in order to measure the effect of loading points to the water quality in terms of the dissolved oxygen (DO) and biological oxygen demand (BOD), (2) to analyze the uncertain stimulated results for much better model performance and to determine the important parameters for water quality, (3) to level the stimulations to understand the impact of the variations in the point loads and flow rates and (4) to integrate the results of the QUAL2E with the GIS (Geographical Information System) to locate the contaminated locations. The outcome results were shown in terms of maps by the use of GIS and provided text by QUAL2E, however, the generated results revealed that the river has water quality issues in terms of DO depletion and high BOD concentration [18]. Another water quality case study was carried in Lake Yilongwhich which is one of the biggest lakes in China. The lake has been facing a crucial issue because of the eutrophication in the last years [19]. The serious problem started when an unexpected increase in Chlorophyll along with turbidity occurred in 2009 [19]. Three-dimensional hydrodynamic and water quality model was developed. Environmental Fluid Dynamics Code (EFDC) was used as the computational base for the model. It simulates the flow motion, water temperature, the produced pollution and its mobility, and the interfaces between nutrients, phytoplankton and macrophytes. Three scenarios were run to understand different cases for load reduction. The study summarized that with even a decrease in nutrients by 77%, the Chlorophyll A will be reduced by 50% [19].

Recent studies for the Gulf region water surfaces recorded low organic level and heavy metal contaminations [5]. However, organic waste within Dubai Creek was neglected in those studies because of the creek topography [5]. A pollution survey was conducted for the water of Dubai Creek analyzing its environment status by evaluating water samples that were taken during December 15 and 27, 2005 and January 15 and 22, 2006 [5]. The topography of Dubai creek plays a role in the movement of the flow where the tidal velocities are increasing toward the mouth and getting lower towards the upper part. This situation had divided the creek into two zones which are the lower creek and the upper creek [5]. The sources of pollution in the creek integrate more discharges coming from Dubai Ship Docking Yard industrial waste, dhows which are wooden traditional boats, untreated discharges, and the Aweer Sewage Treatment Plant. In 1997, Dubai Municipality had reported that the discharging is more than 100,000 m^3 per day into the upper part of the creek with 22.6 mg/L phosphate and 11.6 mg/L nitrate [5]. The pollution survey measured the organic pollution, water characteristics and the benthic macrofaunal community and showed that the upper zone of the creek is contaminated with the macrofaunal communities along with organic pollution and eutrophication. On the other hand, the lower zone found to be less contaminated with pollution matter, and had beneficial macrofaunal communities. The organic pollution has increased because of the low tidal within the creek and high residence time in lagoon [5].

2.4. Open Channel Hydraulics

Most of open channel flows are in steady state flow condition. In steady state flow, the velocity at any location does not change with time, whereas in the unsteady flow; the velocity changes with time. Also, the flow called uniform if the depth of flow and the velocity remain the same along the channel. In this case, the depth is called normal depth. On the other hand, for non-uniform flow condition the flow depth and velocity vary along the channel. In nature, most of the open channels experience steady or unsteady and non-uniform flows. Natural channels tend to be non-prismatic where the cross section, alignment and slope are not consistent along the channel [20].

The non-uniform flow can be classified in:

- Gradually varied flow which requires the analysis of the energy equation.
- Rapidly varied flow which requires the analysis of the momentum equation.

2.5. Basic Governing Flow Equations

Continuity, momentum and energy equations govern the flow in an open channel. Any flow with a free surface should satisfy the three equations [21]. The continuity equation can be written as [22]:

$$\rho_2 A_2 V_2 = \rho_1 A_2 V_1 \tag{3}$$

where:

ρ = Flow density (kg/m^3)

A = Area of flow (m^2)

V = Mean of velocity (m/s)

Momentum equation can be written as [22]:

$$F = \frac{1}{2}\gamma y_1 A_1 - \frac{1}{2}\gamma y_2 A_2 + W \sin\theta - F_a - F_f \tag{4}$$

$$\gamma \overline{h_1}\, A_1 - \gamma \overline{h_2}\, A_2 = \rho Q(\beta_2 V_2 - \beta_1 V_1) \tag{5}$$

where:

F = Force (N)

F_a, F_f = Friction Forces (N)

W= Weight (N)

A = Cross sectional area (m^2)

F = Force (N)

V = Flow velocity (m/s)

Q = Flow rate (m^3/s)

V = velocity (m/s)

γ = Unit weight (kN/m^3)

y = Depth (m)

$\overline{h}$ = Depth of the area centroid blow water surface (m)

ρ = Flow density (kg/m^3)

The energy equation can be written as [21]:

$$z_2 + y_2 + \frac{\alpha^2 V_2^2}{2g} = z_1 + y_1 + \frac{\alpha^2 V_1^2}{2g} + h_e \quad (6)$$

where:

y_1, y_2 = Water depths cross sections (m)

z_1, z_2 = Elevation of bed above project datum (m)

V_1, V_2 = Average velocities (total discharge/total flow area) (m/s)

α_1, α_2 = Velocity weighting coefficients

g = Gravitational acceleration (m/s^2)

h_e = Energy head loss (m)

2.6. HEC-RAS Commercial Software

There are many computer programs available for the water quality modeling such as SWMM, SMS, HSPF, TRISULA, QUAL2E, DIVAST, MIKE11, and WASP4.Hydrologic Engineering Center- River Analysis System (HEC-RAS) is commercial software that models the hydraulics of rivers, water flow and other channels from a single reach to complex networks. Hydraulic structures such as bridges, culverts, weirs and levees can also be defined and added [23]. HEC-RAS software was developed by the Corps' Civil Works Hydrologic Engineering Research and Development Program of the U.S division of Institute of Water Recourses. The first version was released in 1995, and from that time till now many versions have been released [24]. The software was generated as a part of the Hydrologic Engineering Center's "Next Generation" of Hydrologic Engineering software. It is an assimilated system of software which can be used for multi environment cases. Graphic and reporting facilities, graphical user interface, data storage and management capabilities, separate analysis components are included in the system. HEC-RAS is a 1D model which is capable of investigating the complete natural and constructed hydraulic channels [24]. The system has four components for the river analyses, which are the steady flow water surface profile computation, unsteady state simulation, movable boundary sediment transport computation and water quality analysis [23].

The advantage of HEC-RAS can be listed as [23].

- One of the most commonly used free software.
- Easy to learn with the enhancement of the provided documentations.
- HEC-RAS simulate both steady and unsteady state conditions.

2.6.1. Hydraulic Modelling with HEC-RAS

2.6.1.1. Geometric Information

The main objective of HEC-RAS is to calculate the water surface elevations for all the required locations either for steady or unsteady state simulations. The basic geometric data needed for the river analyses are the cross section information, reach length, energy loss coefficients that include friction losses, and contraction and expansions losses, and stream junction data. In the case that the widths or depths are varying significantly between the cross sections, the interpolation can be used through HEC-RAS geometric option [25].

2.6.1.2. Cross Sections information

Cross sections are representatives for the locations along the river, and they indicate the changes of slopes and roughness of river section. The spacing between channels is important depending on the type of the study. The cross section is defined by entering the station and elevation (X-Y coordinates) with a given station number. Normally the given station numbers will be numerically reduced from the upstream to downstream in order to identify the exact location within the software. Reach lengths which defines the distance between two consecutive cross-sections should be entered as well. The distance between the left banks and right banks of two consecutive cross sections represent how the river reach's meanders. Energy loss coefficients, which are roughness, expansion and contractions, should be included [24].

2.6.1.3. Steady State Flow Simulation

In HEC-RAS steady state condition, the number of profiles, peak flow and boundary conditions are required [24]. For calculating the water surface profile, HEC-RAS uses the energy equation (see equation (6) with the standard step method). Moreover, the energy head loss (h_e) that is caused by the contraction and expansion between the cross sections is calculated by the following equation [24]:

$$h_e = LS_f + C\left|\frac{\alpha^2 V_2^2}{2g} - \frac{\alpha^2 V_1^2}{2g}\right| \quad (7)$$

where:

L =Discharge weighted length (m)

S_f = Representative friction slope between two sections

C = Expansion or contraction loss coefficient

The friction slope S_f is calculated by using the Manning's equation [24]:

$$\mathrm{Q} = \frac{\mathrm{AR}^{2/3}\mathrm{S_f}^{1/2}}{\mathrm{n}} \quad (8)$$

where:

Q= Flow rate (m^3/s)

n = Manning's roughness coefficient

A = Area of the channel (m^2)

R= Hydraulic radius (m)

2.6.1.4. Unsteady State Flow Simulation

Time dependent boundary conditions and initial conditions are required to be entered in HEC-RAS in order to simulate the constructed model in unsteady state condition. Each model needs certain boundary conditions for upstream and downstream. Flow hydrograph, stage hydrograph or flow and stage hydrograph can be considered as an upstream boundary condition whereas the rating curve, normal depth, flow hydrograph, stage hydrograph or known flow and stage can be considered as the downstream boundary conditions. On the Other hand, the internal boundary condition can be lateral inflow hydrograph, uniform lateral inflow hydrograph, groundwater inflow hydrograph, and internal in stage and flow hydrograph. In addition, the initial condition can be done by entering the flow data for each reach [24]. The principles of conservation of continuity and momentum are used to calculate the flow of water in terms of differential equations; see equations (3) and (5).

2.6.2. Water Quality in HEC-RAS

This component in HEC-RAS allows the user to perform water quality analyses with detailed temperature and limiting water quality parameters to algae, dissolved oxygen, carbonaceous biochemical oxygen demand, nitrates, nitrites, organic nitrogen, organic phosphate, orthophosphate and ammonium [23]. At the beginning, the user can define the water quality cells which are located between the cross sections. Boundary conditions should be selected which can be downstream, upstream, and lateral where a combination of boundary conditions can be used. Also, initial values for each constituent and dispersion coefficient should be known [24]. Yet to model water temperature, at least one completed meteorological data should be available which includes air temperature, humidity, cloudiness, solar radiation, wind speed and atmospheric pressure. The meteorological data set requirements include latitude, longitude and site elevation physical information. After that, the meteorological data sets should be assigned to the different water quality cells [24]. The user has the ability to control the pathway between the state variables of algae, dissolved oxygen, carbonaceous biochemical oxygen demand, nitrates, nitrites, organic nitrogen, organic phosphate, orthophosphate and ammonium by using the built in nutrients parameters ranges [24]. The nutrient parameters include constant rate for the chemical and physical reactions among the above mentioned variables. Moreover, those constants govern the source (S) in the advection dispersion equation [24].

$$\frac{\partial}{\partial t}(V\emptyset) = -\frac{\partial}{\partial x}(Q\emptyset)\Delta x + \frac{\partial}{\partial x}\left(\Gamma A\frac{\partial \emptyset}{\partial x}\right)\Delta x \pm S \tag{9}$$

where:

V= volume of water quality cell (m^3)

$\emptyset$=water temperature of concentration (^oC)

Q = flow (m^3/s)

Γ= user defined dispersion coefficient (m^2/s)

A = cross sectional area (m^2)

S = sources or sinks (mg/L)

Chapter 3: Materials and Methodologies

3.1. Materials

3.1.1. Data for Dubai Creek

To develop the water quality model, two models (hydrodynamic and ecology) were used [26]. There are several types of data required for development of the models.

