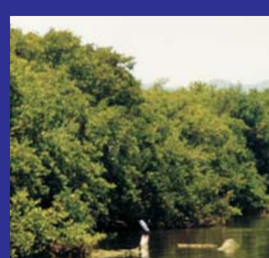
Institutional Strengthening & Preparation of a Zoning & Physical Development Master Plan for Kingston Harbour

Water Quality Model Selection Report

Submitted to the

National Environment and Planning Agency

Project No. ATN/SF-8164-JA



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January 2005

Document Objective

This document has been prepared as a major deliverable for *Component A – Institutional Strengthening and Preparation of a Zoning and Physical Development Master Plan for Kingston Harbour* of the Inter-American Development Bank (IADB) project titled *Institutional Strengthening to Support Environmental Management of Kingston Harbour* (Project No: ATN/SF-8164-JA). This report presents the process that has been followed in the selection of a suitable coastal water quality model. It is intended to be a summary document for the purpose of conveying pertinent information about the water quality simulation aspects of the project and also is intended to contribute to the further completion of this project.

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1. Introduction

1.1. Background

Kingston Harbour is the main receiving water body for the city of Kingston, and accepts inflows from adjacent rivers, gullies, industrial and commercial facilities, as well as sewage treatment plants. Furthermore, Kingston Harbour is the primary port for the island, handling large volumes of marine traffic and the associated exposure to vessel-generated wastes and pollutants. The harbour water quality is badly degraded and numerous studies have indicated that, in fact, Kingston Harbour is contaminated and has suffered significant environmental degradation over the past several decades.

The poor condition of the harbour has long been recognized and over the past few decades there have been several attempts to address its environmental health. However, to date none of these efforts have been successful. It is now apparent that the failure of previous attempts to clean up the harbour has been directly related to:

1. The lack of clarity as to the authority for and responsibilities of the many institutions that have a role in the use and management of the harbour, and
2. The limited communication and coordination between the relevant agencies.

This situation needs to be addressed sooner, rather than later, before the overall costs are so high that rehabilitation of the harbour becomes infeasible. The logical solution requires that the diverse number of stakeholders be coordinated through an institutional setting, such that ultimately an overall investment plan for the clean-up of Kingston Harbour can be supported and implemented.

Based on a recognition of the previous limiting factors to successful harbour rehabilitation, the Ministry of Land and Environment (MLE) led the Government of Jamaica (GOJ) in negotiations with the Inter-American Development Bank (IADB), to formulate a project for *Institutional Strengthening to Support Environmental Management of Kingston Harbour* (Project No: ATN/SF-8164-JA). The first component of this project, *Component A - Institutional Strengthening and Preparation of a Zoning and Physical Development Master Plan for Kingston Harbour* (KgnHrbr – A)*,* seeks to specifically address the environmental management framework for the Harbour.

This document represents a major deliverable for Component A, which is a presentation of the process of selection for a coastal water quality model for Kingston Harbour.

Water quality modelling is a process that attempts to simplify and reproduce a highly complex environment that is influenced to varying degrees by physics, biology and chemistry. Simplified versions of the processes that occur in nature are represented by a series of mathematical equations that may best be solved by computer. In its earliest form, water quality modelling was used primarily to describe the potentially toxic decrease in dissolved oxygen levels as sewage (represented as BOD) was dumped into rivers and lakes. As water quality modelling has become more sophisticated, equations describing the chemical and biological reaction of nutrients (Nitrogen and Phospherous) have been introduced in order to model eutrophication (over-nourishment of the receiving waters), which primarily manifests itself through the growth of algae. More recently, the ability to predict the impact of toxic chemicals such as heavy metals, mercury, and PCB's on receiving waters has been added to water quality models.

Present-day water quality models have therefore become important tools to facilitate the protection of an environment that may be subjected to a wide range of polluting conditions, and the promotion of much needed development. As such, as a tool that is to be used to promote change in the management of a natural resource, a water quality model must be robust, proven and tested. To achieve this, water quality models often require extensive data collection programmes to facilitate the calibration stage, and also to provide model validation once any clean-up efforts begin.

1.2. Scope of Work

The following is a presentation of the scope of work reported on in this deliverable:

Task 10 Acquire Coastal Water Quality Model

The selection and implementation of the coastal water quality model will involve five (5) steps, outlined below:

10.1 Review of existing literature

This will involve reviewing the information gathered in Tasks 1 and 2 of the project, specifically the water quality, ecological health, sediment quality, circulation studies, and pollutant source identification.

