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Mathematical Modeling of Point Source Pollutants Transport in the Little Akaki River

Thesis submitted to the school of Graduate Studies of Addis Ababa University in partial fulfillment of the

Masters Degree in Environmental Engineering

By: Natnael Tesfaye Hamda

Advisor: Berhanu Assafa (PhD)

Co-Advisor: Alemayhu Ambaw (MSc)

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It is common knowledge that no academic advancement is achieved by the efforts of a single person. This thesis is obviously no exception, as the information provided is largely a collection of others' work. And though the credit rewarded becomes my own, I hope it is understood by all who offered their assistance that it is their success as well. Included in this group is my brother, Ing. Axum Tesfaye and his family who have given me genuine and committed support to my endeavors.

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ACRONYMS AND NOTATIONS

AAU	Addis Ababa University
AAWSA	Addis Ababa Water Supply and Sewerage Authority
a.s.l	Above Sea Level
BOD	Biochemical Oxygen Demand
CBOD	Carbonaceous Biochemical Oxygen Demand
DO	Dissolved Oxygen
EPE	Environmental Policy of Ethiopia
EPO	Addis Ababa Environmental Protection Office
ESID	Ecologically Sustainable Industrial Development
FEPA	Federal Environmental protection Authority
GPS	Geographical Positioning System
GIS	Geographical Information System
IRBM	Integrated River Basin Management
LAR	The Little Akaki River
NBOD	Nitrogenous Biochemical Oxygen Demand
NH_3-N	Ammonia Nitrogen
OEPO	Oromiya Environmental Protection Office
SOD	Sediment Oxygen Demand
UNIDO	United Nations Industrial Development Organization

ABSTRACT

Computer models are becoming increasingly important tools in every environmental management aspects. A general one dimensional water quality model has been developed for one of the most industrially concentrated and polluted river in Ethiopia; the Little Akaki River. The study covers a total of 27.4 km length along the river where pollution issues are significant. The spatial and seasonal variation of hydro-geometric properties that affect mixing and transport of chemicals in the river were estimated by correlating the river hydro-geometry in a power law model. For this 20 locations were systematically selected and field data was collected at five different months. The river have been conceptualized as 1370 equal length completely mixed computational elements; and a functional representation that includes mass transport and hydrodynamic equations were written for each computational elements. The general one-dimensional model equation was solved using the numerical technique by finite volume spatial discritization and finite difference temporal discritaization. A computational solution procedure was prepared by writing a computer program in MATLAB platform (version 7.0). The result from the model was first verified by comparing it with theoretical expectations. BOD and -DO were selected as water quality indicators and the longitudinal dispersion coefficient of the river and the kinetic parameters that affect fate of DO and BOD in the river were calibrated. The model is in good correspondence with . The performance of the model in predicting calibration data was satisfactory. After calibration the performance of the model in predicting data not used during calibration was also estimated and the result was in good agreement with these targeted water quality data. The applicability of this model as decision making tool for pollution control activities was also assessed and the result is encouraging.

Recommendation; which takes into account the existing water quality problem in the study area, have been suggested for improvement and wider application the model. As works like this are an open ended; recommendations have been also given for additional research works.

CHAPTER 1 INTRODUCTION

1.1 General

Concern for environmental degradation in Ethiopia has been growing in recent years. Among others; the sustainable use of available natural resources is the main environmental management issue in the country. In the past the issue was not given particular attention, thus this has led to direct and indirect adverse environmental impacts (EPE, 1997). Among these different environmental issues, surface water quality degradation in urban and industrialized areas of the country is one of the major environmental problems of these days.

In this context the problem is significant on the highly exploited Awash River. Particularly the Little and Big Akaki Rivers, which are the major tributaries of the Upper Awash River are used as disposal routes for liquid and solid wastes of different sources. Currently the pollution pressure on both Akaki Rivers has risen so high that the rivers are unfit for most of the purposes they have been utilized for. However, most studies conducted show that the Littlie Akaki River (LAR) is more polluted than the Big Akaki River because of the presence of a higher number of industries that discharge their waste directly into this river (Abegaz, 2005; Mebratu & Redda, 2005; Nigussie, 1998).

The LAR has been/is used as a receptacle of all kinds of wastes. However industrial wastewater is the primary cause of water pollution as most of the factories along the river discharge their effluent directly into the LAR and its tributaries (EPO, 2004).

1.2 Water Resources Management Aspects

Water management involves development, control, protection, regulation, and beneficial use of surface (rivers and reservoirs) and ground water resources. Services provided by the water management community include: water supply for agricultural, industrial, and municipal uses; wastewater collection and treatment; protection and enhancement of environmental resources; pollution prevention; recreation; navigation; hydroelectric power generation; stormwater drainage; erosion and sedimentation control; and controlling flood waters and reducing damages due to flooding. Water resources planning and management activities include: policy formulation; national, regional, and local resource assessments; regulatory and permitting functions; formulation and implementation of resource management strategies; planning, design, construction, maintenance, and operation of structures and facilities; scientific and engineering research; and education and training (Mebratu and Redda, 2005).

1.3 Thesis Overview

Computer models play important roles in essentially all aspects of water management infrastructures. There is a great diversity of ways in which they can be applied. During the construction era of the 1950s-1970s, model development was oriented toward the water management emphasis on planning and design of constructed facilities, and these types of applications continue to be important. However, water resources management and associated modeling applications shifted during the 1970s and 1980s to a major focus on resource management and operation of existing facilities. Protection of water quality and environmental resources has become a driving concern in recent years (Wurbs, 1994).

In this thesis; a water quality model that can be used as a tool to simulate and predict the spatial and temporal distribution of industrially discharged point source pollutants in the LAR is developed. The theoretical background describing chemical transport processes in rivers and streams used in the model development were discussed step by step.

The physico-chemical principles which were used for constructing the model as well as the fundamental mathematical elements, which are bases for the mathematical description of the relationships, were presented. The solution algorithm for solving the resulted governing mathematical relationships and model calibration and evaluation results were also presented in this thesis.

The stream hydro geometries that affect chemical transport in the river system have been estimated based on field measured data and metrological data. The river width and depth was measured for five different months at selected 20 locations and the data was used for correlating the river discharge rate and the stream geometries. It was assumed that the straight section of the river to have a uniform hydro-geometry; the 27.4 km long river further divided into 559 straight river segments and the correlation together with metrological data, DEM and digital photogramethric map were used for estimation of other hydrological model parameters.

The 559 river segments were divided into 1370 conceptualized completely mixed computational elements. A general one dimensional continuity equation was developed for each computational cells of the river and a numerical solution algorithm was developed for them. An iterative computer program was developed using a MATLAB 7.0 program package for solving the numerical problem. The performance of the model was evaluated primarily by comparing it with expected theoretical solutions on different scenarios.

The model was calibrated for the two important water quality indicators; BOD-DO. Secondary water quality data obtained from previous works was employed for calibrating and evaluating the model. The applicability of the model to be used as analytical tool is demonstrated on different cases.

Including this 'INTRODUCTION' part, the thesis is organized in seven chapters.

The remaining sections of this introduction chapter provide background information about the study area and the rationale for the study. Statement of the problem, the study objectives and methodologies employed, the scope and importance of the study are discussed in this section as well. Chapter 2 outlines the literature reviews on river water quality models and summarizes findings of the gaps and relevance of previous works in relation to the problem statement.

The theoretical groundwork of the study and the model formulation processes adopted in this study are discussed in Chapter 3. Prior to the detail discussion of the river water quality model formulation process, the first section of the chapter presents the general theoretical considerations required in any water quality modeling. Practical issues to be considered in river water quality modeling are also discussed in this chapter. The one-dimensional LAR water quality model development process adopted in the study is also commenced. For the sake of integrating the study work with the basic water quality model development framework, the conceptual representation of the LAR; the functional representation of contaminant fate and transport in the LAR; the computational representation for solving the functionally represented system is presented in this chapter as well.

Chapter 4 presents the core elements of the study work. Those theoretical aspects considered in Chapter 3; which formed a framework for developing one dimensional LAR water quality model, are addressed in this chapter of the paper. This chapter of the paper presents the model delineation process; type of collected model input data as well as techniques employed for the collection and analyzing them. The structure of the developed one dimensional LAR water quality model; and the numerical solution algorithm presented as well. The execution procedure for the developed iterative MATLAB program for solving the model together with preliminary model test results were also presented in this part of the paper.

Chapter 5 presents the research work: case study findings, the model calibration study for CBOD and DO deficit models and different aspects related to the development of a steady state one dimensional BOD-DO model in the highly polluted section of the LAR.

Chapter 6 presents overall results discussion and interpretation.

The last chapter, Chapter 7 is dedicated to conclusion and recommendation. This includes concluding remarks on the capability of the model to be used as decision making tool for integrated water quality control on the LAR as well as suggested recommendations for future works.

This thesis also contains a number of Appendices. Appendix A is a tabular presentation of the BOD-DO model calibration result out put values. Appendix B contains primary model input data collected from the study site and secondary data obtained from previous studies and other literatures. Appendix C represents data used for the BOD-DO model calibration. Appendix D contains the different MATLAB files written for simulating the LAR water quality model.

1.4 Background Information

1.4.1 General Description of the Study Area

The study was conducted on the Akaki River Basin. The basin is the most industrially populated basin so far in Ethiopia. The catchment area of the basin that totally includes the city of Addis Ababa is divided into two sub-catchments by approximately a north-south running surface water divide. These are the Big Akaki River (eastern) sub-catchments and the Littlie Akaki River (western) sub-catchments. The Little and Big Akaki Rivers are the major tributaries of Awash River (Bekele, 1999).