3.1.1.1. Geometric Information

In this study, a map was created by compiling geographic data using ArcGIS. ArcGIS was used to develop Dubai Creek geometric data in HEC-RAS, with 121 points represented Dubai creek centerline along with its depth in meters below the creek's water surface (Figure 2). The water depths in the creek varied between 7.2 m and 3.1 m and the width of the Creek varied from 100 m at the mouth to 1.2 km at the Sanctuary (see Appendix A). However, the information in ArcGIS was obtained by the extraction of the Dubai Creek bathymetry from WorldView-2 imagery, a high resolution satellite image. Bathymetry, a bed topography or water depth, can be obtained using a few methods including echo-sounding, hydrographic Light Detection and Ranging (LiDAR) mapping, and satellite remote sensing. Due to the increasing cost of echo sounding and hydrographic LIDAR mapping, remote sensing is currently becoming very popular due to its relatively low cost, simplicity, and rapid productivity [27, 28]. In this study, the bathymetry of the creek was derived from a multispectral image of WordView-2 satellite. Water depth (D) was extracted from the coastal blue (cb) and green bands (g) of WordView-2 image using an algorithm developed by Stumpf et al. [29], which is shown below:

$$D = \left(\frac{g(\ln(cb))}{\ln(g)}\right) - o \tag{10}$$

where

cb, g = Coastal blue and green bands of the WordView-2 image

o, g = Offset and gain parameters

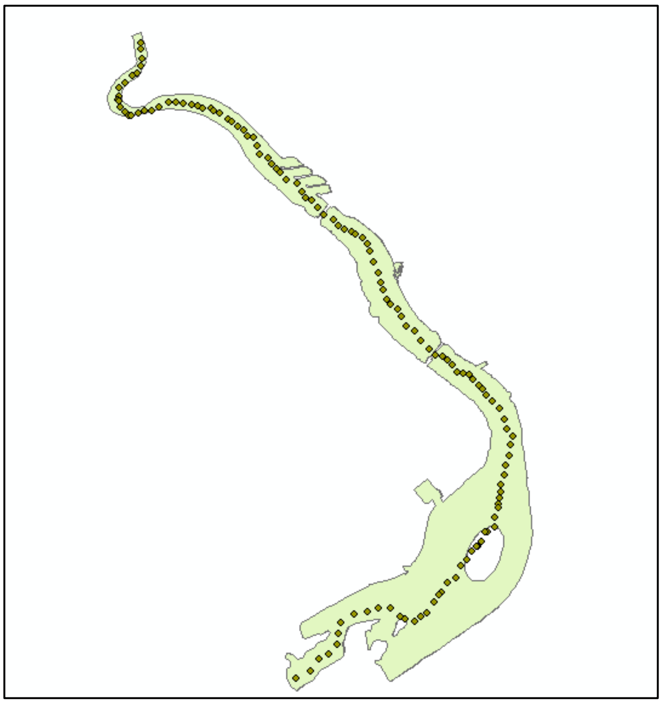

Figure 2: ArcMap Dubai Creek Map

3.1.1.2. Tidal Information for Hydrodynamic Model

Dubai Municipality provided the tidal information for two locations; Dubai Festival City and Al Shindagha for 2010, and the lateral flow of STP outfall station which was 260,000 m^3/ day. The tidal level, lateral flow and creek slope data were used as boundary conditions in unsteady state hydrodynamic model for the Dubai Creek.

3.1.1.3. Water Quality Parameters

Dubai Municipality uses 10 monitoring stations along the creek to observe its water quality characteristics in a quarterly year base (Figure 3). The recorded parameters in those stations are (chlorophyll, DO percentage, DO concentration, turbidity, nitrates, total nitrogen and phosphates). The available water quality parameters data for this study were the period of 2012-2013 (see Appendix B). Some of the provided data were interpolated for the month of December to be used in the water quality modeling.

Figure 3: Dubai Creek Stations

3.1.1.4. Meteorological Data

Daily mean air temperature, atmospheric pressure, humidity, cloud cover, wind speed and daily radiation in the directions at Dubai Airports and Jebel Ali Airport, and water temperature of the Jabel Ali shore data for 2010-2013 were provided by Dubai Air Navigator Service, Dubai International Airport.

3.2. Methodologies

3.2.1. Hydraulic Modelling

Two types of hydraulic modeling were available for this study; the steady state and the unsteady state. However, choosing the methodology was based on the nature of the water surface. The steady state modeling is inherently conservative as it assumes that the peak flow occurs immediately and continuously in all parts of the hydraulic model during the simulation. On the other hand, unsteady state modeling is applicable for time dependent problems such as the flood wave attenuation, time based operation of control structures, pumps and variable flow. In this study, unsteady state modeling was utilized for Dubai creek as the tidal effect was considered. Also sensitivity analysis was carried out for the model.

3.2.1.1. Development of the Geometric Profile in HEC-RAS

The schema of the river system was created by importing a previously developed HEC-RAS file with the center line points (Figure 4). After that, the cross sections data for 46 cross sections have been entered along with Manning value of 0.030 for the main channels and of 0.04 for the floodplains. The Manning's values were later adjusted for the calibration purposes. Channel roughness parameters were derived for each cross-section from a combination of site inspections and comparison of survey photographs with published values [30].

3.2.1.2. Development of the Cross Sections

For the development of hydrodynamic model, rectangular cross-sections were assumed for the creek due to lack of available information. Due to the geographic nature of Dubai Creek, the distance between each cross-section in the model was assumed to be more or less 250 m. The widths and depths at each cross section were extracted using ArcGIS from WorldView-2 imagery. The slope of Dubai Creek from Ras Al Khor Wildlife Sanctuary to the creek mouth was assumed to be 0.00025 in the HEC-RAS model and a total of 46 cross-sections were generated along the Creek (Figure 5). Upon several visits to Festival City shore, it was observed that a free board was around 60 cm which was implemented in the model.

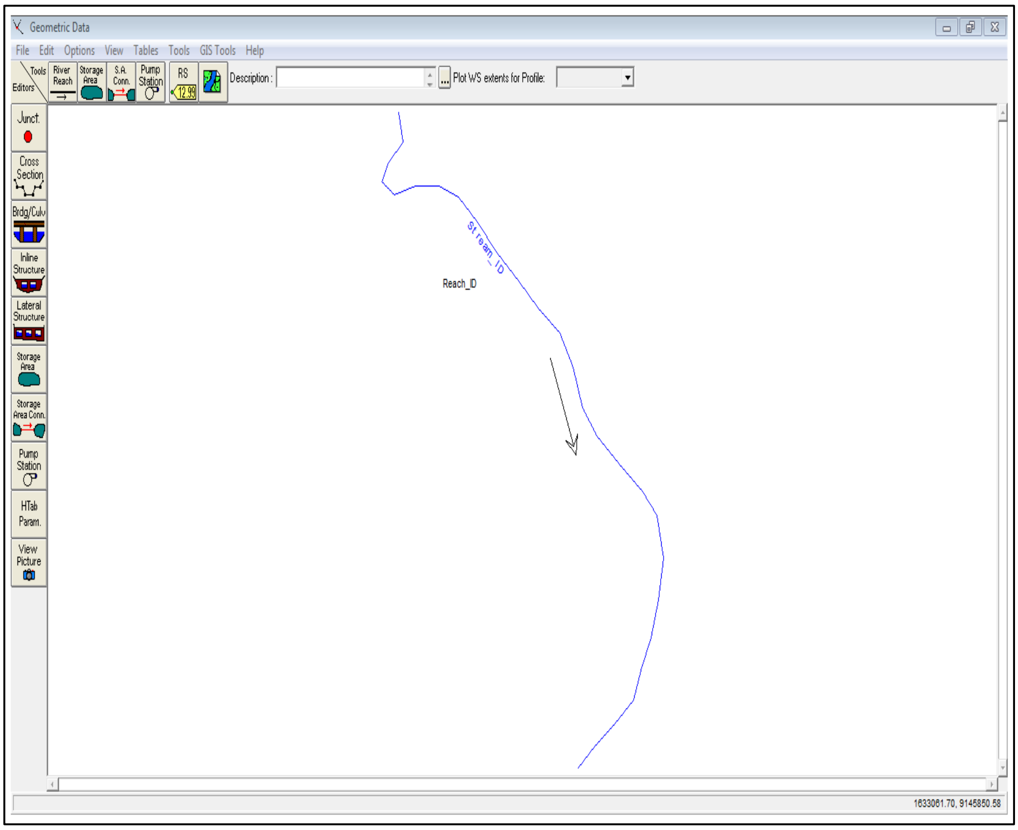

Figure 4: River System Schematic

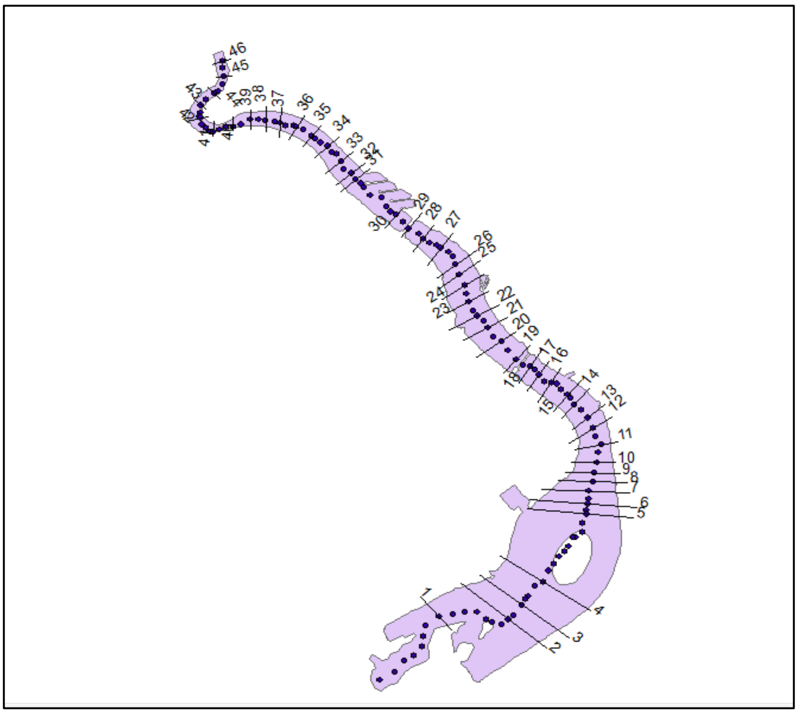

Figure 5: The 46 created river stations

3.2.1.3. Boundary Conditions for Unsteady State Model

The model required the upstream and the downstream boundary conditions. A stage hydrograph condition was selected for the upstream, and normal depth having the slope of 0.00025 was selected for the downstream boundary condition. In addition to these, two intermediate river stations were selected for the boundary conditions in order for them to be defined in the water quality model. Table 1 shows all boundary conditions that were used in the hydrodynamic model. The uniform lateral inflow of 2.3 m^3/s and 3.0 m^3/s at these two intermediate river station were used to represent the outfall from Wharfage and STP. As HEC-RAS allows using 100 tidal level points only, the highest 97 tidal level information of Al Shindagha were used for the stage hydrograph (see Appendix C). Also, the initial flow value was assumed to be 50 m^3/s in the Creek Mouth to simulate the model.

Table 1: River Stations Boundary Conditions Representation

Station	Location	Boundary Condition in Hydrodynamic Model
Most Upstream (station 46)	Creek Mouth	Stage Hydrograph
Intermediate Section (station 31)	Wharfage	Uniform Lateral Flow
Intermediate Section (station 5)	STP Outfall	Uniform Lateral Flow
Most Downstream (station 1)	Sanctuary	Normal Depth

3.2.2. Development of Water Quality Profile

For water quality modeling in HEC-RAS, temperature and nutrients options were selected. The boundary conditions in the model were represented by four stations (Table 2). For each boundary condition, different water quality parameters were added to the model.