10.2 Creation of baseline conditions (Map/GIS).

In order to bring all of the relevant baseline conditions together in a useable form, a map will be created to display the extent and severity of environmental degradation. This map will be compatible with the NEPA GIS and will be extremely useful as presentation material for public presentations.

10.3 Determine clean-up parameters

Guided by the findings of Task 4 (Review and Assess International Experiences in Harbour Clean-up) relevant water quality parameters will be targeted for reduction. These may include, amongst others, Dissolved Oxygen, BOD, nitrogen, phosphorous, suspended solids and heavy metals.

10.4 Assess the modeling requirements

An assessment will be carried out of the objectives of the modeling, which include, inter alia:

- Demonstrating the impacts of the clean-up options,
- The evaluation of impacts of individual sources, and
- Determining the future impacts of enforcement actions.

10.5 Select and acquire water quality model.

The widest possible range of hydrodynamic and water quality models will be investigated to determine the most suitable model for Kingston Harbour. Both commercially available and public domain/open source models will be evaluated. A matrix will be developed in conjunction with NEPA to allow for a fully transparent and rigorous evaluation of the various models. The following list outlines some of the criteria that will be evaluated:

- Underlying mathematical formulations for hydrodynamics and chemical reactions;
- Model track record and user feedback;
- Ease-of-use and computational speed;
- Graphics / GIS capabilities;
- Acquisition cost (some of the high-end models offer less costly institutional or site-specific licenses);
- Training cost; and
- Maintenance costs including updates and technical support.

Professor James Martin has extensive experience in the evaluation of hydrodynamic and water quality models. In his textbook "*Hydrodynamics and Transport for Water Quality Modeling*", he presents perhaps the most thorough comparison of existing water quality and hydrodynamic models. We will use this information as the basis for the evaluation, updating Professor Martin's evaluations as necessary.

2. Literature Review

Existing data and information that would be pertinent for water quality modeling includes measurement of the parameters listed below. The hydrodynamic and water quality input boundary conditions used in running these models can consist of either measured data or synthesized information, whereas calibration data must be measured:

- Hydrodynamic boundary conditions
  - Bathymetry - measured
  - Tides – measured or synthesized
  - Winds - measured
  - River and gully flow rates, including temperature and salinity – measured or synthesized
- Hydrodynamic calibration data
  - Annual time series measurements of currents and water levels - best
  - Seasonal time series measurements of currents and water levels - acceptable
  - Spot measurements of tides and currents - minimum
- Water Quality boundary conditions
  - Baseline conditions – profiles of temperature, salinity, and DO
  - Baseline conditions – whole-water concentrations of nutrients, and chlorophyll-a
  - Baseline conditions – sediment oxygen demand
  - Loadings – BOD, nutrients, and suspended sediments
- Water Quality calibration data
  - Measured depth profiles of DO
  - Measured Chlorophyll-a and nutrient concentrations
  - Measured seasonal temperature and salinity profiles

2.1. Bathymetry

Detailed bathymetric charts exist for Kingston Harbour, including updates showing the dredging and reclamation works undertaken in 2002. Figure 2.1 shows British Admiralty chart 456. The source data guide, located in the upper right hand corner indicates that inside the harbour most of the data source is from 1996-1999 Government of Jamaica surveys except for Hunts Bay (1985-1990) and the port and entrance channel (2002).

More detailed data sources do exist, including the Cuban surveys and others. These data sources have proven to be difficult to access and have therefore not been included. While more detailed information may be incorporated into the model at a future date, as it becomes available, the detail presented in the following figure is sufficient for this stage in the modeling exercise.

The depth information contained in this chart has been digitized using the JAD coordinate system and converted to an ArcVIEW system file.

Some initial calculations of the characteristic parameters of Kingston Harbour have been undertaken, which are listed in the following table:

Harbour Segment	*Surface Area (m^2)*	*Water Volume (m^3)*	*Average Depth (m)*	*Inflow or Exchange*
Outer Harbour	18,950,883	159,193,186	8.40	Hunt's Bay, open sea & Inner Harbour
Hunt's Bay	3,929,448	6,438,303	1.64	Rio Cobre, Duhaney River, Sandy Gulley & Outer Harbour
Inner Harbour	15,619,988	9,877,286	6.32	Gullies, Upper Basin & Outer Harbour
Upper Basin	13,953,346	182,641,304	13.1	Springs (Rockfort), Gullies & Inner Harbour
Entire Harbour	52,453,665	358,150,079	6.82	

These characteristics can be used to gain some insight into the circulation patterns and water quality issues facing Kingston Harbour. First, the average water depth of the entire harbour (6.8 metres) relative to the daily tide range (0.15 m), suggests that at least 45 tide cycles would be required to exchange the water within Kingston Harbour, if mixing were complete, which is unlikely. Second, the location of the Inner Harbour and Upper Basin is such that the main freshwater input (Rio Cobre & Duhaney River) is bypassed directly from Hunt's Bay to the Outer Harbour and then to the open sea. Third, the Upper Basin average water depth is greater than the Inner Harbour, which tends to decrease flushing as water exchange occurs higher up in the water column, leaving the deeper water undisturbed. Furthermore, the Upper Basin has very little freshwater inflow. All of these characteristics of Kingston Harbour will be considered during the configuration of the hydrodynamic and water quality model.