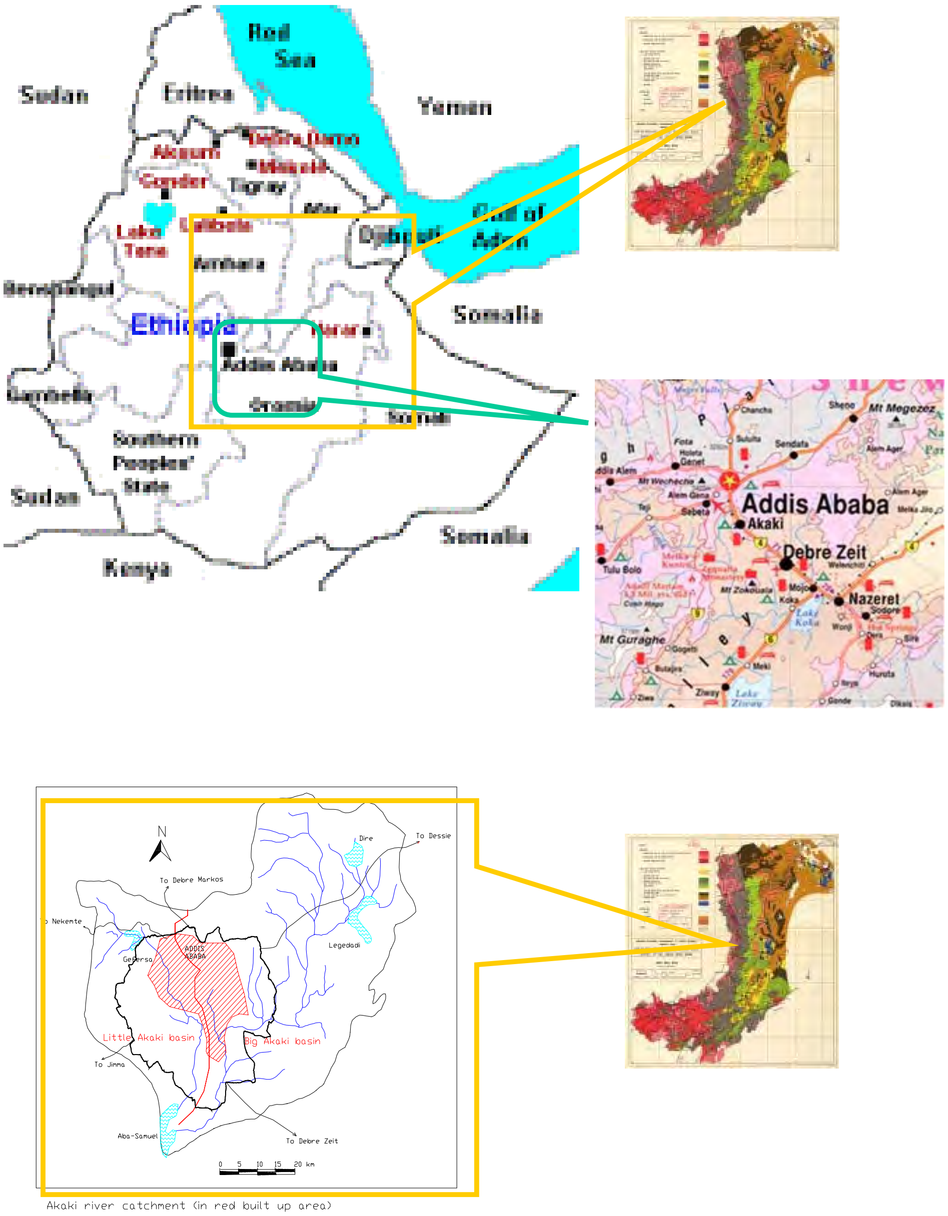
1.4.2 River Water Pollution Problem in the Akaki River Basin and Proposed Control Measures

The LAR and BAR are used for a variety of purposes including irrigation, drinking and industrial purposes. Unfortunately they are also used as an open waste recipient of the waste generated by industries and other sources from Addis Ababa and the surrounding (Bekele, 1999). However studies indicate that the LAR is more polluted than the BAR (Mohamed, 2002).

The major sources of Littlie Akaki River water pollution are industrial effluents, municipal liquid wastes, consisting of sewage, surface run-off, human excreta, and other types of domestic wastewater and municipal, domestic and industrial solid wastes. The major pollutant industries include tanneries, breweries, wineries, distilleries, battery factories and, a slaughter house. Industrial effluents are discharged either directly into the LAR and its tributaries or after partial treatment. As a result the river is highly polluted it is difficult to see aquatic life such as fish in the river. Despite its bad odour, black colour and toxicity, the Littile Akaki River is still used for various purposes including laundry, bathing, swimming, irrigation and cattle drinking (Mebratu and Redda, 2005).

The LAR originates from many small streams that flow down from a range of Entoto mounts. The river sources, tributaries and main streams pass through the Western-Central part of Addis Ababa, and a few rural areas to join in the Aba Samuel Lake (Figure 1.1) and end at Awash River. As the river crosses through densely populated residential, commercial and industrial areas of Addis Ababa, it is exposed to various sources of pollutions (Mebratu and Redda, 2005).

Fig. 1. 1 Location Map of the Study Area



Currently the pollution pressure on both Akaki Rivers has risen so high that the rivers are highly unfit for most of the purposes they have been utilized for. However, most studies conducted show that the Littlie Akaki is more polluted than the Big Akaki River because of the presence of a higher number of industries that discharge their waste directly into this river (Bekele, 1999).

Studies indicated that this unabated industrial discharge has tremendously contributed to the pollution of the Akaki Rivers resulting in elevated levels of a variety of pollutants with consequent diverse bio-physical and socio-economic impacts. The rivers do not sustain higher aquatic species like fish. The only species to be found are worms that could survive under low oxygen conditions (Abegaz, 2005). The pollution problem has significant human health impact particularly for the people living downstream location in the East Shoa Zone of Oromia region situated at the vicinity of Addis Ababa, where there is no alternative source for drinking water (EPO, 2004). Urban poverty due to lack of clean water and health care expenses for the control of water related diseases are the main economical impacts of the problem (EPO, 2004. Apart from these ecological, social and economical negative impacts; degradation of the quality of the groundwater resources in the area is the other significant negative impact of the problem. The high infiltration rate of surface polluted water down to a very good aquifer, extending the problem of the pollution of Akaki River to underground regional water resources (Bekele, 1999). This groundwater quality degradation is significant on those boreholes located along and close to the bank of the highly polluted Littlie Akaki River (Alemyahu, 2005).

Even though there have been different fragmented efforts made in the area aimed at improving the situation, it is recognized that the scope of the problem requires an integrated approach and Akaki River initiative launched in May 2005 by proposing 'Programme on Sustainable Consumption and Production in The Akaki River'. The programme is part of 'The African 10 Year Framework Programme on Sustainable Consumption and Production'; in which such river basins are recognized as a strategic entry points for the development and implementation of this programme (Mebratu and Redda, 2005).

The programme recognizes an Integrated River Basin (Catchment) Management (IRBM) as an integral approach towards the promotion of sustainable livelihood and development within the basin through continuous improvement of the river ecosystem. It is also developed as a multidimensional comprehensive programme that will be implemented through broad stakeholder cooperation and active participation (Mebratu and Redda 2005).

1.4.3 Study Rationale and Statement of the Problem

The above paragraphs attempted to briefly describe the water pollution problem in the Akaki River Basin and contributor for the pollution problem in the LAR.

Generally, IRBM recognizes the multifunctional use of the rivers and the basin for the present and future generations. Since the capacity of the river basin to accommodate different uses is always limited, priorities have to be set. Apart from that, priorities should depend on the natural, social, and economic conditions in the pertinent basin and the values and interests of its population. This broad spectrum and interacting dimensions of IRBM makes it a complex task. Therefore, it is very essential that different and multidisciplinary tools are made available to support and to carry out IRBM in efficient and effective way. Among these tools, an analytical tool that supports both the planning and implementation of IRBM is the main.

Regarding the Akaki River Basin, restoring the healthy functioning of the existing river water quality and ensuring a sustainable consumption and production of the river basin are the main IRBM issue. Since industrial and other intermittent point source wastewater discharges (including wastewater treatment plants) are among the significant contributors to the state of pollution on the Akaki Rivers, reducing the impact of industrial activities on the rivers by enhancing the environmental compliance of industries and wastewater treatment plants through enhanced enforcement measures, is one of the main proposed programme component (Mebratu and Redda, 2005).

Concerning this programme component, currently Ethiopia has different environmental management tools that can be used as management tools for the implementation of the programme component. The standard emission limit values to water bodies for specific industrial sectors, standard for wastewater treatment plants effluent limit values to land, ambient environmental standards, consideration water pollution impacts in EIA for industrial development projects etc are among these management tools. However all these management tools require information that can describe the state of problems, compare levels of stress, prioritize problem areas, predict trends, extrapolate monitoring data, and evaluate systems.

Therefore, the success of the proposed programme component prominently lies on the availability of tools for monitoring, data collection and processing, oriented towards making facts and figures about the "as is" situation available in order to provide stakeholders bases for targeted interventions; and tools or systems to support decision-making with a view to the future, typically oriented to the "ex ante" identification, analysis and evaluation of alternative allocations, policies or plans; and to help managers to make the right decisions as well as assess and provide the current situation and explore developments in the future.

1.5 Objectives of the Study

The study work aimed on developing a model that can be used as analytical tool for supporting the proposed environmental management solution, particularly for the implementation of industrial water pollution control measures in the LAR.

The primary objective of the study was, therefore, to model the transport and transformation of point source pollutant constituents in the industrially polluted section of the LAR.

Thus, the study was aimed to develop a mathematical model that can simulate the fate and transport of chemicals and can predict the spatial and temporal distribution of any point source industrially discharged point source pollutants downstream in the LAR.

Therefore, the main objectives of the present study were the following:

- To assess and identify the best modeling technique to be used

- To represent the LAR prototype conceptually in a manner suiting the selected model type
- Modeling the hydrodynamic condition of the LAR system under consideration; which describes the transport or conservation of mass for the water system
- Modeling the transport and transformation of the wastewater discharge constituents in the river system
- Integrating the hydrodynamic and material transport model to develop a one-dimensional water quality model that represent the fate and transport of point source pollutants in the LAR
- Developing numerical solution algorithm for solving the one-dimensional LAR water quality model
- Testing the functionality and capability of the developed model