Table 2: Water Quality Parameters (mg/L) Input Values

RS	Water Temp (C^o)	Algae	DO	CBOD	N	NH_4	NO_2	NO_3	P	PO_4
46	24	0.002	6.8	2.5	14.6	0.3	1.26	0.18	0.98	0.0204
31	24	0.0058	6.5	2.7	10.4	0.02	0.56	0.5	1	0.078
5	21	0.018	7.5	4	19.7	14.2	1.9	6	2.2	0.8
1	21	0.048	8.2	3	18.52	4.4	1.6	4.8	1.4	0.58

Initial values for the water quality parameters were entered to be the same as the boubndary conditions values mentioned in Table 2. The required dispersion coefficients were assumed as fixed values for the location of the four boundary conditions' to be 25.6 m^2/s. After that, meteorological data sets (as mentioned in Section 3.1.1.4) were entered. The two entered datasets were assigned to the different 40 water quality cells river stations (Table 3 and Table 4).

Table 3: Meteorological Input Data in Creek Mouth Station

Date	Sea Temp (C^o)	Cloud Fraction	wind (m/s)	Humidity (mb)	Short Radiation (MJ/m2 day)	Pressure (mb)
5/12/2010	24	0.07778	4.1634	54	459.8	1017
6/12/2010	24	0.02222	2.9812	50	458.5	1017

Table 4: Meteorological Input Data in Sanctuary Station

Date	Sea Temp (C^o)	Cloud Fraction	wind (m/s)	Humidity (mb)	Short Radiation (MJ/m^2 day)	Pressure (mb)
5/12/2010	24	0	2.2616	40	369.3	1013
6/12/2010	21.9	0	2.5186	36	397.5	1013

3.3. Limitations and Assumptions

3.3.1. Limitations

Various water quality modeling approaches can be used for modeling [10]. Usually 2D and 3D software models require detailed data. Due to limited availability of Dubai Creek's data, a 1D HEC-RAS model was used in this study. Yet, some assumptions should also be considered in the 1D model; the cross-sections accurately represent the watercourse, the flow is primarily perpendicular to the cross section and the design flows are an accurate representation of flows of a given return period. In 1D model, the flow is assumed to be parallel to the main channel and the model fails in the recirculation areas and near to the hydraulic structures [10].

There was a limitation in the availability of the historical water quality information about the Arabian Gulf, marine and the surrounding coastlines. Therefore, collecting Dubai Creek bathymetric and water quality data was a problem, which led to the use of remote sensing method for data collection.

3.3.2. Assumptions

3.3.2.1. Hydrodynamic Model

In this study the following assumptions were used in the hydrodynamic model because of the lack of available data:

- The creek roughness for the 46 cross sections along the main channel and flood plains were selected based on Manning's n values provided by Chow [30]. In HEC-RAS hydrodynamic model, Manning’s ’s n values were used as 0.030 for the main channels and of 0.04 for the floodplains.
- Contraction and expansion coefficients were assumed to be 0.1 and 0.3 respectively along the creek.
- Bridges along Dubai Creek were neglected in the model, as they do not have any effect on water level.
- Al Shindagah tidal (December 2010) was used for the upstream boundary condition as Al Shindagah is located near the Creek Mouth.
- The uniform lateral flow value of the Wharfage station was assumed to be in the same range of the uniform lateral flow value of river station STP Outfall.
- Initial flow value was assumed to be 50 m^3/s in the Creek Mouth to run the model.

3.3.2.2. Water Quality Parameters

The available water quality data about Dubai Creek was obtained from Dubai Municipality for the period of 2012-2013. Moreover, the data was recorded in quarterly year base which led to linear interpolation sets for the boundary conditions during December 2012 for the following parameters: chlorophyll, dissolved oxygen, and nitrate and phosphates. Some of the provided water quality data by Dubai Municipality were not required for HEC-RAS water quality modeling such as salinity and pH. However, other required parameters values were assumed in order to run the water quality model. Carbonaceous BOD, organic nitrogen, ammonium nitrogen, nitrite and organic phosphorus data for the boundary conditions were assumed from different literature studies [2, 3].

The available meteorological data (as mentioned in section 3.1.1.4 for Jabel Ali shore) was used in the model. However, in this study Dubai Creek was considered having the same meteorological conditions as the Jabel Ali offshore. The dispersion coefficients were assumed to be fixed and the values were selected based on the United States Environmental Protection Agency report for lakes [31].

Chapter 4: Results and Discussion

4.1. The Hydrodynamic Model

The accuracy of a model depends on the accuracy of the input data such as cross-sections and meteorological information [32], and thus the quality of the model developed in this study was limited to the accuracy of the provided data. The output results in Appendix D showed that the maximum depth of 7.16 m occurred at the creek mouth and the minimum depth of 3.25 m occurred at the downstream end. The results also revealed a maximum velocity of 1.61 m/s at the upstream side of the creek and the minimum velocity of 0.22 m/s at the further downstream end. These results were consistent with previous study identifying the maximum flow velocity in the creek to be 1.5 m/s while the water depth varied between 5.5 m and 8 m [5]. The flux from the upstream to downstream was found to be small whereas the retention time within the creek was high [5].

Eight different locations were selected randomly for the calibration process. The hydrodynamic model was calibrated by adjusting the Manning's n values. The comparison between the calibrated and observed water levels was within the range of +0.14 to +0.15 cm as seen in Table 5 and represented respectively in Figure 6. The maximum depth was found to be in the Creek Mouth; the source of the water entering towards the creek and the lowest depth was recorded in the most downstream (Figure 7). The topography of the creek impacted the velocities as it decreased from the upstream to the downstream (Figure 8). The velocities in the narrow sections were higher in comparison to wider sections as anticipated. Figure 9 shows the water surface profile in model along the creek.

Table 5: Hydrodynamic Model Calibration

River Station (RS)	Nearest Dubai Creek Station to RS	Distance between the nearest Dubai Creek Station and RS (m)	ArcGIS Water Depth below Surface (m)	Resulted Depth (m)	Difference (m)
46	Creek Mouth	-	7.02	7.16	0.14
40	Creek Mouth	1500	6.40	6.56	0.16
30	Wharfage	806	5.60	5.71	0.11
27	Floating Bridge	500	5.50	5.49	0.01
21	Floating Bridge	1900	5.00	5.11	0.11
15	Floating Bridge	3400	4.60	4.66	0.06
9	Festival City	150	4.50	4.26	0.24
1	Sanctuary	-	3.40	3.25	0.15