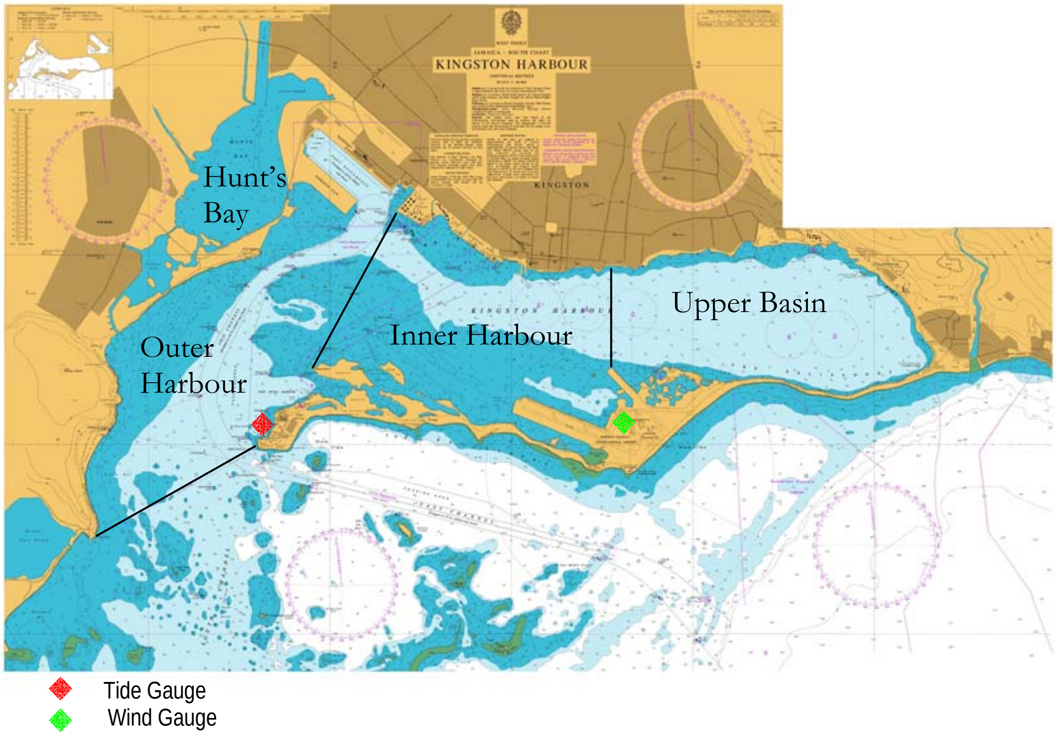


Figure 2.1 **Bathymetry for Kingston Harbour**

2.2. Tides

Measurements of tide levels have been made at Port Royal at several times over the years. Digital, hourly data obtained from MACC (formerly CPACC) contains records of tide measurements made in the 1960's and in 1998 and 1999. In addition, tide measurements were made by the Cubans in 1995. This data was, however, not digital. Most recently, a pressure sensing tide gauge was installed at the Port Royal Marine Lab in 1998, and digital data was obtained for 1999 and 2000.

The following figure (Figure 2.2) shows the typical tidal heights measured during a month. It can be seen that the signal exhibits both diurnal and semi-diurnal characteristics (i.e. both one and two highs and lows per day). The average tide range appears to be approximately 0.15 metres.