1.6 Material and Methods Used

1.6.1 Methods Used

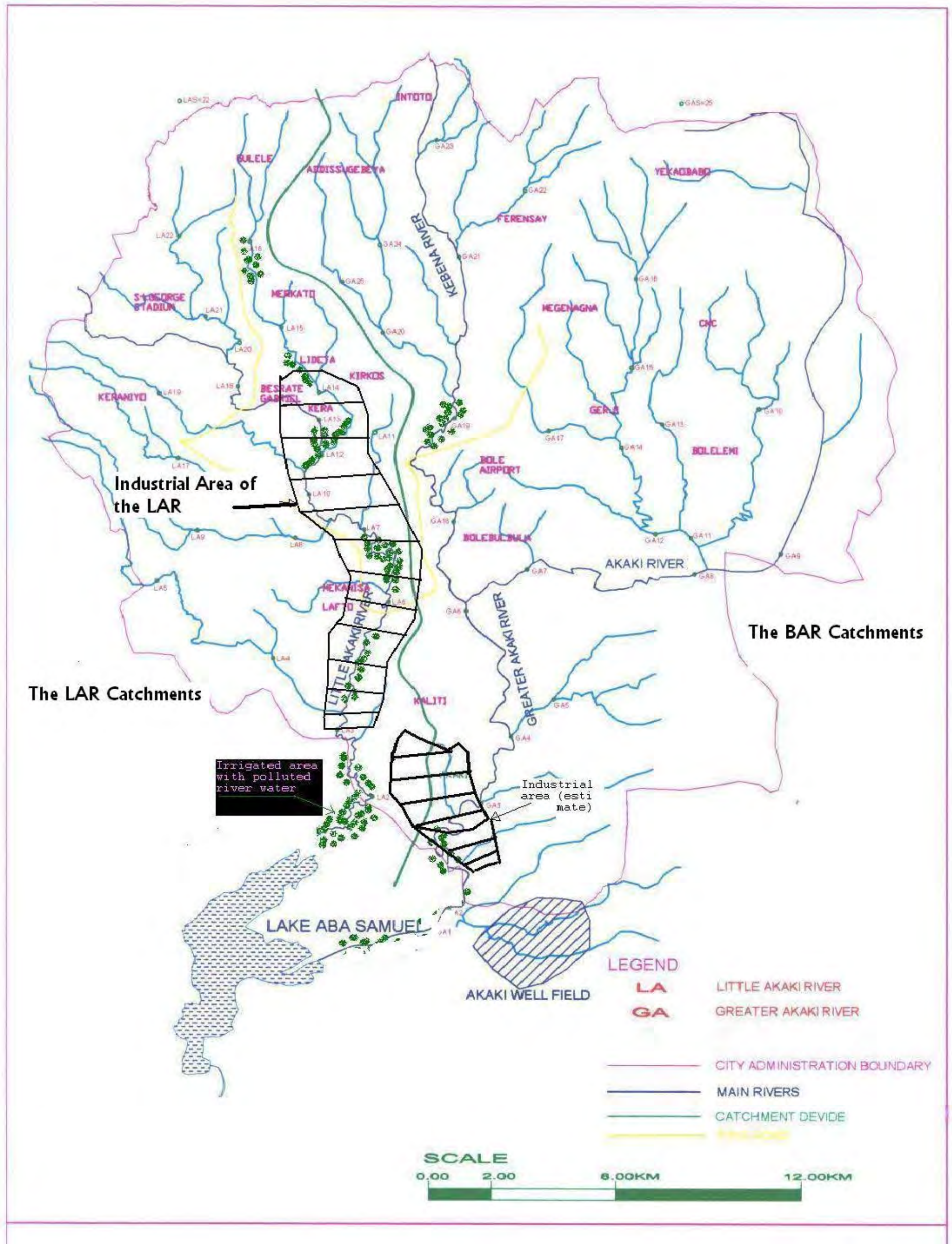
In order to achieve the above objectives of the study the following methodology was adopted:

Scoping the study area: Prior to data collection and detail field investigation, the river section where industrial pollution is significant identified and geographically referenced. Thus, the upper and lower boundaries of the river section to be modeled identified and geographically referenced.

Model delineation and river segmentation: The river section to be studied delineated in to 6 hydrological homogeneous river reaches, 22 topographically similar sections and 559 straight river segments.

Develop conceptual model and Data collection: The river section to be studied graphically was idealized as a one-dimensional system and the river was treated a series of equal length of computational elements or control volumes. For each of the control volume a material

Fig. 1. 2 The Watershed of the studied area showing the LAR and BAR catchments



balance and continuity equation was developed. Based on these equations the physical as well as the geographical data that influence the set of equations was collected.

Design the model: The conceptual model was put into a form suitable for modeling by discritizing temporally and spatially using the fully implicit finite volume numerical method.

Selection of the computer program to be used: For solving the numerically discritized set of linear equations, a MATLAB program was selected to exchange, store and load model inputs and execute model solutions.

Model Testing: The functionality of the developed model was tested based on the idealized condition by comparing it with an analytical condition.

Model calibration and application examples: The capability of the model for practical work was enhanced by calibrating and validating the model using secondary data obtained from different sources. The model calibration and validation test was performed by analyzing the effect of industrial point sources on the river BOD and DO level.

Model demonstration: The applicability of the model as decision making tool was demonstrated by considering different conditions.

1.6.2 Materials

The different materials used and utilized in the study work were:

1. Field equipments:
    a. GPS and downloading cables
    b. Dipsticks and steel meters for measuring the depth and width of the river
2. Maps of scale 1:50,000, and DEM
3. Hydrometrological data
    a. Monthly rainfall data
    b. River discharge data
4. Softwares:

a. Globalmapper for digitizing maps creating shape files, reading DEM
b. ArcView GIS for overlaying attributes
c. MATLAB for solving the model
d. MS Office (Excel, Word and access) for write-up and data processing

CHAPTER 2 LITERATURE REVIEW

2.1 River Water Quality Modeling Approaches

A lot of sources exist that discuss the state of the art in river water quality modeling In general; river water quality models seek to describe the spatial and temporal changes of constituents of concern. Water quality changes in rivers due to physical transport and exchange processes (such as advection and diffusion/dispersion, the description of which requires one way or another, the application of a hydraulic model as an input) and biological, chemical, biochemical, and physical conversion processes. The above processes in the water phase are governed by a set of well-known extended transport equations. The fundamentals of chemical transport in river system are covered in detail in the text books by Bruce E. Logan (1999) and Hemond, H.F. and Fischer-Levey (2000). In addition the text book by Geza Jolanki (1997) and the book by Steven Chapra (1997) provide a comprehensive treatment of mathematical modeling of chemical transport in rivers and streams.

2.2 Empirical and Mechanistic Models

Based on the solution techniques used for solving the model equations, Chapra (1997) classifies water quality models as empirical and mechanistic models. The empirical models are based on an inductive or data-based approach. It involves obtaining set of model input data from large numbers systems that are similar to the water system going to be modeled (Chapra, 1997). The mechanistic models are based on a deductive or theoretical approach. The mechanistic model involves the use of theoretical relationships or organizing principles.

The advantages of mechanistic models over empirical models were cited by different authors. As stipulated by George (1978); if Mechanistic models are employed appropriately, they have several advantages over empirical models. They provide greater scientific insight, a better basis for extrapolation, and usually more parsimonious representation. Mechanistic models are typically based on differential equations and are usually nonlinear in the parameters. Numerical methods exist for solving the differential equations and fitting such models to data. As described in Chapra (1997); mechanistic water-quality models are based on the conservation of mass. The same author express this mechanistic water quality models principle in a quantitative terms as a mass balance equation that accounts for all transfer of matter across the system's boundaries and all transformations occurring in the system.

In this study, the mechanistic modeling approach based on solving material balance was employed.

2.3 Previous Studies in Relation to the water quality problem in the area

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Numerous reports have been published in relation to river water quality problem in the Akaki River Basin in general and the industrial river water pollution of the LAR in particular. Important previous works in relation to this water quality degradation problem are: Surface Water and Groundwater Pollution Problems in the Upper Awash River Basin, Ethiopia, by Bekele (1999); Evaluation of Water Quality and Suggested Improvement Measures, The Case of the Little Akaki River, by Nigussie (1998); Industrial Waste Management in Ethiopia, Addis Ababa, Ethiopia by Mebratu (1990); Industrial Pollution and Its Impact on the Little Akaki River, by Mohamed (2002); Assessment of Socio-economic Impacts of Akaki River Pollution, Adama, (2004) by Oromia EPO; Investigation of Input and Distribution of Polluting Elements in Tinishu Akaki River, Ethiopia, Based on the determination by ICP-MS, by Abegaz (2005); Industries and Akaki River. Seminar on Akaki River Pollution, by Belete and Girmay (1999).

Most of these works were restricted on collecting data and presenting the situation according to their collected data findings. Identical to this study objective, there was an attempt made by Nigussie, (1998). The study tried to predict the effect of industrial point source wastewater discharge on BOD and DO level of the LAR. In the study the modified Streeter-Phelp's equation was used for predicting the spatial distribution of biochemical oxygen demand (BOD) and dissolved oxygen (DO) deficit caused by point source pollutants.

In the review it was found that, the complex nature of the river system, made the model incomprehensive for using as analytical tool. As an example, the spatial variation of the different hydro-morphological features of the river that can affect transport of contaminants was not considered in the model. The incapability of the model for predicting non point source distributed pollutants and lack of flexibility for different scenarios (like establishment of new industrial pollutants) were the other drawbacks observed in this analytical method based model.

In this study, the drawbacks observed in Nigussie's, (1998) work tried to be addressed by integrating the mechanistic modeling approach which is based on a deductive or theoretical approach. Most importantly the study is aimed on developing a versatile and flexible water quality model that can be used for simulating the fate and transport of any chemical constituent in the river system.

2.4 Practice of Water Quality Modeling

2.4.1 Historical Development of Water Quality Models

Biswas, (1981) defines water quality models as a set of mathematical expression defining the physical, biological and chemical processes that are assumed to take place in a water body. Thus water quality modeling requires information on not only the physical and other environmental conditions of the water system to be modeled but also the physical, biological and chemical changes that affect the quality of the water system. Mathematical formulation of these interactions and integrating with the hydrodynamic condition of the water system is core for the model.

The historical development of water quality models is also a function of the formulation of these interactions and the availability computational tools for solving them.

Chapra (1997) classified the development of water-quality modeling in four major periods. Fig 2.1 shows the schematic description used by Chapra for indicating these four periods in the development of water-quality modeling.

Most of the early modeling work focused on the urban waste load allocation problems (1925-1960). In the 1960's digital computers become widely available. This led to major advancement in both the models and the ways in which they could be applied (1960-1970). In the 1970's another shift occurred. Societal awareness moved beyond dissolved oxygen and urban point sources to a more general concern of the environment (1970-1977).