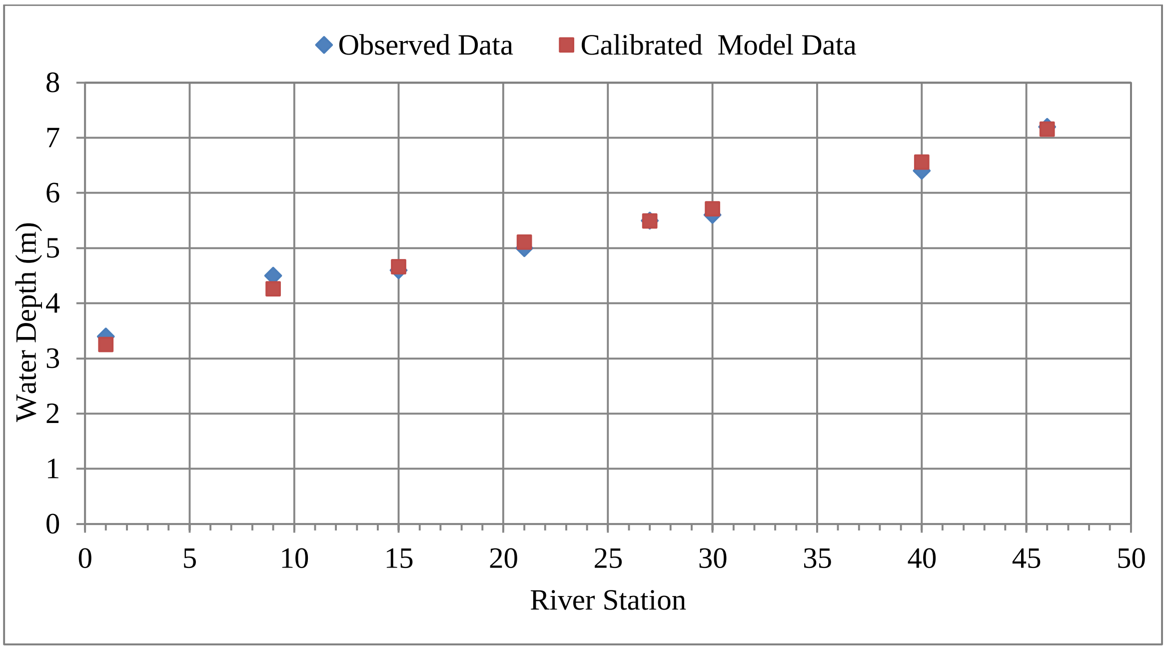

Figure 6: Hydrodynamic Model Calibration Graph

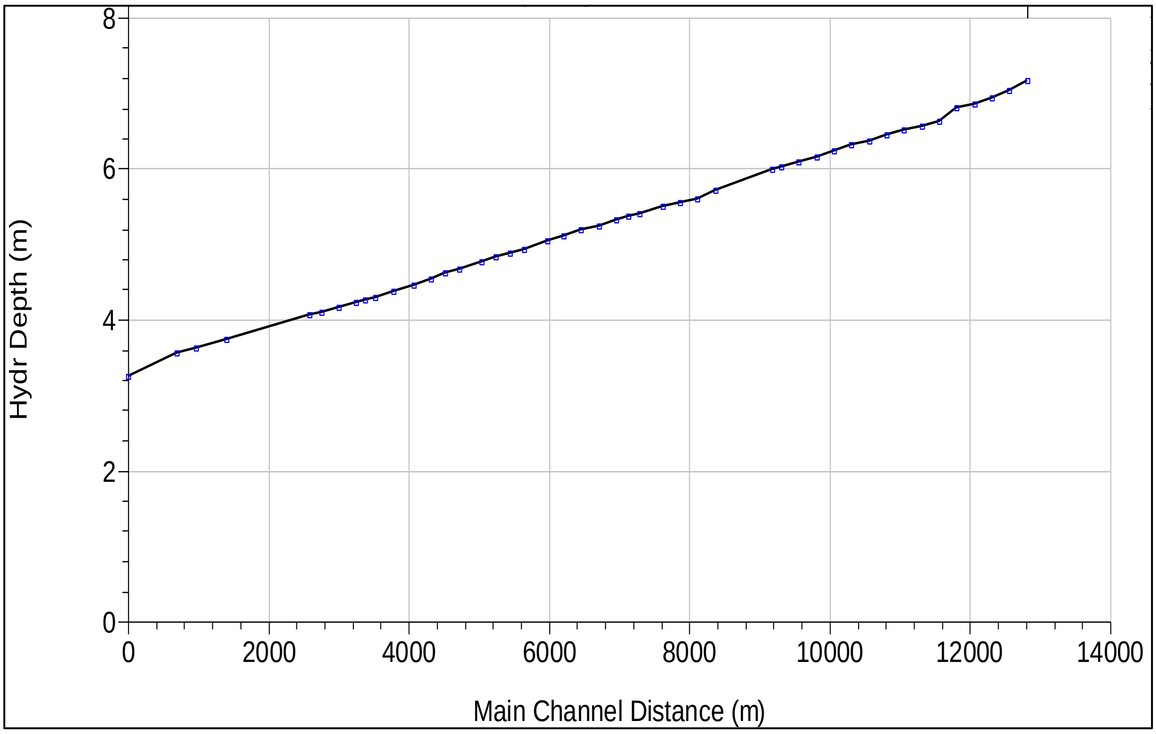

Figure 7: Water Depth

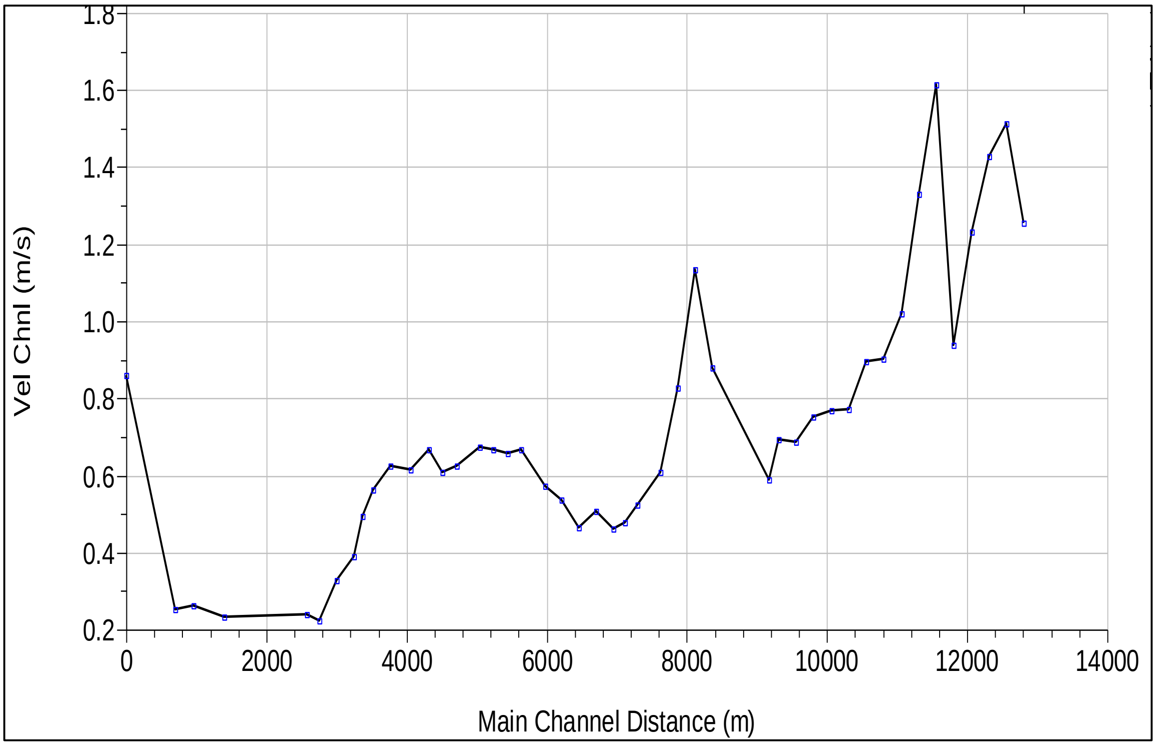

Figure 8: Velocity along the Creek

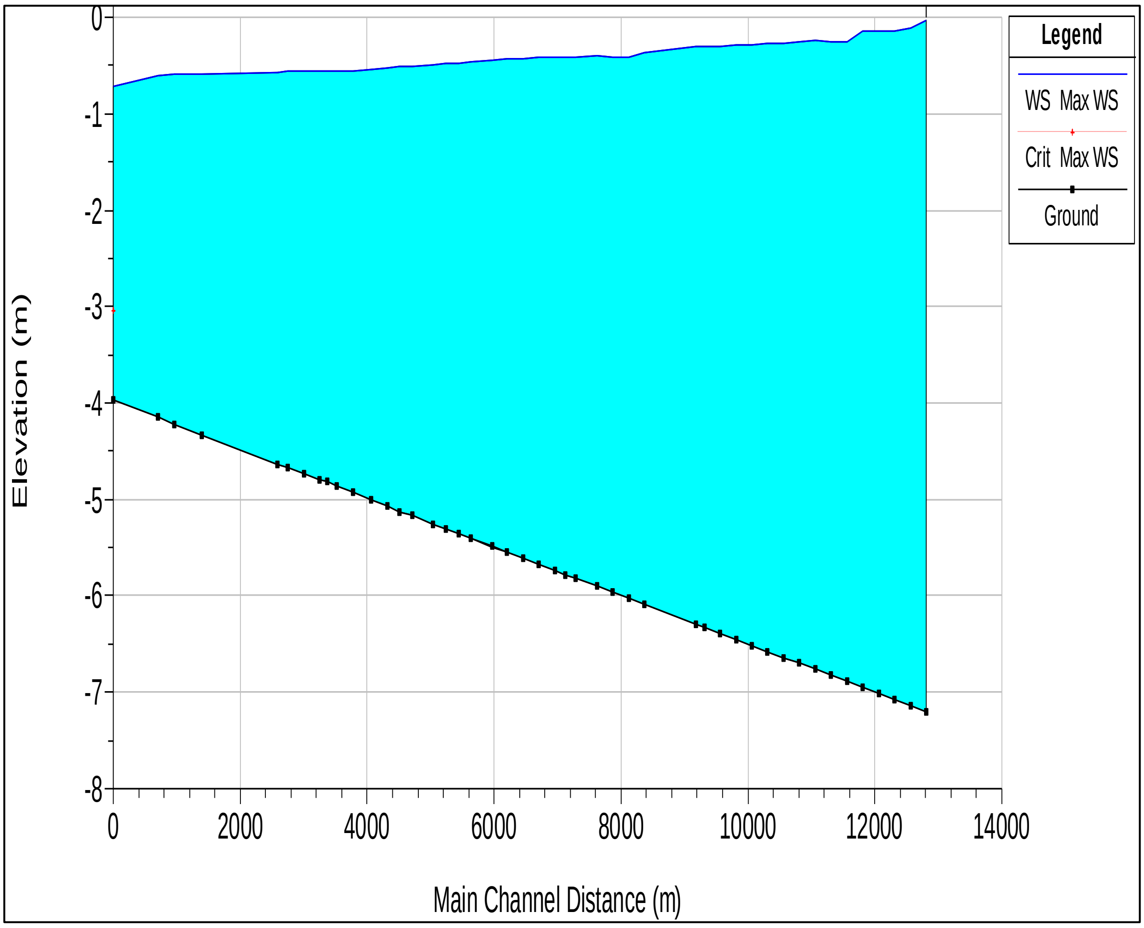

Figure 9: Water Surface Profile along the Creek

4.2. Sensitivity Analysis

Even though the model was calibrated, the modeling validation was also undertaken by carrying out the sensitivity analysis to main channel roughness and initial flow. The results of the sensitivity analysis were considered on the same location that has been used for the calibration.

4.2.1. Sensitivity to Roughness

Decreasing or increasing the Manning's value by ±0.01 for the main channel (n = 0.03) showed no significant change in water levels. The results of the sensitivity analysis showed that in general all models appear to be fairly insensitive to channel roughness of this magnitude.

4.2.2. Sensitivity to Initial Flow

Decreasing or increasing the initial flow value by ±20 m^3/s in the unsteady state hydrodynamic model showed no significant changes in the depths and the velocities. The results of sensitivity analysis showed that in general all models appear to be fairly insensitive to initial flow of this magnitude.

4.3. The Water Quality Model

The hydraulic model coupled with ecology revealed the water quality results for nine stations excluding Hayat Regency station as it was not located on the main modeled stream (Table 6). The water quality model results were compared with the Dubai Municipality interpolated data for the third quarter 2012. Wharfage and Floating Bridge stations were selected for the calibration and STP Outfall station was used for the verification for the targeted parameters (Tables 7 and 8). In Wharfage station, the water quality parameters had an increase of algae from 0.0058 mg/L to 0.0059 mg/L, DO from 6.50 mg/L to 6.52 mg/L, NO_3 from 0.5 mg/L to 0.5799 mg/L and PO_4 from 0.078 mg/L to 0.0882 mg/L. Floating Bridge station recorded an increase of algae from 0.0060 mg/L to 0.0069 mg/L and DO from 5.400 mg/L to 6.590 whereas a decrease was recorded of NO_3 from 1.00 mg/L to 0.9930 mg/L and $P0_4$ from 0.2000 mg/L to 0.1427 mg/L. During verification, STP Outfall recorded an increase of algae from 0.0180 mg/L to 0.0219 mg/L, DO from 7.50 mg/L to 7.58 mg/L and recorded a decrease of of NO_3 from 6.00 mg/L to 5.78 mg/L and PO_4 from 0.800 mg/L to 0.762 mg/L. The recorded percentage errors in calibration and validation processes were acceptable due to the limitation in this study in terms of the interpolated and assumed input values (Table 9).

Table 6: River Stations and their Representation in Dubai Creek

River Station	Station in the Creek
46	Creek Mouth
38	Abra
31	Wharfage
29	Floating Bridge
14	Al Garhoud Bridge
10	Dubai Festival City
6	Jaddaf
5	STP Outfall
1	Sanctuary

Table 7: Observed Water Quality Parameters

River station	Interpolated Algae (mg/L)	Interpolated DO (mg/L)	InterpolatedNO_3 (mg/L)	InterpolatedPO_4 (mg/L)
Wharfage	0.0058	6.5000	0.5000	0.0780
Floating Bridge	0.0060	5.4000	1.0000	0.2000
STP Outfall	0.0180	7.5000	6.0000	0.8000

Table 8: Simulated Water Quality Parameters

River station	Simulated Algae (mg/L) Results	Simulated DO (mg/L) Results	Simulated NO_3 (mg/L) Results	Simulated PO_4 (mg/L) Results
Wharfage	0.0059	6.5200	0.5799	0.0883
Floating Bridge	0.0069	6.5900	0.9930	0.1427
STP Outfall	0.0219	7.5840	5.7800	0.7627

Table 9: Percentage Errors

River station	Algae % Error	DO % Error	NO_3 % Error	PO_4 % Error
Wharfage	2.31	0.30	15.98	13.17
Floating Bridge	14.90	22.03	0.70	28.65
STP Outfall	21.72	1.12	3.66	4.66

4.3.1. Algae

Results showed the highest algae concentration to be in the most downstream Sanctuary station (0.0480 mg/L) and the lowest concentration to be in the upstream Creek Mouth station (0.0021 mg/L) (Table10 and Figure 10). The water quality in the creek mouth was expected to be good and it would get contaminated as the flow passes through the streams. The topography of the creek played a major role in the stream circulation and flow velocity [33].