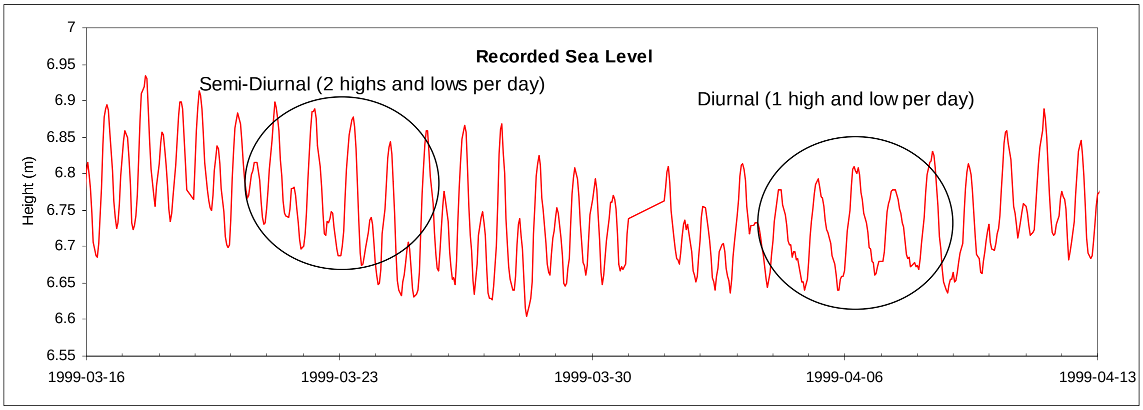


Figure 2.2 Simple Tide Record from Port Royal

These data can be used to generate input boundary conditions, either to simulate conditions during the measurement time, or to undertake a tidal constituent harmonic analysis to predict tides at other times.

2.3. Winds

Hourly meteorological measurements have been made at Norman Manley International Airport for many years. Summaries based on historical data are available and indicate a predominance of winds from the east and ESE, between 7 and 11 kts (3.6 to 5.6 m/s). Seasonal variations in the wind conditions are also evident, with strongest winds occurring in June and July, and a noticeably different pattern in December and January, which shows the land-sea breeze phenomenon, whereby winds blow from the north (i.e. from the land) during the nights. More recently, on-line storage and retrieval systems make this data instantly accessible (e.g. www.wunderground.com). This data has been used to produce the following Figure 2.3, which is a "straw plot" showing a time series of the wind vectors. As can be seen there is a period of several hours in the afternoon when the wind is from the southeast, whereas during the remainder of the day, the wind is much weaker. This is quite a typical pattern for Kingston Harbour.

Figure 2.3 Sample Wind Measurements from NMIA

2.4. River & Gully Flows

At present, and with the exception of the Rio Cobre, there are no operational gauging stations on any of the rivers or gullies entering Kingston Harbour. In terms of short-term measurements, flows were measured on a monthly basis during non-flood conditions at 22 locations entering into Kingston Harbour from 1993-1995. These data were used to estimate flow and pollutant loadings (Webber and Wilson-Kelly, 2003). In addition, various hydrologic and stormwater studies have been conducted to establish "high" and "low" flow rates, based on drainage areas and rainfall. These rates are listed in the following table.

River or Gully	**Mean Flow (m^3/s)**	**Peak Flow (m^3/s)**
Rio Cobre	6.8	1500
Duhaney River	2.8	85
Sandy Gully	1.9	930
Kingston gullies	1.7	80
Total	12.6	2595

These data represent the best available information on gully and river flows, although for the most part the basis is not on continuous measurements, but using hydrological synthesizing techniques, which therefore include significant uncertainties.

The river and gully flow rates can be used along with the previous data on bathymetry to gain some further insight into the overall circulation and flushing within Kingston Harbour.

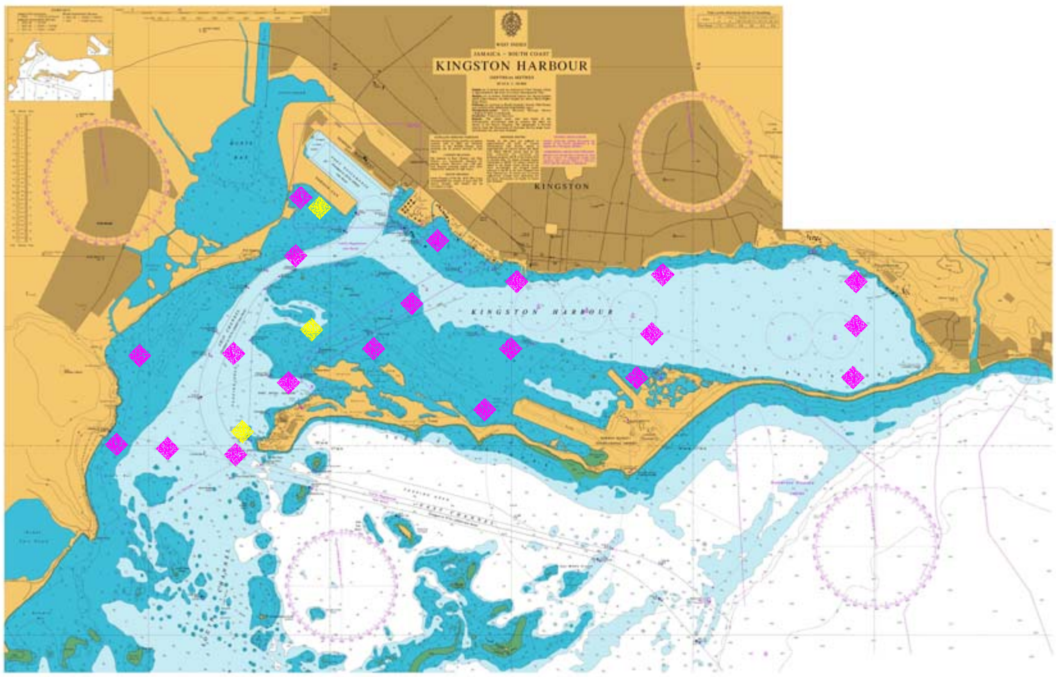
The total annual river and gully flow into Kingston Harbour amounts to approximately 12.6 m^3/s, which corresponds to an annual flow of 397,000,000 m^3. This flow, divided by the harbour water volume corresponds to a flushing time of 0.90 years. Using the peak flow rates, the flushing time reduces to 38 hours. This represents a significant variation in flushing times, and hence very different hydrodynamic conditions. In addition, these inputs carry significant pollutant loadings, which would impact the water quality.