Fig. 2. 1: Historical Development of Water Quality Modeling

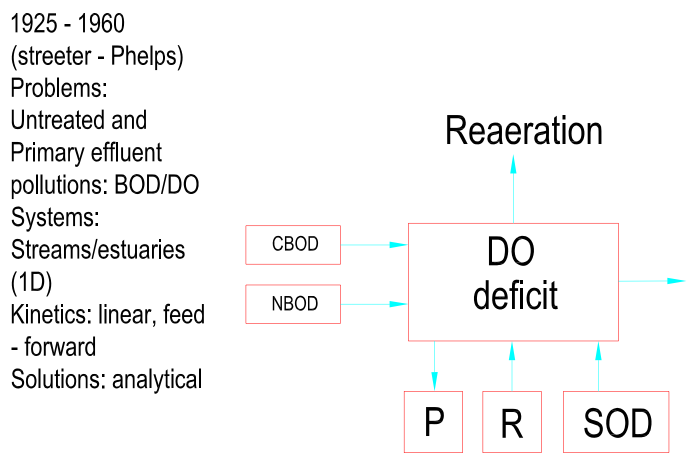

Fig. 2. 2a 1925-1960: Streeter – Phelps Period

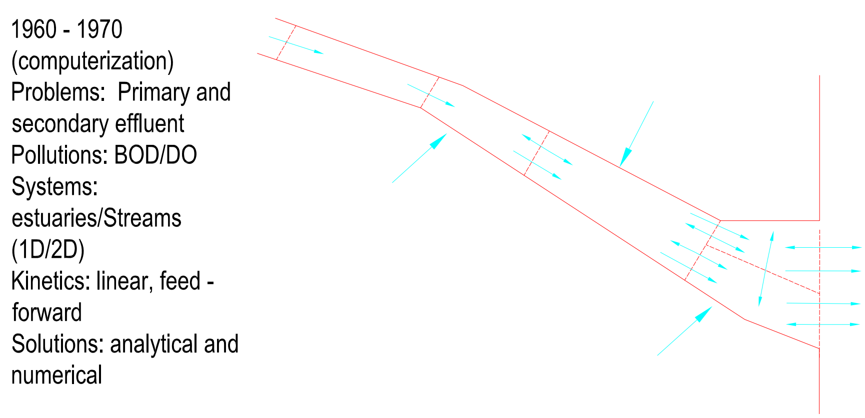

Fig. 2. 3b 1960 - 1970 Computerization periods

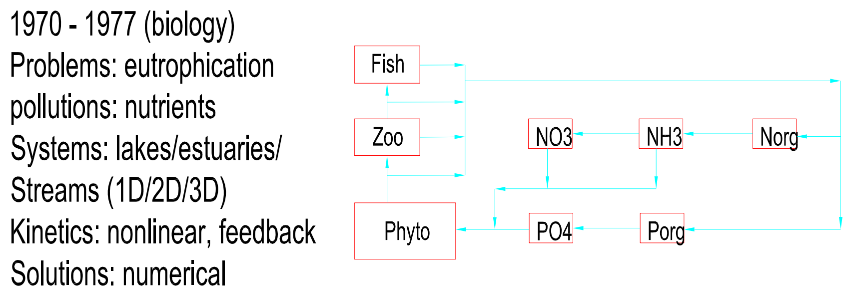

Fig. 2.4C 1970 - 1977 Mechanistic Representation of biological processes

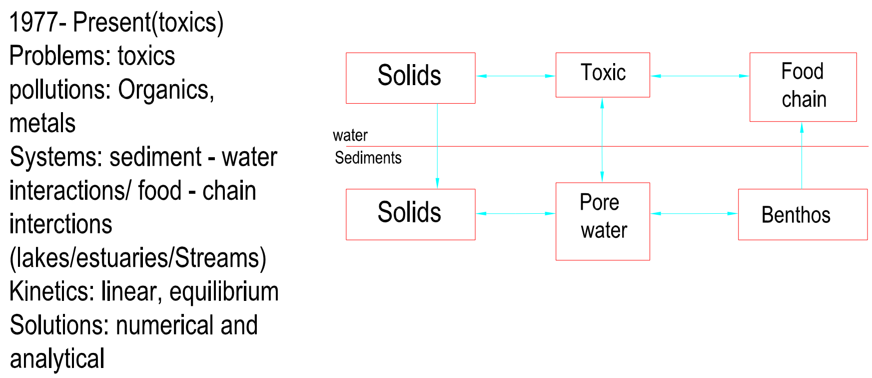

Fig. 2.5d 1977 – present: Modeling the effect of solid matter in the transport and fate of toxicants

The current practice in water quality modeling is largely driven by legislation and regulations. Accordingly, the practice of water quality modeling varies from jurisdiction to jurisdiction as the regulatory framework also varies. The most widely known and used computer program for river water quality modeling is the QUAL2E model developed by the U.S. Environmental Protection Agency (Brown and Barnwell, 1987). QUAL2E has a long history, having been preceded by another version of QUAL2 (Roesner et al., 1981) and the similar but simpler QUAL1 model (TWDB, 1971). QUAL2 E simulates dissolved oxygen and associated water quality parameters in rivers and streams under conditions of steady stream flow and pollutant discharge. While QUAL2 E has clear limitations - do not address some of practical problems such as nonpoint source pollution, and transient streamflow - its formulation derives directly from the U.S. regulatory framework for which it was developed and for which it is generally well suited.

Few other countries have established water quality management laws in which water quality modeling is an integral part of the process as in the U.S. Although water quality modeling is often used, it is typically as a planning tool in special studies of particular rivers. These models are frequently developed on a custom basis for each individual application. Thus, without the standardizing requirements as created in the U.S. wasteload allocation system, alternative modeling standards have yet to emerge in most other countries. Consequently, the operating standard for river water quality modeling is QUAL2 in Europe and elsewhere as well as in the U.S.

2.5 Mathematical Models in Water Resource Management

2.5.1 General

As exemplified by Wurps (1994) water management involves development, control, protection, regulation, and beneficial use of surface (rivers and reservoirs) and ground water resources. The water management service providers may engage in activities such as: water supply for agricultural, industrial, and municipal uses; wastewater collection and treatment; protection and enhancement of environmental resources; pollution prevention; recreation; navigation; hydroelectric power generation; storm water drainage; erosion and sedimentation control; and controlling flood waters and reducing damages due to flooding. Water resources planning and management activities include: policy formulation; national, regional, and local resource assessments; regulatory and permitting functions; formulation and implementation of resource management strategies; planning, design, construction, maintenance, and operation of structures and facilities; scientific and engineering research; and education and training.

Computer models play important roles in essentially all aspects of water management. There is a great diversity of ways in which they are applied. According to Ralph (1994); during the construction era of the 1950s-1970s, model development was oriented toward the water management emphasis on planning and design of constructed facilities, and these types of applications continue to be important. However, water resources management and associated modeling applications shifted during the 1970s and 1980s to a major focus on resource management and operation of existing facilities. Protection of water quality and environmental resources has become a driving concern in recent years. As rationalized by Percival (1996), the ever increasing pollution problem of available water resources due to industrialization and urbanization are the rationale for this shift.

As defined by GESAMP (1988); pollution of aquatic environment means the introduction by man – directly or indirectly, of substances or energy which result in such deleterious effects as (i) harm to living resources, (ii) hazardous to human health, (iii) hindrance of aquatic activities, (iv) impairments of water quality with respect to its use in agricultural, industrial, and often economic activities, and (v) reduction of amenities.

2.5.2 Types of Management Models

According to US EPA's classification of models for water resources management, there are three major categories:

Generalized models: the computer model is designed for application to a range of problems dealing with systems of various configurations and locations, rather than being developed to address a particular problem at a specific site.

Operational models: the model is reasonably well documented and tested, and is designed to be used by professional practitioners other than the original model developers.

Site specific models: are models developed for specific water resource management issue. It consists of user developed input data files combined with one or more generalized software packages.

2.5.3 Issues in Developing Water Quality Models

According to Ralph (1994), the development and application of water management models requires a thorough understanding of the following points:

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1. the role of the models in the overall water resources management decision-making
2. the processes and the questions to be answered by the modeling exercises,
3. the real-world processes being modeled and the capabilities and limitations of methods
4. how processes are represented with mathematical equations,
5. computational techniques for solving the equations,
6. how to extract available data and overcome limitations,
7. model calibration and verification techniques,
8. the availability of computer software and hardware and the skills required to use these tools, and
9. the communication capabilities required to assure that model development and application is responsive to water resources planning and management needs and that model results are effectively incorporated into decision-making processes.

From the scope of the study due attention was given for the first five issues.

2.6 River Water Quality Models as Management Tools

Mathematical modeling is a useful tool for estimating the development of water quality under different circumstances (Biswas, 1981). Fried (2005) summarized the purposes of the mathematical modeling of chemical fate and transport in river waters as: (1) description of the problem; (2) parameter identification; (3) prediction of time evolution problem; and (4) management.

Generally river water quality models simulate the hydrodynamic as well as the water quality conditions of a river. Hydrodynamics and river water quality are often reflected in separate interfacing sub-models. The models incorporate equations for transport or conservation of mass for water and equations for transport and transformation of materials in the water. The hydrodynamic equations deal with water volumes, flow rates, velocities, and depths. The materials transport and transformation equations include for chemical equilibrium or chemical and biological kinetics. Classical formulations for nutrient uptake, growth, photosynthesis, predation, and microbial decomposition have been used in many models.

Fried (2005) categorized river water quality models in two families according to scale: global and local. Global models are further subdivided into black box and grey box. Black box models represent the water body as a system with no assumed physical structure, considering only inputs and outputs which are mathematically related usually by a convolution equation or by an ordinary differential equation (e.g., a mass balance dilution equation). These oversimplified models generally provide a first approach to the phenomenon. Grey box models represent the water body as a system with a few structural properties. An example of such a model is a sequence of river segments with various mixing properties.

2.6.1 Global Models

The basis of global models is the mass conservation principle relating inputs and outputs of the system, taking into account the reactions within the system that either increase or decrease contaminant concentrations or masses. Most models are adapted from Streeter-Phelps equations predicting the biochemical oxygen demand (BOD) and dissolved oxygen (DO) concentrations or deficits resulting from the discharge of biodegradable organic wastes into river systems, and completed by simple decay, dilution or sedimentation models for other contaminants.

In this study work the modified Streeter – Phelps equation was used for different study objectives, including for the calibration of the kinetic parameters of the model.

2.6.2 Local Models

The local or structural models, accounting for the various mechanical and physico-chemical phenomena taking place in the river system, are based on a set of equations describing water flow and contaminant transport. They usually consist of three equations: conservation of total mass, conservation of momentum, and dispersion-convection.

For a river where the flow changes continuously due to downstream tidal effects, Tucci and Moretti (1982) have used the group of equations considering conservation of total mass, conservation of momentum, and dispersion-convection to represent BOD and DO; while for a small river with stable bottom influenced by storm conditions Bedford et at. (1983) also use the same system but assumed that, due to increased cross-sectional mixing, longitudinal dispersion can be neglected.

2.6.3 Dimensional Classification of Models

In general, water quality models can be grouped into four different classes based on their dimensional representation as follows, in increasing complexity (McCutcheon, 1989): (i) zero-dimensional models, where a segment of the stream is described by a single computational element, ignoring any lateral, vertical, and longitudinal variation that may occur; (ii) one-dimensional models, where lateral and vertical variations are ignored, and the stream is described by a series of computational elements extending downstream and describing the longitudinal gradients that are prevalent in streams; (iii) two-dimensional models describing lateral and longitudinal gradients and assuming vertical variations are insignificant; and (iv) three-dimensional models describing vertical, lateral, and longitudinal gradients of water quality parameters.

These classifications are based on the way the stream is divided into computational elements and the way relevant equations are represented. Three-dimensional models are the most complex and thorough models, but are far too data intensive to be computational efficient for simulating stream water quality conditions in large river basin networks. On the other hand, the simplest zero-dimensional models are only applicable for screening-level analysis in a mixing zone. The less precise two- and one-dimensional models are the most common and practical approaches to simulating stream water quality conditions. Two dimensional models require a more extensive data base for model calibration. Lacking the requisite data requirements for two-dimensional models, one-dimensional models may be more appropriate, particularly for streams where longitudinal gradients dominate vertical variations.