Table 10: Algae Input Data vs Output Results

RS	Station in the Creek	Observed Algae (mg/L)	Simulated Algae (mg/L) Results	Algae % Error
46	Creek Mouth	0.0020	0.0021	5.65
38	Abra	0.0035	0.0039	12.17
31	Wharfage	0.0058	0.0059	2.31
29	Floating Bridge	0.0060	0.0069	14.90
14	Al Garhoud Bridge	0.0140	0.0127	9.14
10	Dubai Festival City	0.0200	0.0148	26.00
6	Jaddaf	0.0162	0.0158	2.59
5	STP Outfall	0.0180	0.0219	21.72
1	Sanctuary	0.0480	0.0480	0.00

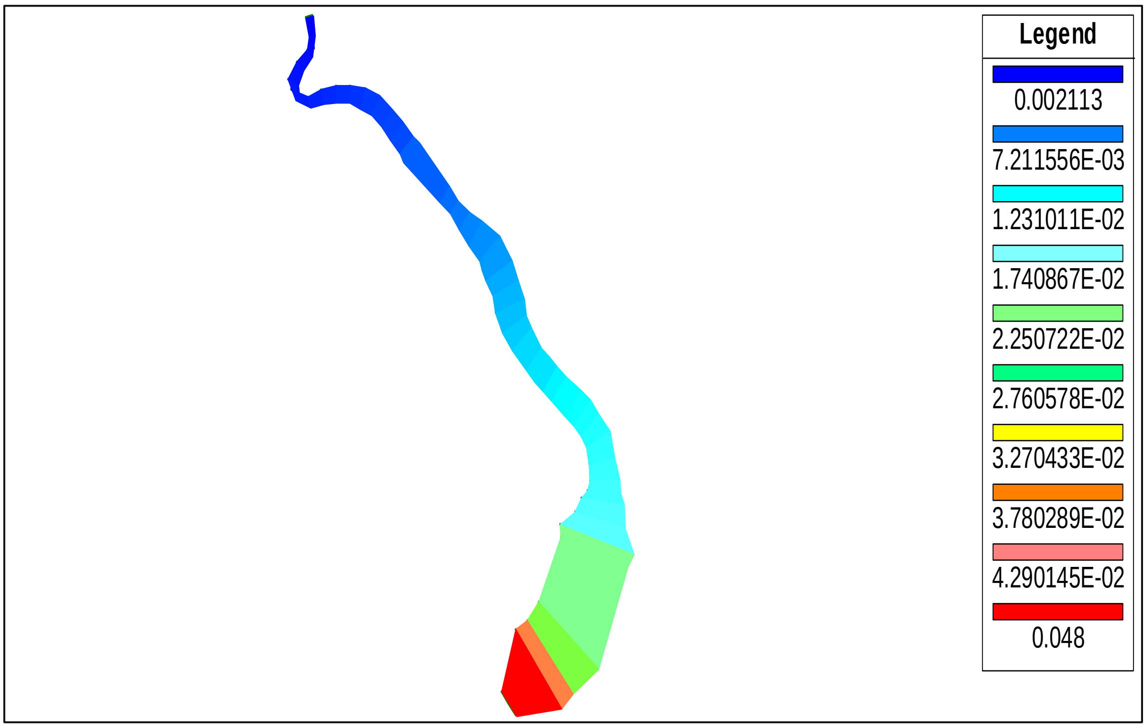

Figure 10: Algae Schematic Plot

The algal bloom was recorded in the stagnant areas that have low velocity [34]. Both the circulation and flow velocity along with a combination of physical (i.e. currents, wind) and chemical (nutrients) factors, impact the occurrence and distribution of the algae population. The existence of nutrients in streams was neither associated with storm water, nor induced wind that mixes the deep nutrients and brings them to the surface. On the other hand, the anthropogenic loading can lead to eutrophication [33]. The natural conditions of the weather and water were controlling the algal occurrence in nature; most likely algal bloom occurrence in Dubai Creek depends on the local conditions and the hydraulic characteristics of the water [34].

The proposed hydrodynamic model was simulated under the condition of winter in the United Arab Emirates in December, a typical rain fall season with active wind events. This would be a reason for transporting the contamination along the creek. Factors, such as narrow stream topography from Creek Mouth to wider sections towards Sanctuary, showed low flow velocity with no remarkable circulation. The non-point sources discharge coming from ships might have affected the algal formation. Rate of photosynthesis increases with the excessive algal presence in the surface, preventing the sun light penetration to affect the plants. Also, the algal presence would be consuming DO in two cases; respiration process during night and decomposition by the bacteria after algal death.

4.3.2. Dissolved Oxygen

The results showed the highest DO concentration in the most downstream Sanctuary station to be 8.2 mg/L and the lowest concentration in Wharfage station to be 6.52 mg/L (Table 11 and Figure 11). According to the interpolated data, the highest DO concentration was in the Sanctuary station and the lowest concentration was in Floating Bridge station. Both Wharfage and Floating Bridge stations were located within the same area, and due to the modeling limitation, the DO difference between the two stations came to be 0.07 mg/L which is very small variation. The Wharfage station area is famous for the traditional boats (dhows) activities that resulted the organic contamination in the area. Decomposition for the organic matter by the bacteria requires dissolved oxygen which leads to oxygen depletion. On the other side, the Sanctuary station witnessed highest level of algae concentration and DO. As mentioned earlier, high level of algae consumes high level of DO. In this case the model and interpolated data showed that the highest DO was in the downstream stations. The pollution in the creek increased from the mouth toward Sanctuary; however, the DO had the opposite pattern along the creek [5]. DO levels vary seasonally and over 24-hour period. They also fluctuate with changes in the water temperature and the altitude [35].

Table 11: DO Input Data vs Output Results

RS	Station in the Creek	Observed DO (mg/L)	Simulated DO (mg/L) Results	DO % Error
46	Creek Mouth	6.80	6.79	0.13
38	Abra	7.00	6.65	5.02
31	Wharfage	6.50	6.52	0.30
29	Floating Bridge	5.40	6.59	22.03
14	Al Garhoud Bridge	6.20	7.07	13.98
10	Dubai Festival City	8.10	7.24	10.65
6	Jaddaf	7.00	7.32	4.54
5	STP Outfall	7.50	7.58	1.12
1	Sanctuary	8.20	8.20	0.00

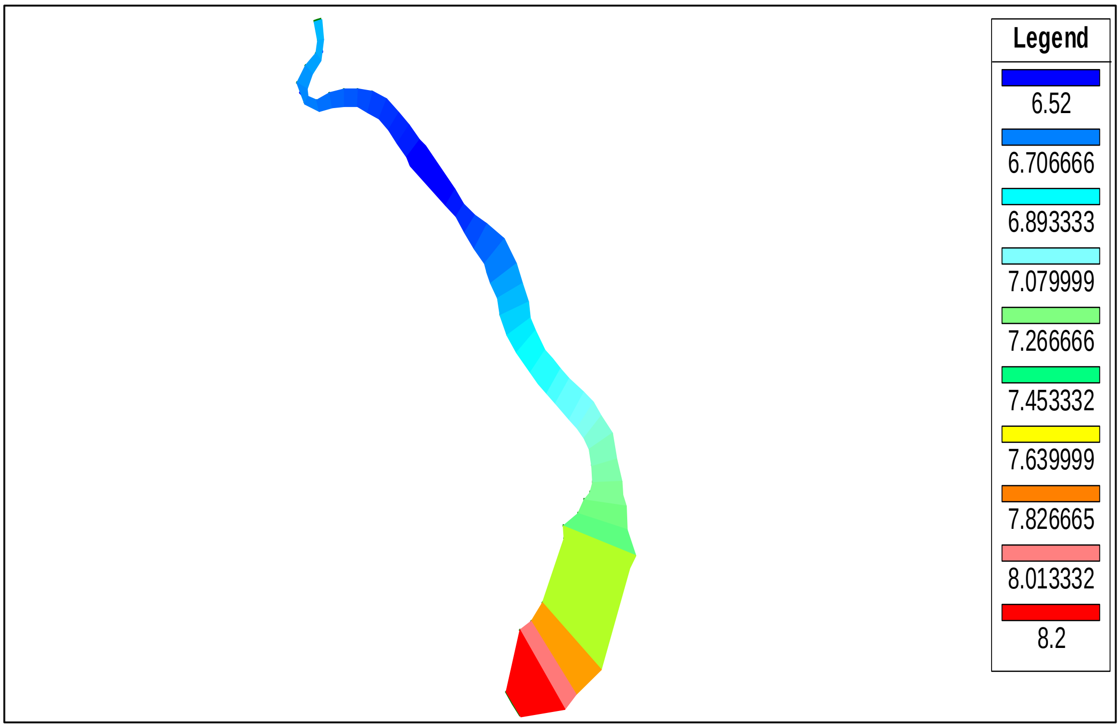

Figure 11: DO Schematic Plot

4.3.3. Nitrate and Orthophosphate

The results showed highest NO_3 and PO_4 concentrations in STP Outfall station to be 5.78 mg/L and 0.7627 mg/L respectively and the lowest NO_3 and PO_4 concentrations in the upstream Creek Mouth station to be 0.1895 mg/L and 0.02212 mg/L respectively (Table 12 and 13), (Figures 12 and 13). Al Awir Sewerage Treatment Plant treats 260,000 m^3/d which is exceeding its designed capacity 130,000 m^3/d. The plant has been located in an area where the effluent to be discharged into the creek by pumping [36]. The high levels of nutrients may indicate eutrophication, and that would carry a change in the structure and the function of the marine system as well as the stability of the ecosystem [37]. The nutrients level was found to be increasing over the last decade in station 5. This resulted in an increase in the algae in the upper creek where low levels of nutrients were recorded in the stations near to creek mouth [6]. It could be due to the conversion of nutrients to algae, making the algal concentrations high and nutrients concentrations low.

NO_3 Dissolves much faster in water in comparison to phosphates, and the combination of NO_3 and PO_4 in big amounts leads to an increase in the aquatic plant as well as algae. This would reduce the DO concentration impacting the entire aquatic system [35].

Table 12: NO_3 Input Data vs Output Results

RS	Station in the Creek	Observed NO_3 (mg/L)	Simulated NO_3 (mg/L) Results	NO_3 % Error
46	Creek Mouth	0.18	0.1895	5.27
38	Abra	0.3	0.3422	14.06
31	Wharfage	0.5	0.5799	15.98
29	Floating Bridge	1	0.993	0.70
14	Al Garhoud Bridge	2	3.62	81.00
10	Dubai Festival City	3	4.555	51.83
6	Jaddaf	3.3	4.999	51.48
5	STP Outfall	6	5.78	3.66
1	Sanctuary	4.8	4.8	0.00

Table 13: PO_4 Input Data vs Output Results

RS	Station in the Creek	Observed PO_4(mg/L)	Simulated PO_4(mg/L) Results	PO_4% Error
46	Creek Mouth	0.0204	0.02212	8.43
38	Abra	0.04	0.0496	24.00
31	Wharfage	0.078	0.08828	13.17
29	Floating Bridge	0.2	0.1427	28.65
14	Al Garhoud Bridge	0.25	0.4876	95.04
10	Dubai Festival City	0.45	0.6104	35.64
6	Jaddaf	0.4	0.6686	67.15
5	STP Outfall	0.8	0.7627	4.66
1	Sanctuary	0.58	0.58	0.00