Given the importance of the freshwater flows to the hydrodynamics and the pollutant loadings that these inputs convey and the fact that most of the available information is not measured but synthesized data, it is important that a programme to reduce the inherent uncertainties is established.

2.5. Hydrodynamic Calibration Data

In order to calibrate a hydrodynamic model of Kingston Harbour, measurements of current speeds or tide heights are required. Several studies have been undertaken to determine flow patterns inside Kingston Harbour. Noteworthy among these are the studies by the Cubans, who installed combined tide and current meters at three locations inside Kingston Harbour, and by Doreen Williams, who made bi-monthly current measurements at some 20 stations over a 15 month period (see Figure 2.4 for locations).

Several attempts were made to obtain the raw data for this project, however, these all proved unsuccessful. Published reports and journal papers contain abbreviated data sets and summaries, which have a much diminished utility compared with the raw data.



Tide & Current meter Cubans (continuous for 7 days)
Instantaneous current measurement (repeated for 15 months)

Figure 2.4 Locations of Main Measuring Locations in Harbour

The time series measurements made by the Cubans show currents less than 5 cm/s, but it should be noted that these were limited to the outer harbour area, and only lasted for 7 days. The instantaneous current measurements collected over 15 months have been grouped into blocks depending on seasonality or forcing functions (e.g. dry season, high wind, ebb tide). The surface patterns showed a series of possible gyres and other features, depending on the selected grouping, with speeds of up to 12 cm/s. Often net flow appeared to be out of the harbour. Deep currents were measured at a depth of 9.0 metres and were quite strong (up to 15 cm/s). These tended to indicate sub-surface flow into the harbour. This system of surface outflow and sub-surface inflow replacement is typical of estuarine environments.

Previous hydrodynamic models of Kingston Harbour, in particular Bigg and Webber (2003), have used 2-dimensional depth-averaged flow velocities. Calibration of that model involved the comparison of measured and predicted tidal heights at the three sites shown in Figure 2.4 and comparison with measured current speeds in the Outer Harbour. A reasonable calibration was achieved, however, in the Inner Harbour and Upper Basin the 2D model results typically predicted negligible current speeds, contrary to the measurements of Webber *et al* (2003). **The model results and measured current patterns strongly suggest the**

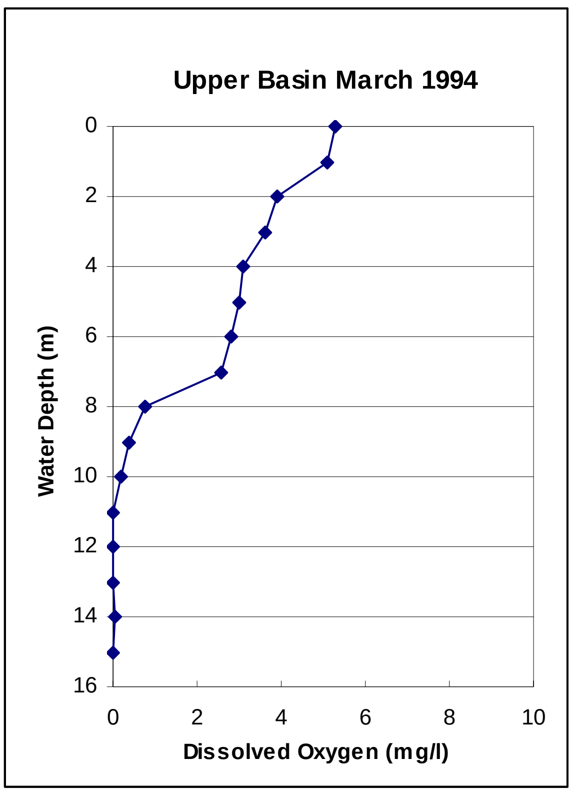
need for a 3-dimensional hydrodynamic model to properly describe the circulation patterns within Kingston Harbour.