All of these aforementioned modeling approaches share a common basic principle: conservation of mass. Conservation is often applied by first defining a control region in the space to be analyzed. The following materials balance equation is written for each constituent over the control section:

QoCo = Q,Ci - Decay Rate - Accumlation Rate

In general, the sophistication of the model employed for a particular task should be consistent with the quality of the data available, the degree of process understanding and the purpose for which the model is intended.

For the purpose of this thesis, model is developed for predicting the down stream concentration of point source pollutants and its spatial distribution from their discharge point.

CHAPTER 3 THEORETICAL BACKGROUND

3.1 Theoretical Consideration

3.1.1 General Introduction

As with any physical system, a thorough understanding of chemical interaction in the natural environment requires an ability to apply measurable characteristics to a mathematical model. These models serve several purposes; to verify our understanding of the physical system, to determine un-measurable parameters from those which are known, and to predict the future state of a system.

In general the development of a mathematical description of fate and transport of chemicals in the natural environment system often begins by writing the generalized transport equations for all potential physical as well as bio-chemical processes in each phase. Thus, any water quality models, including rivers, start from basic mass transport and transformation processes, relying on continuity and conservation of mass considerations.

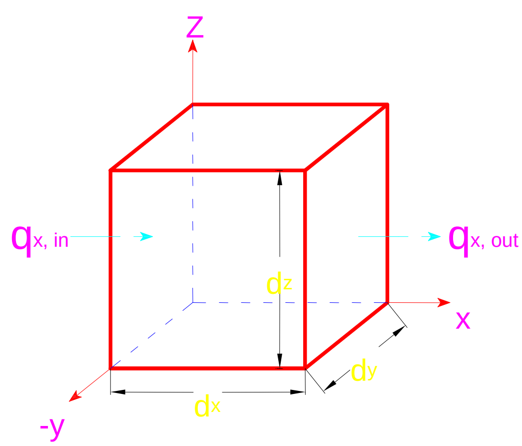
Consider an elementary water body, a cube of dx, dy and dz dimensions as shown in Figure 3.1. The quality of water within this elementary water body depends on the mass of a polluting substance present there. Water quality models then should describe the change of the mass of a polluting substance within this water body. The change of the mass of this substance is calculated as the difference between mass-flows (mass fluxes) entering and leaving this water body, considering also the effects of internal sources and sinks of the substance, if any. The mechanism of mass transfer into and out of this water body includes the following processes:

- Mass transported by the flow, by the Vx, Vy and Vz components of the flow velocity vector. This process is termed the advective mass transfer. The transfer of mass, that is the mass flux (in mass per time, $M\ T^{-1}$, dimension) can be calculated in the direction x as C*Vx*dy*dz, where C is the concentration of the substance in the water (in mass per volume dimension, $M\ L^{-3}$), see also Equation. 3.1.

- The other means of mass transfer is termed the dispersion or dispersive transport. Here one has to explain this term because there is usually considerable confusion with the terms diffusion and dispersion; -in short: dispersion is a term used for the combined effect of molecular diffusion and turbulent diffusion, and both of these latter processes is caused by pulsating motion, that is
    - by the "Brownian" thermally induced motion of the molecule (molecular diffusion), and
    - by the pulsation of the flow velocity around its mean value, caused by turbulence (called the turbulent diffusion).

The dispersive mass transfer (Ex, Ey, Ez,) has the dimension of mass per time per area (M T^{-1} L^{-2}) and it is usually expressed by the law of Fick's which states that the transport of the substance in a space direction is proportional to the gradient of the concentration of this substance in that direction the proportionality factor being the coefficient of dispersion, as shown in equation 3.1.

Fig. 3. 1 Differential Control Volume for derivation of the Basic Water Quality Model Equation



3.1.2 Mass Transport Terms for Deriving the Basic Model

These equations describe the dispersive and advective transport of a polluting substance from the x direction into an elementary water body. The first term is actually the law of Fick's which states that the diffusive (dispersive) transport of the substance in a space direction is proportional to the gradient of the concentration of this substance in that direction the proportionality factor being the coefficient of dispersion. The second term is the advective transport term, which states that the specific (per unit area) transfer of mass to a spatial direction is the product of the concentration of a substance and the velocity of flow in that spatial direction. These are the terms used in writing the overall mass balance (that is Eq. 3.2) of an elementary water body as shown in Figure 3.1.

$$E_x = D_x \frac{dC}{dx}$$

$$ADV_x = CV_x \qquad (3.1)$$

Where:

- **Ex**: is the dispersive mass flux in the spatial direction x (in M LF2 T-l dimension), with the assumption that the law of Fick holds for the joint effect of molecular diffusion and turbulent diffusion, that is for dispersion.
- **ADVx**: is the advective mass flux in the spatial direction X (in M L^{-2} T^{-1} dimension)
- **C**: is the concentration, the mass of the quality constituent in a unit volume of water (mass per volume, M L^{-3});
- **D***x* - is the coefficient of dispersion in the direction of spatial coordinate x (in surface area per time, $L^{-2}T^{-1}$ units);
- **Vx**: is the component of the flow velocity in spatial directions X.(length per time, L T^{-1});

3.1.3 The Mass-Balance Equation of an Elementary Water Body

This equation was derived by writing a mass balance of in- and out flowing advective and dispersive mass fluxes of an elementary water body (Figure 3.1) and expressing the change of the mass of the substance with time. The terms for each spatial direction include the inflowing mass flux and the out flowing mass flux, which latter is the difference between inflowing flux and the change of the flux within the water body.

$$
\begin{aligned}
&\frac{\partial C}{\partial t}dxdydz = \\
&\left[(V_xC)+E_x\right]dydz+\left[(V_yC)+E_y\right]dxdz+\left[(V_zC)+E_z\right]dxdy \\
&-\{(V_xC)+E_x+\frac{\partial}{\partial x}\left[(V_xC)+E_x\right]dx\}dydz \\
&-\{(V_yC)+E_y+\frac{\partial}{\partial y}\left[(V_yC)+E_y\right]dy\}dxdz- \\
&\{(V_zC)+Ez+\frac{\partial}{\partial z}\left[(V_zC)+E_z\right]dz\}dxdy
\end{aligned}
\qquad (3.2)
$$

Where:

- **C**- is the concentration, the mass of the quality constituent in a unit volume of water
- **Ex, Ey, Ez** - are the dispersive mass fluxes in the spatial directions X, Y, and Z with the assumption that the law of Fick holds for the joint effect of molecular diffusion and turbulent diffusion, that is for dispersion;
- **Vx, Vy, Vz** - are the components of the flow velocity in spatial directions X, Y , and Z,
- **dx,dy,dz** - are the side lengths of an elementary cube, an elementary water body.

3.1.4 The Basic Water Quality Model Equation

This equation forms the basis of all water quality models. The derivation is from Equations 3.1 and 3.2, by combining them, carrying out the operations, rearranging the result and dividing the equation by the elementary water volume dx.dy.dz and also by considering internal sources and sinks of the substance, as well as external sources

(Muschalla, 2001). The basic equation describes the variation of the concentration of a quality constituent C with the time and space. Apart from the advective and dispersive transport terms that were discussed in relation to Equations 3.1 and 3.2 in this basic equation there is a general term, the internal source/sink term, or internal reaction term. They are also called the transformation processes with the meaning that the substance in concern is being transformed by various physical, chemical, biochemical and biological processes resulting in the change of the quantity of the substance in an elemental water body. This change is either a "loss" or sink term caused by processes such as settling, chemical-biochemical decomposition, uptake by living organisms or a "gain", a source term, such as scouring from the stream bed, product of chemical-biochemical reactions, biological growth, that is the "build-up " of the substance in concern on the expense of other substances present in the system.

$$\frac{\partial C}{\partial t} + V_x \frac{\partial C}{\partial x} + V_y \frac{\partial C}{\partial y} + V_z \frac{\partial C}{\partial z} = \\ = \frac{\partial}{\partial x}(D_x \frac{\partial C}{\partial x}) + \frac{\partial}{\partial y}(D_y \frac{\partial C}{\partial y}) + \frac{\partial}{\partial z}(D_z \frac{\partial C}{\partial z}) + S(x,y,z,t) \pm S_{\mathrm{int}\,ernal} \qquad (3.3)$$

Where:

- **C**- is the concentration, the mass of the quality constituent in a unit volume of water
- **Dx,Dy,Dz**, - are the coefficients of dispersion in the direction of spatial coordinates x, y, and z,
- **Vx, Vy,Vz** - are the components of the flow velocity in spatial directions x, y, and z,
- **t** - is the time ;
- **S(x,y,z,t)-** denotes external sources and sinks of the substance in concern that may vary in both time and space;
- $\mathbf{S_{internal}}$: denotes the internal sources and sinks of the substance,

3.2 Practical Considerations

The basic three dimensional water quality model is seldom used in its original complex way (Eq. 3.3). Particularly, it is true for rivers and streams as most of natural streams and rivers are relatively shallow in depth and narrow in width compared with their length. Thus a plume emanating from a point source mixes quickly over the entire depth and width then continues to spread in the longitudinal flow directions, which has led to the well established "One-Dimensional Models for Rivers" (Brown and Barnwell, 1987).

Excluding the initial distance required to achieve mixing in the vertical and traversal, the problem can then be effectively modeled by 1D and it can be assumed that variation of water quality parameters occur longitudinally (in X-direction) as the water is transported from upstream to downstream.

On the other hand, Eq. 3.3 is derived based on the assumption that a steady uniform flow (ignoring the spatial variation of water flow). However the practical river water system do not have uniform river flow rate, as there might be tributaries that can change the spatial flow rate of the river.

3.3 One-Dimensional LAR Water Quality Model

3.3.1 Overview

Fig. 3.2 shows a continuous point source entering along side of the LAR. The primary objective of the river water quality model is to be developed aimed on producing a tool that has the capability of simulating the behavior of the hydrologic and the waste water constituent in the river system. The development of this tool to simulate prototype behavior by applying a mathematical model on digital computer proceeds through three general phases (Brown and Barnwell, 1987):

1. Conceptual Representation
2. Functional Representation
3. Computational Representation

Conceptual representation involves a graphic idealization of the prototype by description of the geometric properties that are to be modeled and by identification of boundary conditions and interrelationships between various parts of the prototype. Unusually, this process entails dividing the prototype into discrete “elements” of the size of compatible with objectives of that the model must serve, as integral parts of the whole. Apart from this conceptual structuring is the designation of those boundary conditions to be considered in the simulation.

Fig. 3. 2 Continuous point source wastewater discharge at the side of the LAR

Functional representation entails formulation of the physical features, processes, and boundary conditions into sets of algebraic equations. It involves precise definition of each of variable and its relationship to all other parameters that characterize the model or its input-output relationships.