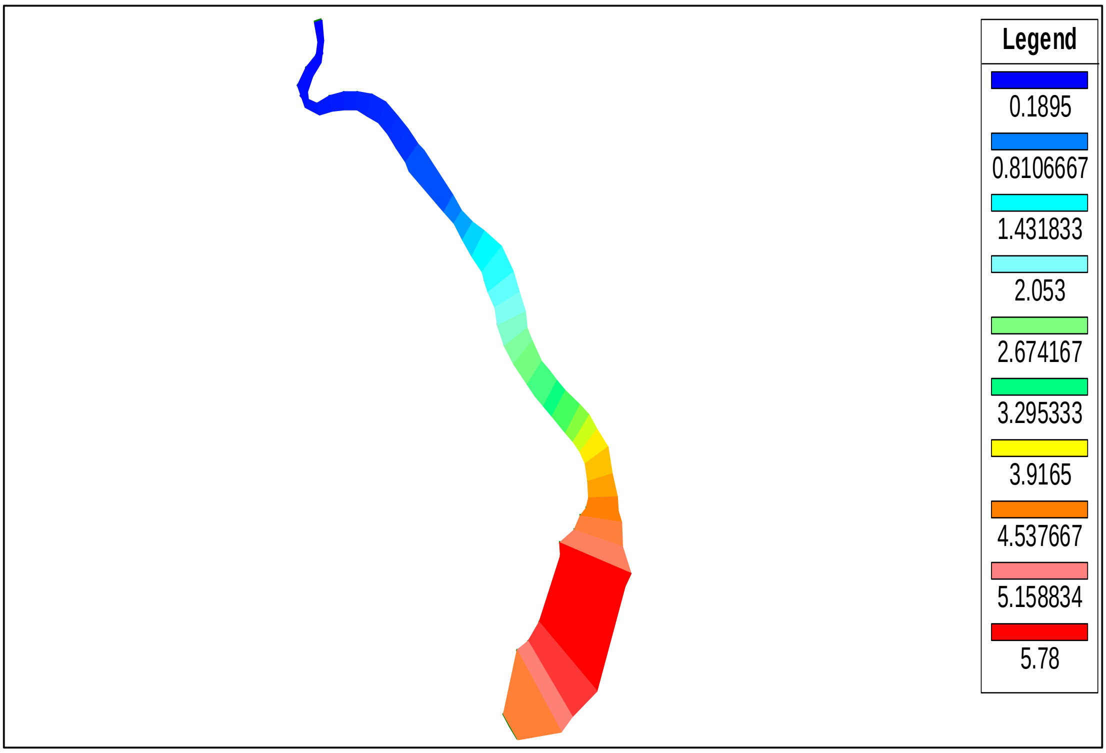

Figure 12: NO_3 Schematic Plot

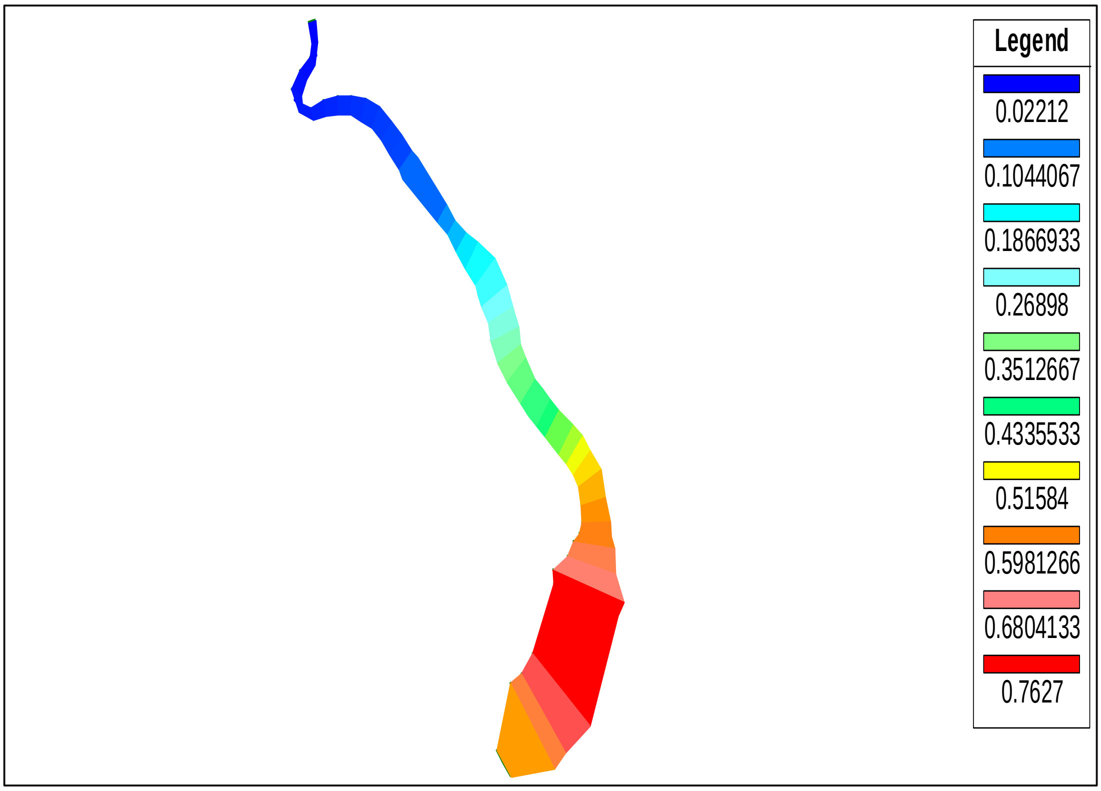

Figure 13: PO_4 Schematic Plot

4.4. Assessment of Factors Affecting the Water Quality

In this section, different scenarios were run in the developed model to explore the effect of changing input data on the water quality parameters. The results of those scenarios were compared with the basic water quality model in this section. Other model parameters remained the same.

4.4.1. Unsteady State Input Data

4.4.1.1. Stage Hydrograph Data

The stage hydrography data for the upstream boundary condition in the unsteady state was increased by +1.0 m. The hydrodynamic model output showed decrease in terms of velocity and depth (see Appendix E). On the other hand, evaluating the water quality model results showed no changes, the results were the same as the obtained in the basic model.

4.4.1.2. Uniform Lateral Flow Data

The lateral uniform flow in the hydrodynamic model in the boundary conditions of Wharfage and STP Outfall station were changed from 2.3 m^3/s to 3.2 m^3/s and from 3.0 m^3/s to 4.5 m^3/s, respectively. This variation did not impact the hydrodynamic results much (see Appendix F).The impact on the water quality model was also insignificant. Introducing the lateral flow in the model prevented the liner simulation in the water quality results where each parameter magnitude was increasing from downstream to upstream.

4.4.2. Water Quality Parameter

4.4.2.1. Algae

In this scenario, the algae concentration was changed in the most downstream Sanctuary station from 0.048 mg/L to 0.030 mg/L. The purpose of reducing the algae concentration was to observe the changes in the algae distribution as the downstream recorded the highest algae concentration. The comparison showed no changes along the creek except for the STP Outfall station that recorded -0.0024 mg/L. Moreover, it was noticed that algae did not impact the other water quality parameters in STP

Outfall station. The maximum and minimum recorded algae concentration locations remained the same as shown in Figures 10 and 14.

4.4.2.2. Dissolved Oxygen

Wharfage station recorded the lowest DO in the output results, therefore, in the scenario analysis DO was changed in the Wharfage station from 6.5 mg/L to 7.2 mg/L to observe how the increase in the DO will impact the simulation. Running this scenario showed that DO has increased in the creek except for the downstream Sanctuary that remained the same with maximum DO concentration to be 8.2 mg/L and the lowest DO concentration was in the upstream Creek Mouth to be 6.90 mg/L (Figure 15). Changing DO did not impact the other water quality parameters.