Another method of calibrating a hydrodynamic model is to use tide measurements. However, in order to use measured tide data for hydrodynamic calibration or verification, it is necessary to have simultaneous measurements at two or more distant locations at minimum 10 minute intervals. It should also be noted that in microtidal regimes such as Kingston Harbour it is important that the daily fluctuations in atmospheric pressure, which can affect readings by 3 to 5 cm, should be compensated for when using a pressure sensing tide gauge.

In summary, the available data for calibration of the hydrodynamic model is quite limited and should be augmented with a data collection programme that has been specifically designed to calibrate a 3D model.

2.6. Water Quality Boundary Conditions

Water quality modelling requires information to define the baseline conditions and also to define the pollutant loadings. As with any computer model, the output is only as good as the input. This is particularly true for highly complex situations such as water quality modelling.



Signs of eutrophication, which can be defined as the ecosystem response to high nutrient levels, have been observed inside Kingston Harbour for many years. As outlined in Task 1 – Literature Review, peak nitrate levels are five to 68 times the recommended levels for sensitive marine tropical ecosystems. These have resulted in very high chlorophyll-a concentrations and depressed dissolved oxygen levels. Measured chlorophyll-a concentrations exceed the threshold for sensitive marine tropical ecosystems by up to 12 times and dissolved oxygen levels often fall below 4.0-6.0 mg/l. Details of the dissolved oxygen profiles reveal that the surface is often well oxygenated, as expected given the dominant wind pattern, however, below this surface layer, oxygen levels decrease below the recommended threshold level. Close to the seabed, a thick layer of unconsolidated silt occurs, where DO levels are near 0.0. Dissolved oxygen profiles like this, coupled with high nutrient and chlorophyll-a concentrations are clear signs of eutrophication.

The possible sources of this eutrophication include:

- Partially and un-treated sewage

- Industrial waste
- Agricultural run-off
- Gullies
- Polluted groundwater

A screening for toxic metals in sediments was undertaken as part of an EIA for expansion of the port facilities. This screening did not reveal significant levels in the sediments.

The main pollutants affecting Kingston Harbour include:

- Bacteria and nutrients and BOD/COD from industry and sewage treatment plants
- Suspended sediment, fertilizers and BOD/COD from gullies and rivers
- Solid waste (garbage) from gullies and rivers

As part of Component B, an inventory of industrial discharges to Kingston Harbour was made. Effluent loadings are normally obtained from the product of flow rate and concentration. Measurements of flow and pollutant concentration were found to be quite rare and therefore loadings had to be estimated from water consumption. Very limited data on effluent quality was available from the STP's. As these plants contribute between 3 and 10 times the BOD loading compare to the industrial discharges, it is important that better estimates of these significant loadings are obtained.

Several studies on Kingston Harbour have focused on the biological rather than chemical impacts. These studies have documented temporal and spatial variations in different plant and animal species, and have drawn conclusions regarding the levels of eutrophication, water quality, etc. Webber, M.K., *et al* (2003) measured water quality and plankton concentrations in the 1990's and compared the values to similar measurements made in the 1970's. The mean phytoplankton abundance had jumped to 29×10^7 cells L^{-1} along with increasing nitrate-nitrite-nitrogen levels.

Suspended solids enter the harbour from sewage, industry and river flows. Results from Component B indicate that the main contributor is due to sewage, followed by industry. Domestic sewage normally has a suspended sediment concentration of 200-300 mg/l. Industrial waste can be much higher, but is also quite variable. River flow has been reported to be almost negligible except during high flow conditions. SWIL undertook an estimate of suspended sediment concentrations in the Rio Cobre, and found peak concentrations to range up to 16,000 mg/l during flood conditions, according to the method of van Rijn. The fact that Hunt's Bay requires periodic maintenance dredging provides some information on the average sediment load.