Computational representation is the process whereby the functional model is translated into the mathematical forms and computational procedures required for solution of the problem over the desired time and space continuum. It is concerned with development of a specific solution technique that can be accommodated by the computer and with codification of the technique in computer language (Brown and Barnwell, 1987).

In the remainder of this section the conceptual representation of the river system assuming it in a one dimensional form will be described together with its general functional representation for the different sub-models (mass transport, hydraulic characteristics, and longitudinal dispersion).

3.3.2 Conceptual Representation

In the study the river system was idealized as a one-dimensional system and it was treated as a series of equal length computational elements or control volumes as it will be discussed in the next chapter.

For each of these control volumes the hydrologic balance can be written in terms of flows into the upstream face of the element (Qi-l), external source or withdraws (Qxi), and the outflow (Qi) through the downstream face of the control volume. Similarly, a materials balance for any constituent C can be written for the element. In the materials balance, both transport (Q.C) and dispersion ($A \frac{D_L}{\Delta x} \frac{\partial C}{\partial x}$) as the movers of mass along the stream axis. Mass can be added to or removed from the system via external sources and withdraws (QxCx)i and added or removed via internal sources or sinks (Si) due to bio-chemical transformation. Each computational element is considered to be completely mixed.

3.3.3 Functional Representation

River water quality models simulate hydrodynamic as well as water quality conditions. Hydrodynamics and water quality are often reflected in separate interfacing sub-models. The models incorporate equations for transport or conservation of mass for water and equations for transport and transformation of materials in the river water (Information in relation to Models). The hydrodynamic equations deal with water volumes, flow rates, velocities, and depths. The materials transport and transformation equations include expressions for energy transfer and expressions for chemical equilibrium or chemical and biological kinetics.

3.3.3.1 Mass Transport Equation

Modifying Eq. 3.3 for the above one-dimensional assumption, the mass transport equation used in the modeling was:

$$\frac{\partial M}{\partial t} = \frac{\partial\left(A_x D_L \frac{\partial C}{\partial x}\right)}{\partial x} dx - \frac{\partial\left(A_x \bar{U} C\right)}{\partial x} dx + \left(A_x dx\right)\frac{dC}{dt} + S \qquad (3.4)$$

where:

- M = mass (M)
- X = distance (L)
- t = time (T)
- C = concentration (M L^{-3})
- Ax = cross-sectional area (L^2)
- DL = dispersion coefficient L^2 T^{-1})
- $\bar{U}$ = mean velocity (L T^{-1})
- S= external source or sinks (M T^{-1})

3.3.3.2 Hydrodynamic Equations

In modeling the flow rate of the LAR is assumed to be steady but non uniform; i.e. the flow rate of the river does not vary temporally, while it varies spatially. Therefore the hydrologic balance for the computational element (elemental volume), ***i*** can be written simply as:

$$\left(\frac{\partial Q}{\partial x}\right)_i = \left(Q_x\right)_i \qquad (3.5)$$

3.4 Model Inputs

3.4.1 Longitudinal Dispersion Coefficient (DL)

Clearly, Equation 3.4 demonstrates the direct dependency of pollutants transport to longitudinal dispersion coefficient. Owing to the importance of longitudinal dispersion coefficient in water quality related issues, many studies have been developed to predict longitudinal dispersion coefficient in rivers after the first study of Taylor in 1953. When the 1D dispersion model is applied to predict concentration variation in rivers, the selection of a proper dispersion coefficient is the most important task. When mixing and dispersion characteristics are unknown, the dispersion coefficient can only be estimated using empirical or theoretical equations (Ayyoubzad; Faramarz, and Mohammadi, 2004).

.Great deals of literature were reviewed in the selection of the appropriate method to be used. The review indicates that dye study (tracer test) is one of the most reliable means of computing a dispersion coefficient (Ayyoubzad; Faramarz, and Mohammadi, 2004). However due to the scale of the study as well as financial and technical constraints the dye study was not the viable option for this study.

There are eight available empirical relations for determining longitudinal dispersion coefficient of a river (Ayyoubzad; Faramarz, and Mohammadi, 2004). According to the comparative examination made on these eight methods, the equation developed by Deng et al. (2001) is found to be most reliable method for predicting longitudinal dispersion coefficient (Ayyoubzad; Faramarz, and Mohammadi, 2004).

Therefore, in the study the empirical relation developed by Deng et al (2001); Equation 3.6, was used for determining the dispersion coefficient of the river.

$$\frac{D_L}{HU^*} = \frac{0.15}{8*\varepsilon_{ro}} * \left(\frac{W}{H}\right)^{5/3} * \left(\frac{U}{U^*}\right)^2 \qquad (3.6)$$

in which ε_{ro} = traverse mixing coefficient and can be calculated as:

$$\varepsilon_{ro} = 0.145 + \left(\frac{1}{3520}\right) * \left(\frac{U}{U^*}\right) * \left(\frac{W}{H}\right)^{1.38} \qquad (3.7)$$

Where:

- H = river depth (L)
- W = river width (L)
- U* = river bed shear velocity ($L\,T^{-1}$)

The river bed shear velocity (U*) is given by

$$U^{*} = \sqrt{gSH} \tag{3.8}$$

Where

- g = gravitational constant (L T^{-2})
- S= river bed slope (L/L)

3.4.2 Width (W), Depth (H) and Velocity (U)

Field, secondary data and empirical relations were employed for the determination of width, depth and velocity of the river. The data collected and used were discussed in the next chapter of the paper.

The power equations that relate mean velocity, width, and depth to flow (Leopold and Maddock, 1953) and the Manning's equation; which is derived from a momentum balance for the channel provides a means to relate velocity to channel characteristics, were the empirical relations employed.

The power equations

$$U = aQ^{b} \tag{3.9}$$

$$H = \alpha Q^{\beta} \tag{3.10}$$

$$W = cQ^{f} \tag{3.11}$$

Where H = mean depth and a, b, α, β, c, f are empirical constants to be determined by curve fitting.

In the study only H and W correlated with Q (read the detail in the next chapter) and the Manning's relation (Eq. 3.12a) and the continuity equation (Eq.3.12b) was used to determine the mean flow velocity (U).

$$U = \frac{C_o}{n} R^{2/3} S_e^{1/2} \tag{3.12a}$$

$$U = \frac{Q}{W * H} \tag{3.12b}$$

Where:

- *Co* = A constant (= 1.0 for metric unit)
- *n* = Manning's roughness coefficient: for straight rivers the value is 0.03 (Chapra, 1997).
- R = Channel's hydraulic radius (m)
- *P* = Wetted perimeter (m)
- *Se* = Slope of the channel's energy grade line (dimensionless)

R is the hydraulic radius of the river.

$$R = \frac{A_x}{P} \tag{3.13}$$

where:

- Ax = cross-sectional area (L²)
- P- is the wetted perimeter of the river (L)

For rectangular shaped river bed

$$A_x = W * H \tag{3.14}$$

$$P = 2 * H + W \tag{3.15}$$

Thus, for rectangular river bed assumption, the hydraulic radius given by

$$R = \frac{W * H}{2 * H + W} \tag{3.16}$$

3.5 Selection of Solution Techniques

Due to the complexity of river water quality modeling, it has been shown that the most appropriate approach is to utilize numerical solution techniques rather than analytical approaches (Marquette, 2005).

Therefore, in the study a backward finite difference scheme based fully implicit finite volume discreatization method was used as discussed in the next chapter.

CHAPTER 4 MODEL DEVELOPMENT

4.1 General Introduction

The model framework is comprised of two components: a hydrodynamic model and a water quality model. The hydrodynamic model simulates the motion of water due to freshwater flow. The water quality model simulates the longitudinal fate and transport of point source pollutants and demonstrates their impact on the river water quality.

The remaining part of this chapter of the Thesis present the LAR water quality model development process (both the conceptual representation and functional representation) as well as the structure of the computer programme used for solving the model equation.

4.2 Scoping the Study Site/Model Delineation/

The study aimed primarily on modeling the fate and transport of industrial discharged point sources pollutant constituents in the river system. Therefore, prior to data collection and detail field investigation, the river section where industrial pollution is significant was identified and geographically referenced. Beside this scoping criterion, consideration was also given for the availability of data for calibrating and validating the model.

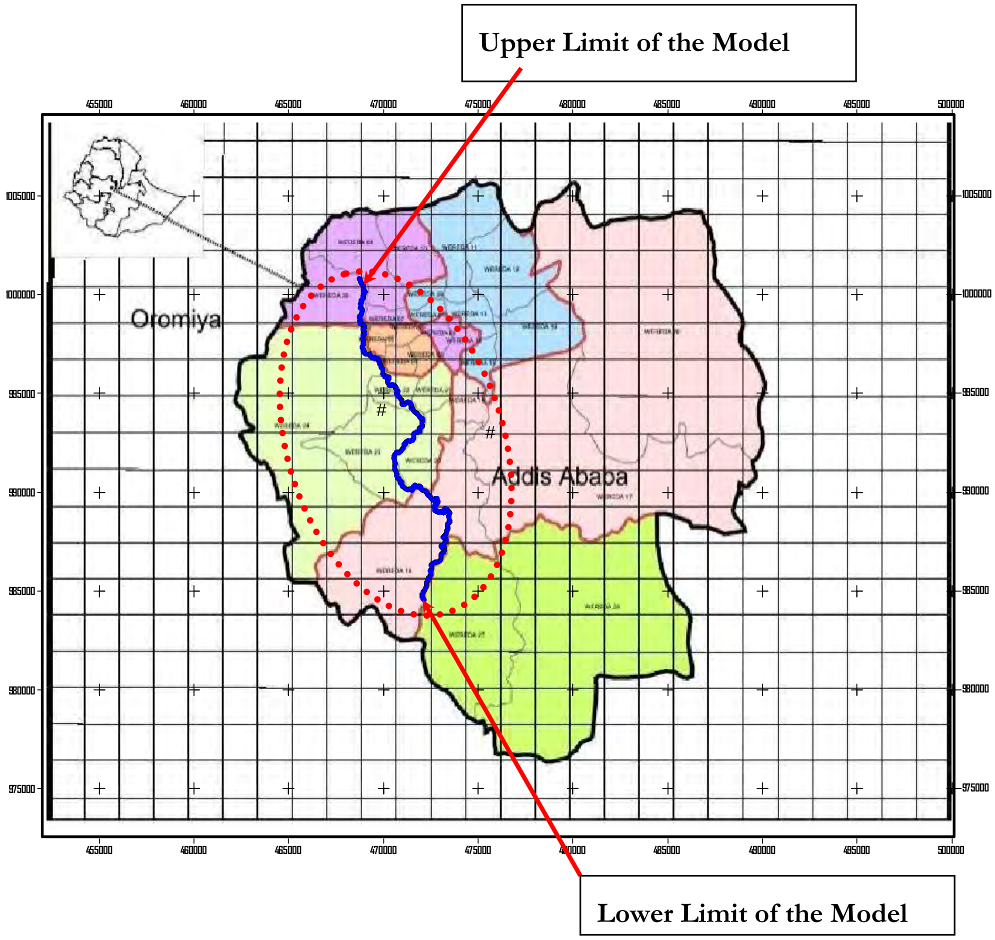
The delineation was aimed on limiting the upper and lower limits and the geographical location of the study area. Fig. 4-1 shows the one dimensional representation of the studied river section indicating the upper and lower limits of the river section.