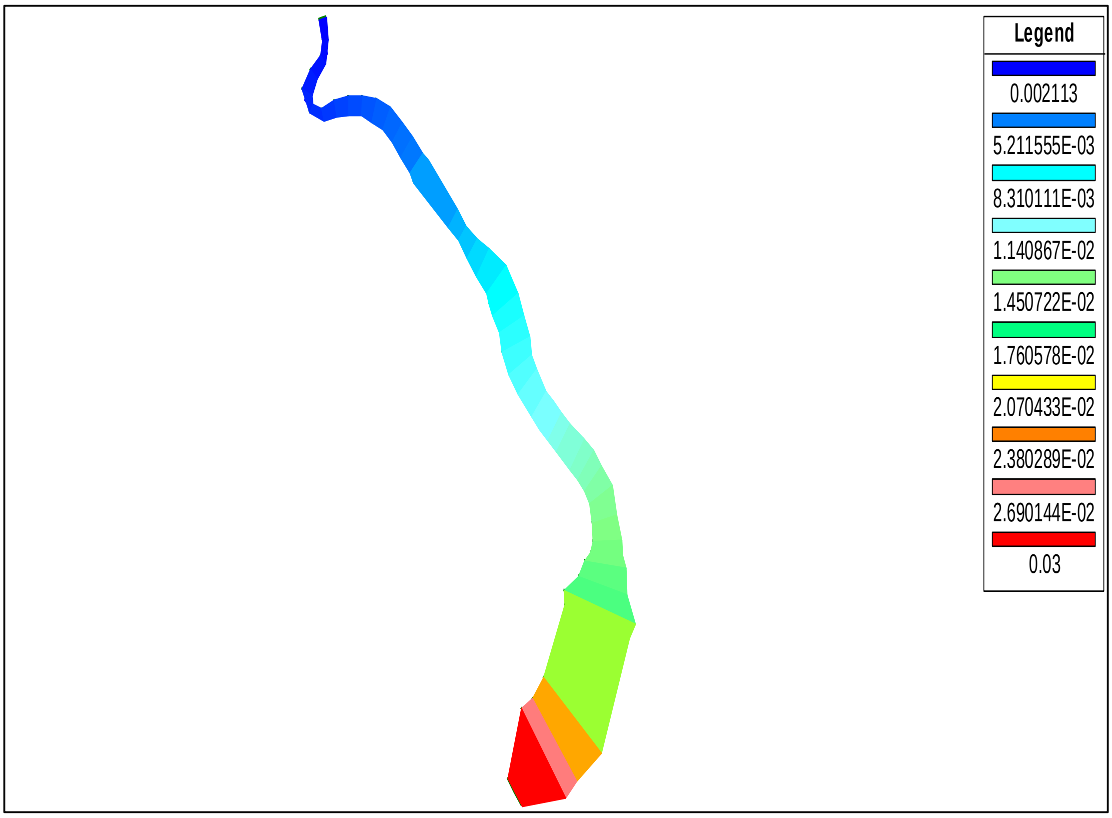

Figure 14: Changing Algae Concentration Scenario Schematic Plot

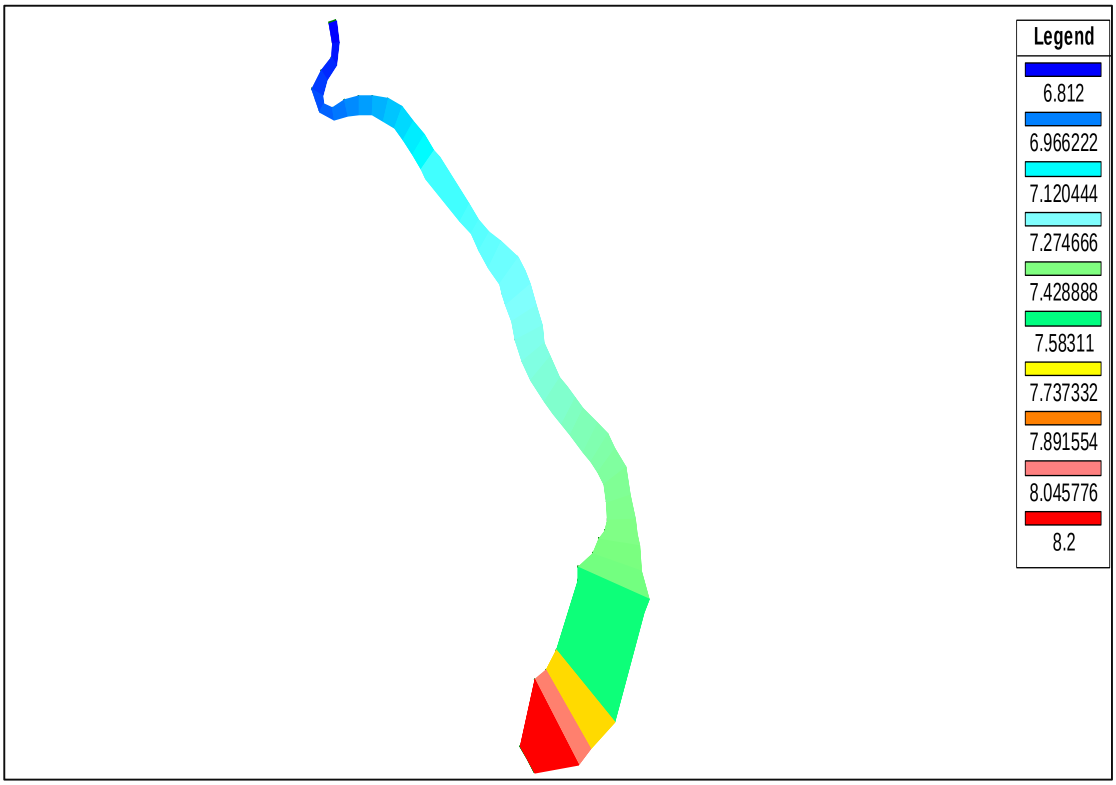

Figure 15: Changing DO Concentration Scenario Schematic Plot

4.4.2.3. Nitrate

The concentration of NO_3 in the STP Outfall station was changed from 6 mg/L to 4 mg/L. The purpose of this change was to observe how the model would represent the variation as STP Outfall was recorded with highest NO_3 in the basic model and nitrogen rich wastewater is being dumped. The scenario showed reduction in NO_3 starting from Wharfage Station towards STP Outfall whereas Sanctuary station recorded the maximum concentration of 4.8 mg/L. The minimum concentration was recorded for the Creek Mouth station to be 0.1895 mg/L (Figure 16). Changing NO_3 did not impact the other water quality parameters.

4.4.2.4. Orthophosphate

The concentration of PO_4 in the STP Outfall station was changed from 0.8 mg/L to 0.5 mg/L. The purpose of this change was to observe how the model would represent the variation as STP Outfall was recorded with highest PO_4 in the basic model and phosphorus rich wastewater is dumped. The scenario showed reduction in PO_4 starting from Wharfage Station towards STP Outfall whereas Sanctuary station recorded the maximum concentration of 0.58 mg/L while the minimum concentration was recorded for the Creek Mouth station to be 0.02212 mg/L (Figure 17). Changing PO_4 parameter did not impact the other water quality parameters.

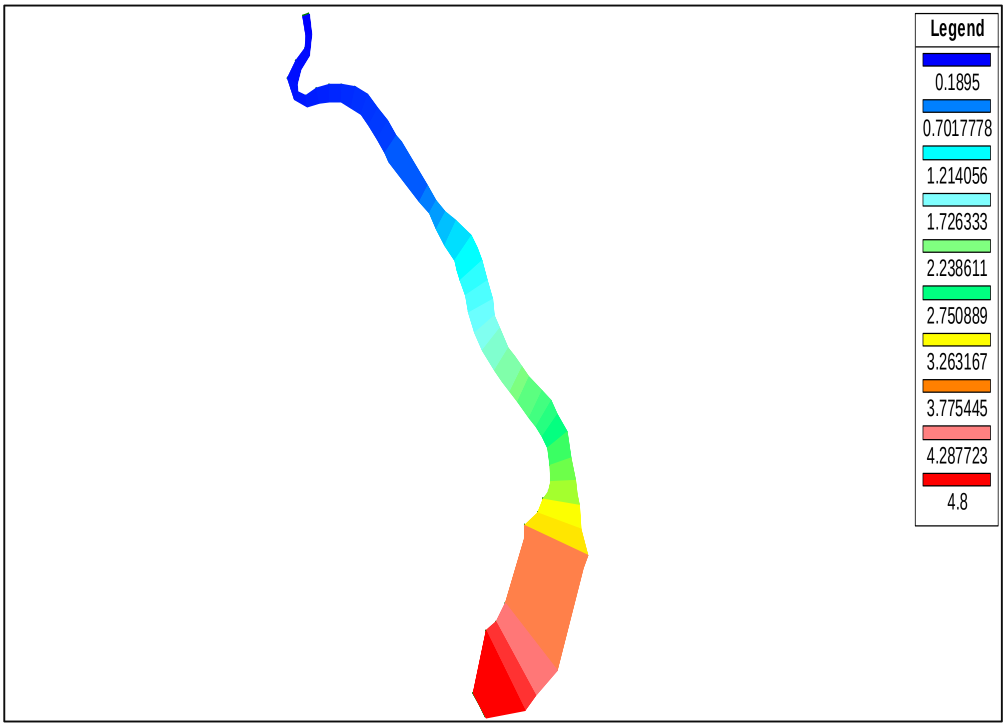

Figure 16: Changing NO_3 Concentration Scenario Schematic Plot

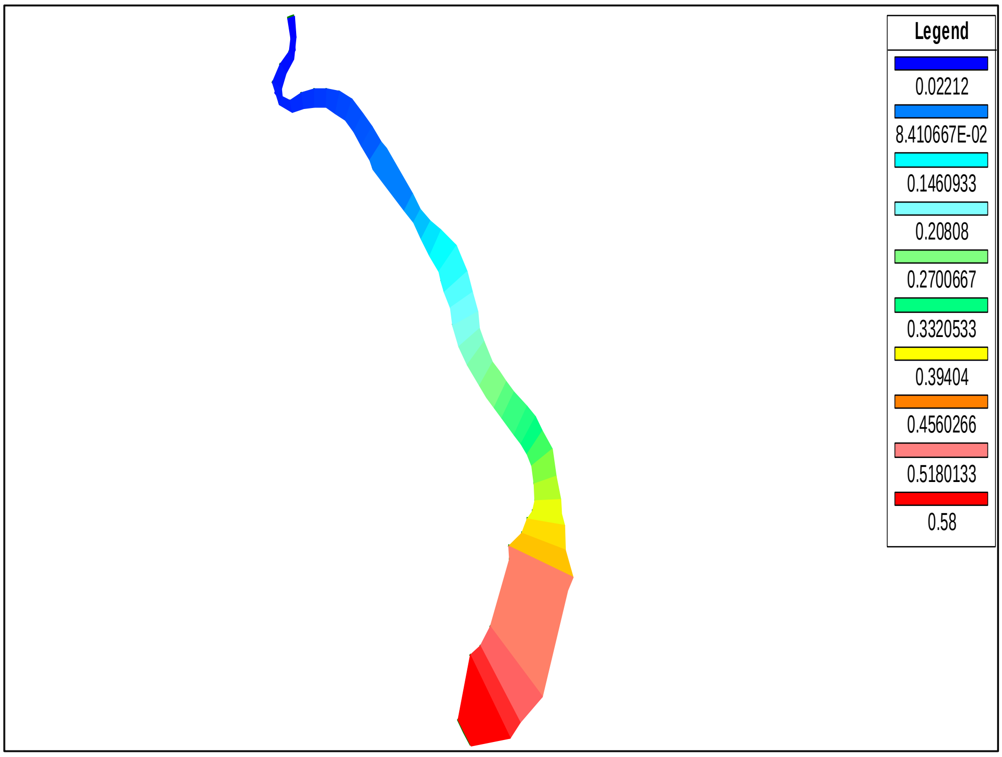

Figure 17: Changing PO_4 Concentration Scenario Schematic Plot

4.4.3. Summary for the Assessment of Factors Affecting the Water Quality

Increasing the flow input value in the stage hydrograph boundary condition (+1.00 m) didn’t affect the water quality simulation. Moreover, increasing uniform lateral flow values for the boundary conditions of Wharfage and STP Outfall stations (+0.9 m^3/s and +1.5 m^3/s respectively), didn’t record any impact on the water quality simulation.

After running the different scenarios in terms of the water quality parameters, the model output did not show a correlation among the parameters. However in nature Algal formation, nutrients and dissolved oxygen are related. Nutrients occurrence causes the growth of the different ecosystems’ plants, yet the recorded N/P atom ratios are not static in the different water bodies whereas some researchers suggested the range of 17.4:1 and 5.5:1. The existence of N/P depends on the marine ecosystem condition [38]. Eutrophication is the nutrient excessive existence; usually it referred to anthropogenic activities and the accumulation of nitrogen and phosphorus in marine systems. The growth of ecosystems’ plants includes free floating algae (phytoplankton), attached algae (periphyton) and aquatic plant (macrophytes). Although the eutrophication process needs long time to take place, human activities accelerate this process [7]. The increase in the ecosystem plant would consume oxygen in the respiration process during night. Moreover, the need of DO varies from one organism to another. The water bodies need minimal 1-6 mg/L of DO in the bottom water bodies while they need higher than 4-15 mg/L of DO in the shallow water fish [39]. Table 14 summarizes the water quality scenarios that had been run for the algae, DO, NO_3 and PO_4 parameters separately in comparison to the basic analyzed model.

Table 14: Observed Stations' Recorded Impact in Terms of Algae, DO, NO_3 and PO_4 Parameters Separately with Compare to the Basic Water Quality Model

WQ Parameter	Input Changing		Observed Stations' Recorded Impact in (mg/L)								
	Increased/ Decreased in (mg/L)	Utilized Station	Creek Mouth	Abra	Wharfage	Floating Bridge	Al Garhoud Bridge	Dubai Festival City	Jaddaf	STF Outfall	Sanctuary
Algae	-0.018	Sanctuary	0	0	0	0	0	0	0	-0.0024	-0.018
DO	0.7	Wharfage	0.022	0.353	0.679	0.626	0.3	0.181	0.125	0.011	0
NO_3	-2	STF Outfall	0	0	-0.0306	-0.1792	-1.235	-1.474	-1.636	-1.63	0
PO_4	-0.3	STF Outfall	0	0	-0.0046	-0.0269	-0.1702	-0.2347	-0.2581	-0.3395	0

Chapter 5: Conclusions and Recommendations

5.1. Conclusions

An unsteady state hydraulic model was developed and integrated with a water quality model for Dubai Creek. The hydrodynamic and water quality models were calibrated. The model validation was also undertaken by carrying out sensitivity analysis on hydrodynamic model and on the water quality parameters. After evaluating the results for the basic model, several scenarios were run to evaluate the factors affecting the water quality simulation.

Calibration results showed that the modelled and observed water levels were within a range of +0.14 m to +0.15 m for the eight selections locations along the creek. The hydrodynamic model output showed a maximum depth of 7.16 m and a minimum depth of 3.25 m, and recorded a maximum velocity of 1.61 m/s and a minimum velocity of 0.22 m/s. The results of sensitivity analysis showed that all models appear to be fairly insensitive to channel roughness and the initial flow.

The water quality model was calibrated and verified by evaluating the simulated results with the interpolated water quality data for three locations along the creek. Water quality output was evaluated for the algae, DO, $\mathrm{NO_3}$ and $\mathrm{PO_4}$. The algae concentration increased towards downstream Sanctuary station while DO had the opposite pattern and was depleting towards upstream. Nitrate and orthophosphate recorded the highest concentrations in the STP Outfall station and lowest concentration in the upstream Sanctuary station.

After running the different scenarios, it was concluded that changing unsteady state boundary conditions did not impact the water quality model. Furthermore, changing the water quality parameters did not show the correlation among the different water quality parameters that exist in nature rather than affecting the same changed parameter along the stream.