2.7. Water Quality Calibration Data

The most detailed campaign of water quality data collection was undertaken by UWI almost 10 years ago. This data will have to be used for setting of the baseline conditions and the calibration component. To use the model in the future for enforcement purposes, it will be necessary to undertake a more thorough calibration phase, using results for a data collection programme that has been specifically designed to support the model. The design of this data collection programme will be undertaken once the water quality model is operational, and the data requirements can be properly assessed.

2.8. Summary

In summary, the review of literature and data has revealed that a number of studies have been conducted on Kingston Harbour. The primary investigating body has been the University of the West Indies, who have conducted several baseline and comparative investigations into the status of the harbour. Unfortunately, the most recent campaign of water quality data collection was completed ten years ago. Since that time it is likely that conditions have worsened as there have been no substantial improvements to the treatment of sewage.

Efforts to model the hydrodynamics inside the harbour have been undertaken, but these have used 2D models, which utilize an average current throughout the water column. Measured currents, temperature and salinity profiles inside the harbour suggest that a 3D model would be more appropriate. Calibration of the 2D model was undertaken, but the data used for comparison was only in the Outer Harbour, and was limited to 7 days. Furthermore, the model results did not indicate the same magnitude of current speeds that were measured in the Inner Harbour and Upper Basin. The available current data could be used to establish a 3D hydrodynamic model, however, the reliability would be substantially improved with an appropriate set of calibration data. The design and recommendations of such a model calibration programme will form part of Task 10 – Water Quality Model.

The data collection programmes undertaken by UWI were not designed to calibrate, verify and support a Kingston Harbour Water Quality Model that would be used for planning, regulatory and enforcement purposes. It is clear from the literature review that a specifically designed data collection programme will be required to support the water quality model.

As a preliminary list to calibrate the hydrodynamics, such a programme should include:

- Continuous current measurements throughout the water column at two or more locations to assess temporal variations in current speeds
- Lagrangian drifters (drogues) to assess spatial variations in surface currents and advection patterns
- Dye-tracer study to measure diffusion,
- Gauging of Rio Cobre at the Highway 2000 bridge to assess the main freshwater input, and
- Salinity, temperature and DO profiles to verify the rates of vertical mixing.

Once the hydrodynamics are well calibrated, it would be necessary to calibrate the water quality model. The following list identifies parameters that need to be collected for this aspect:

- BOD and nutrient loadings from sewage and industrial sources,
- Time series of Chlorophyll-a and nutrient distributions, and
- Sedimentation rates.

3. Establish Baseline Conditions

As described in the literature review, the most recent set of water quality measurements made inside Kingston Harbour was undertaken approximately 10 years ago. Those measurements included profiles of temperature, salinity and dissolved oxygen along with whole water column averages of nutrients, and phytoplankton abundance. Full use of the available hydrodynamic and water quality data will be made during the set-up and calibration of the water quality model.

It is recommended that these results, along with any future data collection programme results, be entered into a suitable water quality database, such as WRDB (www.wrdb.com) which can be used to house existing and future water quality parameters. The literature review has highlighted the fact that, while many studies of Kingston Harbour have been undertaken, the data that was collected is seldom available for other uses. This is unfortunate and needs to be corrected through a centralized data storage facility.

4. Determine Clean-up Parameters

The review of water quality and environmental degradation reports has indicated that the primary water quality issue of concern inside Kingston Harbour is eutrophication. Most water quality models include eutrophication, although the way in which it is treated, and the variables that are included, may vary depending on the model.

Inside Hunt's Bay, the problem is compounded with sedimentation, which is also a parameter that can be readily modelled.

Throughout the harbour there is also a problem with solid waste, particularly floatables, such as plastic drink bottles. Unfortunately, their movement and accumulation cannot be modelled as plastics tend to last many years. A mapping exercise of existing accumulations of solid waste would probably provide some insight into the pathways of debris movement within the harbour.

A screening of heavy metals has not revealed extensive contamination in Kingston Harbour. Modelling of toxins and heavy metals does not yet appear to be a priority, although it may be beneficial for the selected water quality model to have the capability to add these parameters, should the need arise.

Modern eutrophication models simulate algae growth and decay and changes to dissolved oxygen levels in response to nutrient and BOD loadings, light, temperature, salinity, re-aeration, etc. Other variables that control the reaction rates include temperature, salinity and dissolved oxygen levels. The following parameters are normally included in eutrophication models:

- Ammonia
- Orthophosphate
- BOD
- Organic Nitrogen
- Temperature
- Light
- Wind
- Benthic Flux of Ammonia & Phosphorus
- Salinity
- Re-aeration
- Nitrate
- Chlorophyll-a
- DO
- Organic Phosphorus
- Water Velocity
- Fraction of Daylight
- Light Extinction
- Zooplankton
- Air Temperature
- SOD