4.2.1 Upper and Lower Limits of the Study Area

The upper limit of the study area was taken just before entering the Ethiopian Marble Factory; the first significant point source pollutant of the river. The point is located under the bridge of the old main Addis – Ambo Asphalt Road and geographically, the point is located at 468743.448E and 1000818.9380N.

The lower limit of the river section to be studied is taken about 500 m downstream from the Kaliti Sewage Treatment Plant effluent discharge point. This lower point is located in Woreda 27 Kebele 11, and geographically located at 473499.3E and 988449.11.

Fig. 4. 1The Modeled Section of the Little Akaki River



4.2.2 River Segmentation

The geographical study area delineation resulted in an estimated 27.4 km river length. Based on the hydraulic characteristics of the river system, the 27.4 km long river is divided into 559 series of river segments of different lengths. These segments represent a straight section of the river system and each river segment assumed to have similar hydraulic characteristics.

The Hydrological GIS Map prepared by AG Consult and other related maps was used to identify these river segments. The GIS map considers the river as a single major line that comprises number minor lines (which are the straight river segments). Therefore, the straight sections of the river segments are precisely geo-referenced and identified.

4.3 Determination of the River Hydro-geometry

The river's hydro-geometry required for the modeling process consists of its hydrologic characteristics (velocity, flow rate and traversal and longitudinal dispersion coefficients) and its geometry (depth, width, slope and cross-sectional area). The determination of these model input parameters are presented below.

4.3.1 River Flow Rate Delineation

The discharge rate of the river is an essential piece of model input as it is used for the determination of hydraulic characteristics of the river system (Eq. 3.9, 3.10 and 3.11). Therefore due to different discharge rates at different sections of the river system, it was necessary to delineate 27.4 km into a number of reaches having similar discharge rate. To avoid seasonal range inconsistency, the delineation was performed by considering the river situation at the month of October, November, January, February, March and May when there is relatively less precipitation and runoff rate. Accordingly, the location of each tributary within the study range was identified and the LAR was divided into six different river reaches of equivalent flow rate.

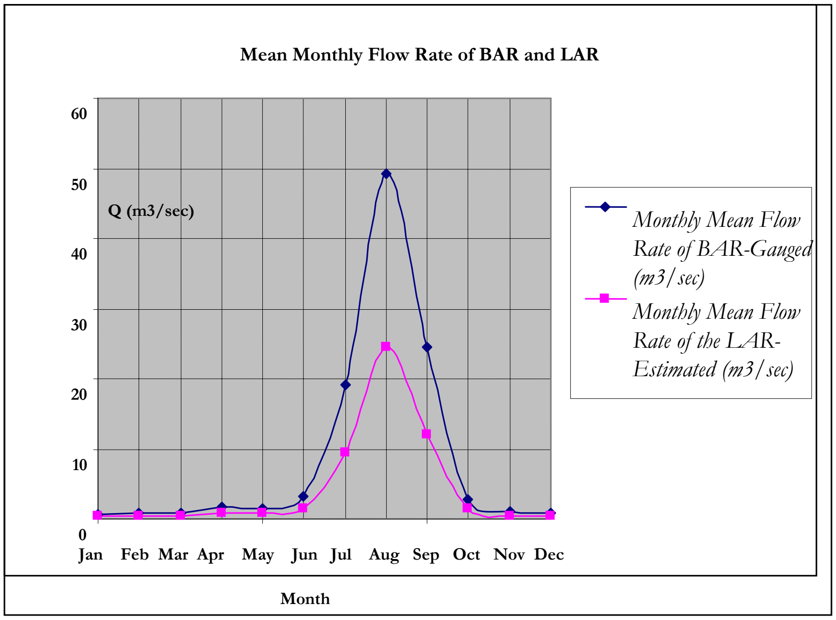
These six sections are:

- Reach 1: 0 – 6710 meters
- Reach 2: 6710 – 9890 meters
- Reach 3: 9890 – 15350 meters
- Reach 4: 15350 – 17750 meters
- Reach 5: 17750 – 18870 meters
- Reach 6: 18870 –27400 meters

The mean monthly discharge of the Big Akaki River gauged near Akaki Town (Attached at Appendix: B) was used to estimate the mean monthly discharge of LAR at the 6th

reach. This discharge rate was used to determine the discharge rate of the other reaches of the LAR on monthly basis based on the catchment area and metrological data obtained from the nearest metrological station in the area (Appendix-B)

Fig. 4. 2Monthly Discharge Rate of the LAR (Estimated) and BAR (gauged)



A preliminary hydrological delineation was performed based on Digital Elevation Model (DEM) data and the river reach file from the Addis Ababa Administration Master Plan. Further refinement of the hydrological segmentation was then completed by reviewing hydrological reports prepared for designing major bridges that exist over the LAR.

The mean discharge rate (in m^3/sec) for these six reaches of the river on monthly basis is as shown in Table 4.1. As shown in the table, the maximum discharge rate is in the month of August; while the minimum is recorded in the month of January.

Fig. 4. 3 The Modeled section of the river showing the tributaries considered in the hydrological delineation

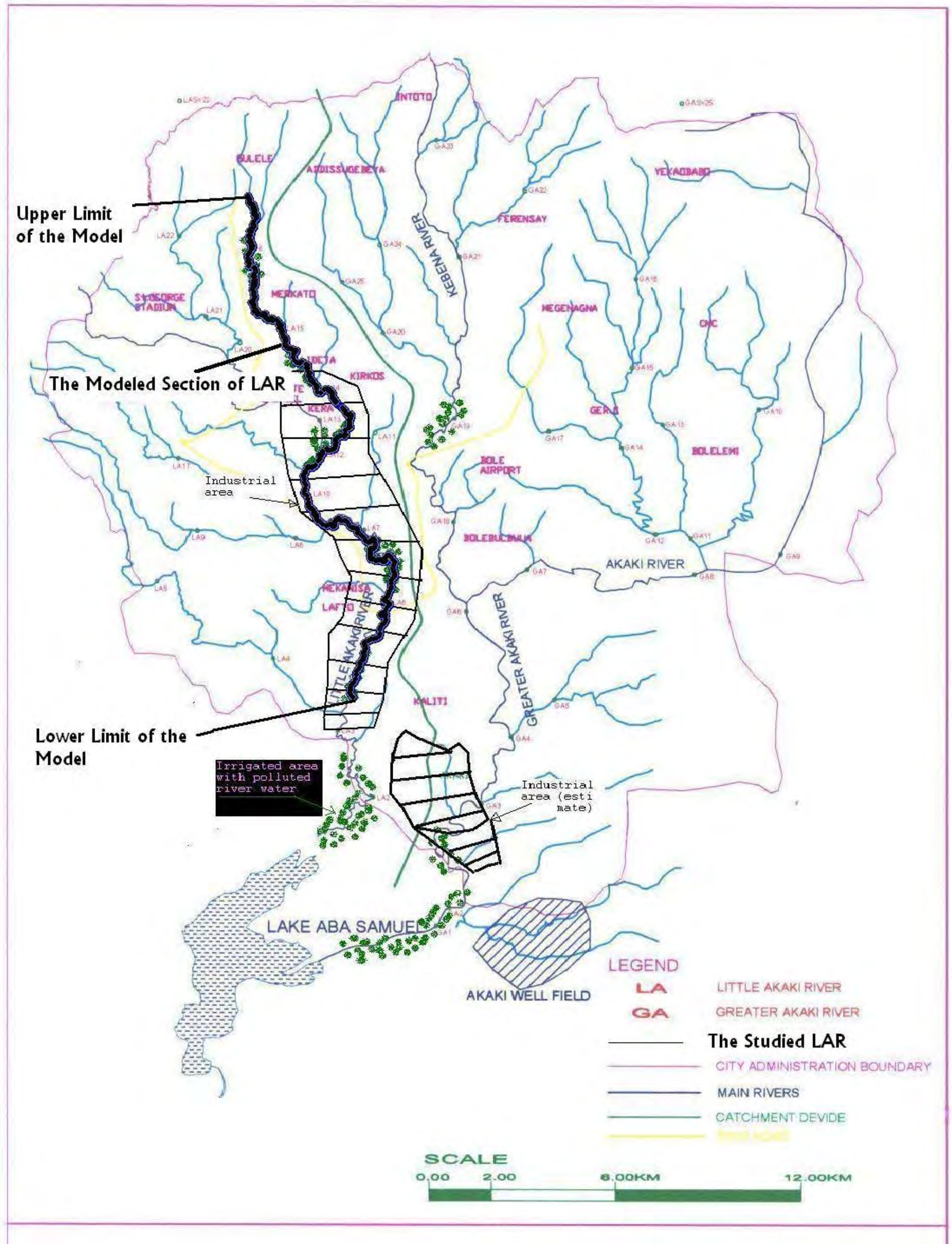


Table 4. 1 Summery of the Monthly Estimated Discharge Rate of the LAR at each sub reach

Month	River Reaches					
	1	2	3	4	5	6
January	0.088	0.113	0.140	0.154	0.263	0.342
February	0.102	0.129	0.161	0.176	0.301	0.391
March	0.124	0.157	0.195	0.214	0.366	0.476
April	0.223	0.283	0.351	0.386	0.660	0.857
May	0.201	0.255	0.317	0.348	0.595	0.773
June	0.402	0.510	0.638	0.696	1.190	1.546
July	2.455	3.117	3.872	4.250	7.272	9.44
August	6.356	8.068	10.02	11.000	18.82	24.45
September	3.155	4.004	4.975	5.46	9.344	12.13
October	0.366	0.464	0.577	0.633	1.084	1.407
November	0.126	0.160	0.199	0.219	0.374	0.486
December	0.107	0.136	0.169	0.185	0.317	0.411

4.3.2 Topographic Delineation

The other important physical parameter required for the hydraulic modeling is the river slope (S). Most of the streams in the study area emanate from the steep and rugged ridges of Entoto and flow crossing the city towards the relatively flat land areas south of the city (Alemayhu, 2005).

The LAR river slopes are determined for different section of the river of 20 meters grid by GIS analysis of a digital elevation model. The slope of the river segment is calculated as elevation difference between up- and downstream of the river section where the segments cross the consecutive contour line divided by the product of their horizontal distance and a meandering factor which was arbitrary estimated at 1.3 as global average (Brown and Barnwell, 1987). Accordingly the topography of the LAR starts at about 2540 m a.s.l and descends up to 2100 m a.s.l. The slope delineation resulted into a classification of 22 slope value categories as shown in Table 4.2.