5.2. Recommendations

Similar study can be conducted by using two or three dimensional models to be compared with the generated 1D model. Also providing researchers with more accurate data in terms of bathymetric and water quality data will result in better simulation with more understanding for the water pollution factors. Moreover, Dubai creek sampling can be done once a month instead of quarterly year base in order to have up-to date record that will allow monitoring the water quality conditions in better ways. In this study, the impact of one water quality parameter each time was investigated; therefore, combination of different water quality parameters can be used in the assessment of factors affecting the water quality simulation. Furthermore, future studies can consider the opening of Dubai Creek’s downstream towards Arabian Gulf and simulating the distribution of pollution along the creek.

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Appendix A

River Stations (RS) Widths along with their Depth below Water Surface and Measured Distance between RS Sections

Table A. 1: ArcGIS and ArcMap Information

RS	RS Width (m)	Depth below Water Surface (m)	Elevation (m) with slop 0.00025	Distance between RS Sections (m)
46	152.323	-7.2	-7.2	250.00
45	128.684	-6.3	-7.14	250.00
44	138.116	-4.9	-7.07	250.00
43	161.564	-5.3	-7.01	250.00
42	214.040	-7	-6.95	250.00
41	127.727	-7.1	-6.88	250.00
40	156.416	-6.4	-6.82	250.00
39	205.501	-6	-6.76	250.00
38	234.302	-5.7	-6.7	250.00
37	238.966	-5.4	-6.64	250.00
36	280.022	-5.5	-6.58	250.00
35	284.987	-5.7	-6.52	250.00
34	293.520	-5.2	-6.45	250.00
33	325.937	-5.6	-6.39	250.00
32	360.403	-5.6	-6.33	136.61
31	383.980	-5.5	-6.29	806.12
30	268.871	-5.6	-6.08	250.00
29	212.606	-5.7	-6.02	250.00
28	294.331	-5.4	-5.96	250.00
27	403.608	-5.5	-5.9	329.00
26	474.765	-5.7	-5.82	166.00
25	524.369	-5.7	-5.78	166.00
24	544.911	-5.6	-5.74	250.00
23	500.933	-5.4	-5.67	250.00
22	554.473	-5.3	-5.61	250.00
21	483.030	-5	-5.55	233.00
20	457.754	-4.8	-5.49	336.00
19	399.970	-4.5	-5.4	195.00
18	411.691	-4.9	-5.35	200.00
17	408.372	-5.5	-5.31	200.00
16	409.972	-5.5	-5.26	330.00
15	448.713	-4.6	-5.17	200.00
14	465.126	-4.6	-5.13	250.00
13	431.069	-4.8	-5.06	250.00
12	474.732	-4.7	-5	288.00

RS	RS Width (m)	Depth below Water Surface (m)	Elevation (m) with slop 0.00025	Distance between RS Sections (m)
11	473.527	-4.7	-4.92	250.00
10	534.272	-4.6	-4.86	150.00
9	611.959	-4.5	-4.82	125.00
8	782.626	-4.6	-4.79	250.00
7	932.057	-5.8	-4.73	250.00
6	1391.157	-5.4	-4.67	170.00
5	1287.171	-5.6	-4.63	1184.00
4	1385.749	-5.5	-4.33	430.00
3	1249.686	-4.5	-4.22	266.00
2	1313.460	-4.3	-4.15	740.00
1	413.026	-3.4	-3.97	0.00

Appendix B

Water Quality Data by Dubai Municipality for 2012-2013 (Third Quarter)

Table A. 2: Water Quality 2012-2013 Third Quarter

Stations	Salinity pot	pH	Chlorophyll (ug/L)	DO+ %	DO+ Conc (mg/L)	Turbidity (N.T.U)	Nitrates as N (mg/L)	Total Nitrogen (mg/L)	Phosphates as P (mg/L)
Creek Mouth	38.76	8.11	3.8	95.1	6.26	1.5	0.13	0.54	<0.02
Hayat Regency	38.29	8.16	7.1	106.1	7.01	1.5	0.18	0.59	0.02
Abra	38.43	8.12	2.2	99.3	6.54	2	0.2	0.66	0.02
Wharfage	37.64	7.98	6.8	91.8	6.1	2	0.43	1.32	0.07
Floating Bridge	37.24	7.96	5.1	71.4	4.63	1.5	0.88	1.71	0.12
Al Garhoud Bridge	36.25	8.01	16.8	89.1	5.82	1.5	0.8	1.98	0.17
Dubai Festival City	33.92	8.17	28.9	119.6	7.99	2	2.5	4.92	0.34
STP Outfall	34.4	8.02	15.8	100	6.59	2	5.3	9.75	0.77
Jaddaf	33.81	7.98	14	92.8	6.18	2	2.27	4.08	0.23
Sanctuary	34.78	8.23	44	119.1	7.95	2	4.6	8.9	0.55

Appendix C

The 97 used Tidal Information Flow in the Stage Hydrography Boundary Condition in the Unsteady State

Table A. 3: Stage Hydrography Data

No	Tidal Information Flow (m)
1	-1.153
2	-1.141
3	-1.12
4	-1.082
5	-1.032
6	-0.975
7	-0.916
8	-0.846
9	-0.776
10	-0.694
11	-0.623
12	-0.539
13	-0.448
14	-0.368
15	-0.276
16	-0.201
17	-0.142
18	-0.09
19	-0.052
20	-0.03
21	-0.005
22	-0.039
23	-0.06
24	-0.113
25	-0.21
26	-0.298
27	-0.423
28	-0.529
29	-0.667
30	-0.814
31	-0.962
32	-1.082
33	-1.231
34	-1.342

No	Tidal Information Flow (m)
35	-1.461
36	-1.528
37	-1.635
38	-1.734
39	-1.767
40	-1.822
41	-1.851
42	-1.888
43	-1.869
44	-1.855
45	-1.815
46	-1.764
47	-1.68
48	-1.573
49	-1.453
50	-1.332
51	-1.21
52	-1.097
53	-0.975
54	-0.878
55	-0.779
56	-0.695
57	-0.616
58	-0.554
59	-0.52
60	-0.487
61	-0.483
62	-0.486
63	-0.523
64	-0.554
65	-0.633
66	-0.692
67	-0.76
68	-0.839
69	-0.915
70	-0.978
71	-1.042
72	-1.101
73	-1.114
74	-1.14
75	-1.144
76	-1.129

No	Tidal Information Flow (m)
77	-1.107
78	-1.072
79	-1.023
80	-0.971
81	-0.902
82	-0.84
83	-0.77
84	-0.682
85	-0.608
86	-0.525
87	-0.43
88	-0.349
89	-0.264
90	-0.193
91	-0.12
92	-0.07
93	-0.015
94	0.006
95	0.026
96	0.022
97	0.008

Appendix D

Dubai Creek Hydrodynamic Basic's Model Results in Terms of Velocity and Depth

Table A. 4: Hydrodynamic Model Output Results

River Station	Velocity (m/s)	Depth (m)
46	1.26	7.16
45	1.52	7.03
44	1.43	6.93
43	1.24	6.86
42	0.94	6.81
41	1.62	6.63
40	1.33	6.56
39	1.02	6.51
38	0.91	6.45
37	0.9	6.37
36	0.77	6.31
35	0.77	6.24
34	0.76	6.16
33	0.69	6.09
32	0.69	6.02
31	0.59	5.98
30	0.88	5.71
29	1.13	5.6
28	0.83	5.55
27	0.61	5.49
26	0.52	5.41
25	0.48	5.37
24	0.46	5.32
23	0.51	5.25
22	0.46	5.18
21	0.54	5.11
20	0.57	5.04
19	0.67	4.93
18	0.66	4.87
17	0.67	4.82
16	0.67	4.76
15	0.63	4.66
14	0.61	4.61
13	0.67	4.53
12	0.61	4.46
11	0.63	4.37
10	0.56	4.3

River Station	Velocity (m/s)	Depth (m)
9	0.5	4.26
8	0.39	4.23
7	0.33	4.16
6	0.22	4.1
5	0.24	4.06
4	0.23	3.74
3	0.26	3.62
2	0.25	3.55
1	0.86	3.25

Appendix E

Dubai Creek Hydrodynamic Model Results in Terms of Velocity and Depth after Increasing Stage Hydrography Condition Data by 1m

Table A. 5: Hydrodynamic Results after Changing the Stage Hydrograph Data

River Station	Velocity (m/s)	Depth (m)
46	0.97	6.16
45	1.16	6.05
44	1.1	5.96
43	0.95	5.9
42	0.72	5.84
41	1.24	5.69
40	1.03	5.63
39	0.79	5.57
38	0.7	5.51
37	0.69	5.44
36	0.6	5.37
35	0.6	5.3
34	0.59	5.23
33	0.53	5.16
32	0.54	5.09
31	0.46	5.05
30	0.69	4.8
29	0.89	4.71
28	0.65	4.65
27	0.48	4.59
26	0.41	4.5
25	0.38	4.46
24	0.36	4.42
23	0.4	4.34
22	0.37	4.28
21	0.43	4.21
20	0.45	4.15
19	0.53	4.04
18	0.52	3.98
17	0.53	3.93
16	0.54	3.88
15	0.5	3.77
14	0.49	3.73
13	0.53	3.65
12	0.49	3.58
11	0.43	3.49

River Station	Velocity (m/s)	Depth (m)
10	0.38	3.42
9	0.34	3.38
8	0.27	3.35
7	0.23	3.29
6	0.16	3.23
5	0.17	3.19
4	0.18	2.87
3	0.2	2.76
2	0.2	2.68
1	0.7	2.39

Appendix F

Dubai Creek Hydrodynamic Model Results in Terms of Velocity and Depth after Changing the Intermediate Uniform Lateral Flow Data

Table A. 6: Hydrodynamic Results after Changing the Intermediate Uniform Lateral Flow Data

River Station	Velocity (m/s)	Depth (m)
46	1.25	7.16
45	1.51	7.03
44	1.43	6.93
43	1.23	6.86
42	0.94	6.81
41	1.61	6.63
40	1.33	6.57
39	1.02	6.52
38	0.90	6.45
37	0.89	6.37
36	0.77	6.31
35	0.77	6.24
34	0.75	6.16
33	0.68	6.09
32	0.69	6.02
31	0.59	5.99
30	0.88	5.72
29	1.13	5.61
28	0.82	5.55
27	0.61	5.50
26	0.52	5.41
25	0.48	5.37
24	0.46	5.33
23	0.51	5.25
22	0.46	5.19
21	0.54	5.12
20	0.57	5.05
19	0.67	4.94
18	0.66	4.88
17	0.67	4.83
16	0.67	4.77
15	0.63	4.66
14	0.61	4.62
13	0.67	4.53
12	0.61	4.46

River Station	Velocity (m/s)	Depth (m)
11	0.62	4.37
10	0.56	4.30
9	0.49	4.26
8	0.39	4.23
7	0.33	4.17
6	0.22	4.11
5	0.24	4.06
4	0.23	3.75
3	0.26	3.63
2	0.25	3.55
1	0.86	3.26

Vita

Heba Hussien was born in Dubai, United Arab Emirates in 1987. She received her high school certificate from Asma bint Omise Secondary School, Ajman. She joined the American University of Sharjah in 2007 and received her Bachelor of Science degree in Civil Engineering in 2011. She started her Master's degree in September 2012. During her graduate studies, she worked for the American University of Sharjah as an Administrative Assistant in the Student and Athletics and Recreation Department, Office of Student Affairs.