5. Assess Modelling Requirements

Based on the literature review and selected clean-up parameters that have been identified, the modelling requirements must address the following:

Hydrodynamics – The literature review indicates the requirement for a three dimensional time-domain model that includes the effects of tides, winds, river flows, salinity, and temperature variations. Based on the limited amount of existing calibration data, a standard model calibration can not be undertaken. Instead, it is recommended that a number of scenarios be developed to encompass the range of conditions that can be expected to occur, and that the current patterns during these scenarios be compared to measurements. At a future date, when sufficient calibration data is available, a more comprehensive exercise can be undertaken. The different hydrodynamic scenarios that are to be used should be based on the findings of previous investigations, which found the following three environmental variables to be important:

- Wet-season versus dry-season
- Wind and No wind condition
- Ebb Tide and Flood Tide

These different scenarios will be further investigated using the hydrodynamic model to ascertain if additional scenarios are required, such as the simulation of Spring and Neap tide ranges.

Water Quality -The main water quality modelling requirement for Kingston Harbour is eutrophication. In addition, suspended sediment modelling should be included. Future requirements of water quality modelling may include toxins and heavy metals.

6. Select Water Quality Model

Professor James Martin undertook a comparison of existing hydrodynamic and water quality models in his textbook "***Hydrodynamics and Transport for Water Quality Modeling***". The model selection process was guided by this comparison, and on an assessment of the situation in Kingston Harbour. Based on this information, the following essential criteria were established for the selection of an appropriate water quality model.

- Applicable to Kingston Harbour – tropical estuary
- Recognized – applied by regulators elsewhere
- Supported – latest computational methods get included
- Cost – including acquisition and on-going training.

Kingston Harbour is a micro-tidal estuary with a long retention time and noticeable 3D circulation patterns. In terms of hydrodynamics, a three-dimensional model is essential. The primary water quality concern inside the harbour is eutrophication, which most water quality models include. Most water quality modeling systems provide a linkage to hydrodynamics, which are usually computed separately. The exact manner in which this linkage is done can be important. The preferred approach is a hydrodynamic model that has been specifically designed to link with a water quality model, and not something that has been added at a later stage.

It is important in the selection of a water quality model that the model is established and recognised. When the results of the water quality model are used for regulatory and resource management purposes, it is possible that the results will be challenged. At that point in time, a well-known model that has been successfully applied elsewhere by regulators will have a distinct advantage.

Water quality modelling is an evolving science and new solution techniques and chemical reaction mechanisms are being continuously developed. It is therefore important in the selection of a water quality model that it be supported and widely used. Some water quality models do not have a wide user base, and are no longer being updated to include these latest developments.

Cost is an important consideration in the selection of a water quality model for Kingston Harbour. It can be divided into two broad categories. The first is the acquisition cost, and the second is the maintenance cost. The acquisition cost is the cost to purchase a licence for the software and get it running for Kingston Harbour. Maintenance includes the cost of annual updates as well any costs for training programmes.

Based on these four criteria, three different types of water quality models were examined. The first type of model is the "Commercial" model, such as MIKE3. The second type of water quality model includes public domain or "open-source" models. The last type of model is a sub-set of the public domain models, but includes only those that are government backed, such as WASP, which was developed and is now used and supported by the US Environmental Protection Agency.

Model Type	**Applicable**	**Recognized**	**Supported**	**Cost**
Commercial	Yes	Yes	Yes	High
Public Domain	Yes	Some	No	Low
Government Backed	Yes	Yes	Yes	Low

Commercial models meet all of the requirements for Kingston Harbour, although the cost is often quite high. The reason for the high costs is not only the licence cost, which can be reach almost US$100,000 for MIKE3 (although substantial discounts can be obtained for government institutions). In addition the on-going licensing requirements and future training costs must also be considered.

Public domain models meet all of the requirements, except recognition in some instances. This problem occurs as the models are "open-source" and slightly different versions become available.

The government backed sub-set of public domain models meets all of the requirements and has a low cost. The US EPA model WASP is applicable to Kinston Harbour and includes a seamless linkage to EFDC a 3-dimenional hydrodynamic model. In addition, it is well recognized and has been used by EPA and state environmental departments for many years. The support network for WASP is very extensive as there is a substantial user base. New releases of the model are produced annually. The source code is available but not routinely distributed, which means that the computational algorithms can be independently verified. Finally, the US EPA conducts training sessions three or four times every year. There is no cost for these training sessions, which are held in various locations in the USA. In addition, free technical support is available for operation of the model.

Based on this selection process, the government-backed water quality model WASP has been selected for Kingston Harbour.