Table 4. 2 Estimated slope value at different sections of the river

No	Location, X (m)	Slope, S (m/m)
1	0 – 630	0.0142857
2	630 – 890	0.0769231
3	890 – 1130	0.0909091
4	1130 – 1710	0.0333
5	1710 – 2330	0.03125
6	2330 – 3230	0.0217391
7	3230 – 3610	0.05
8	3610 – 4410	0.0243902
9	4410 – 6490	0.0095238
10	6490 – 7750	0.0158730
11	7750 – 8850	0.0178571
12	8850 – 10610	0.0112360
13	10610 – 11930	0.0149254
14	11930 – 12650	0.0270270
15	12650 – 14670	0.009839
16	14670 – 16430	0.0113636
17	16430 – 20570	0.0048309
18	20570 – 21970	0.0140845
19	21970 – 22670	0.027778
20	22670 – 24950	0.0086957
21	24950 – 26010	0.0163934
22	26010 – 27400	0.0126316

4.3.3 Width, Depth and Mean Flow Velocity

As mentioned above; the river section to be studied segmented into 559 of straight sections of different length (ranging from the minimum 5.3 up to the maximum 271 m). These straight sections of the river segments assumed to have uniform width (W), depth (H) and average flow velocity (U).

4.3.3.1 Field Data Collection and Correlation

In the aim of correlating the LAR to be studied using the power law (Equation 3.10 and 3.11); field data on Width (W) and depth (H) of the river system at the six river flow rate delineated sections of the river collected for the months of October, November, January, February and March (Appendix-A-1).

The collected data fitted to the general hydro-geometric correlation Eq. 3.10 and 3.11 and a regression analysis was carried out with a dataset of 200 (100 for W and 100 for H) for the six river section to quantify the best-fit coefficients (α ,c) and exponents (β ,f). Fig. 4.4 (a) and (b) show the regressions and coefficients of the power law correlation for the studied section of the LAR.

4.3.3.2 Extrapolation of Field Data

The correlation further refined and corrected for the 559 straight river segments of the river by reading the river bank width at each river segment from the digital photogramethric map compiled by Associated Engineering in JV with HBT AGRA. The map is prepared by using photogrameteric method from aerial photography at a scale of 1:8000. The aerial photograph is taken by the Ethiopian Air Force in 1994. The map provides a bankfull discharge (Q_b) width of the river, therefore the bankfull discharge for LAR was determined for each section of the river from metrological and bridge design reports. Accordingly the bankfull discharge of the LAR at the last and second sections (at the Bridge of Awash Winery) estimated to be 20.3 m^3/sec and 6.699 m^3/sec respectively.

To determine the bankfull discharge at the remaining four sections of the river (i.e. Reaches 1, 3, 4 and 5), a similar approach for the hydraulic delineation of the river (section 4.3.1 above) was employed.

Fig. 4. 4 Power Law Correlation for the Studied Section of the LAR

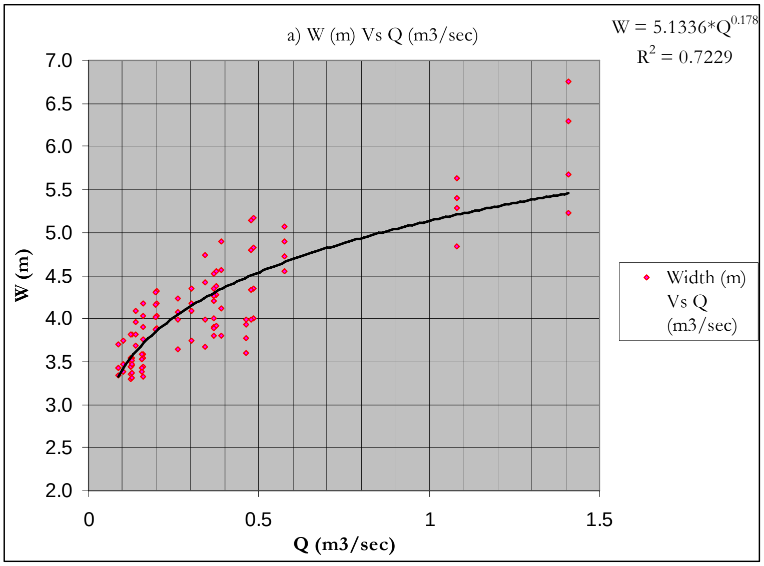


Fig. 4. 4a River Bank Width, W Vs River Discharge, Q

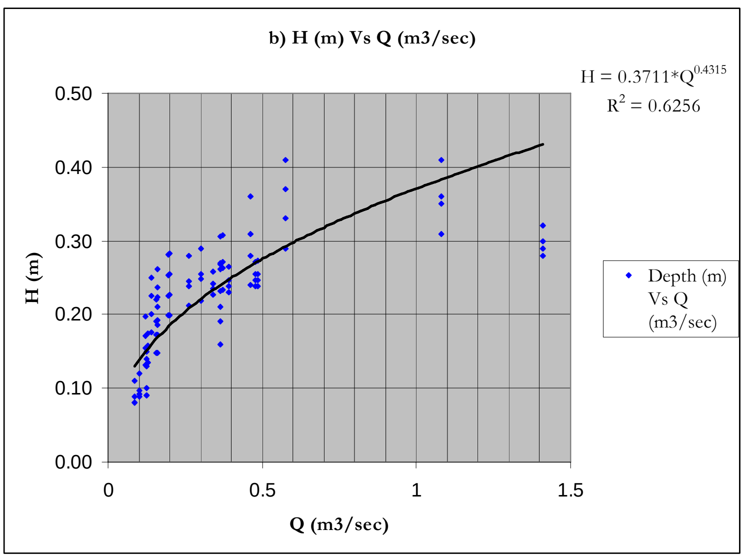


Fig. 4. 4b River Depth, H (m) Vs River Discharge, Q

The width of the LAR at the less than bankfull discharge, scaled down from the map's bankfull discharge width using the following relation (Chapra, 1997):

$$W_{lb} = \frac{W_b}{\left(\frac{Q_b}{Q_{lb}}\right)^f} \qquad (4.1)$$

The depth of the LAR at the less than bankfull discharge was also scaled down using the following relation:

$$H_{lb} = \frac{H_b}{\left(\frac{Q_b}{Q_{lb}}\right)^\beta} \qquad (4.2)$$

where:

- Qb bankfull river discharge rate (L^3 T^{-1})
- Qlb less than bankfull discharge rate (L^3 T^{-1})
- Wb width of the river at bankfull river discharge, Qb (L)
- Wlb width of the river at less than bankfull discharge, Qlb (L)
- Hb depth of the river at bankfull river discharge, Qb (L)
- Hlb depth of the river at less than bankfull discharge, Qlb (L)

Table 4.3 shows the estimated bankfull discharge value for each of the six reaches and the monthly estimated ratio of the less than bankfull discharge width to the bankfull discharge width at different sections of the LAR The regression coefficients and exponents calculated from the regression analysis was used for determination of the depth of the 559 river segments in a monthly bases.

Table 4. 3 Estimated monthly discharge, Q (m3/sec) and the ratio to the bankfull discharge for the LAR

Table 4.3 a Estimated monthly discharge, Q (m3/sec) and the ratio to the bankfull discharge for Reach 1

	Months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Qlb (m^3/sec)	0.088	0.102	0.124	0.223	0.201	0.402	2.455	6.356	3.155	0.366	0.126	0.107
$(Qlb/Qb)^f$	0.482	0.495	0.512	0.569	0.559	0.632	0.872	1.033	0.912	0.621	0.514	0.499

Table 4.3 b Estimated monthly discharge, Q (m3/sec) and the ratio to the bankfull discharge for Reach 2

	Months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Qlb (m^3/sec)	0.113	0.129	0.157	0.283	0.255	0.510	3.117	8.068	4.004	0.464	0.160	0.136
$(Qlb/Qb)^f$	0.483	0.495	0.513	0.569	0.559	0.632	0.873	1.034	0.912	0.622	0.515	0.500

Table 4.3 c Estimated monthly discharge, Q (m3/sec) and the ratio to the bankfull discharge for Reach 3

	Months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Qlb (m^3/sec)	0.140	0.160	0.195	0.351	0.317	0.634	3.872	10.023	4.975	0.577	0.199	0.169
$(Qlb/Qb)^f$	0.483	0.495	0.513	0.569	0.559	0.632	0.873	1.034	0.913	0.622	0.515	0.500

Table 4.3 d Estimated monthly discharge, Q (m3/sec) and the ratio to the bankfull discharge for Reach 4

	Months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Qlb (m^3/sec)	0.154	0.176	0.214	0.386	0.348	0.696	4.250	11.001	5.460	0.633	0.219	0.185
$(Qlb/Qb)^f$	0.483	0.495	0.513	0.569	0.559	0.632	0.873	1.034	0.912	0.622	0.514	0.499

Table 4.3 e: Estimated monthly discharge, Q (m3/sec) and the ratio to the bankfull discharge for Reach 5

	Months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Qlb (m^3/sec)	0.263	0.301	0.366	0.660	0.595	1.190	7.272	18.824	9.344	1.084	0.374	0.317
$(Qlb/Qb)^f$	0.483	0.495	0.513	0.569	0.559	0.632	0.873	1.034	0.912	0.622	0.515	0.500

Table 4.3 f Estimated monthly discharge, Q (m3/sec) and the ratio to the bankfull discharge for Reach 6

	Months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Qlb (m^3/sec)	0.342	0.391	0.476	0.857	0.773	1.546	9.444	24.447	12.134	1.407	0.486	0.411
$(Qlb/Qb)^f$	0.483	0.495	0.512	0.569	0.559	0.632	0.872	1.033	0.912	0.622	0.514	0.499

Assuming a rectangular shaped bed for each of the 559 river segments, Eq. 3.14 was used for determination of the mean cross-sectional area (Ac) for each straight section of the river segment. Thus, the mean river flow velocity (U) of the river at each of the 559 straight segments was determined using Eq. 3.12b.

4.3.4 Determination of the Longitudinal Dispersion Coefficient of the River

The most important hydrological parameter required for the model is the longitudinal dispersion coefficient, Dl of the river.

As Deng et al (2001)'s empirical equation is more reliable for straight river sections (Hemond and Frechner-Levy, 2000), Eq. (3.6) and (3.7) were applied for each straight segments.

With rectangular river bed assumption, Eq. 3.8 was applied for each straight river segment in the determination of the river bed shear velocity (U). Finally; the longitudinal dispersion coefficients (D_L) and the traverse mixing coefficients (ε_{ro}) determined using Eq.3.6 and Eq.3.7, respectively.

4.4 Model Overview

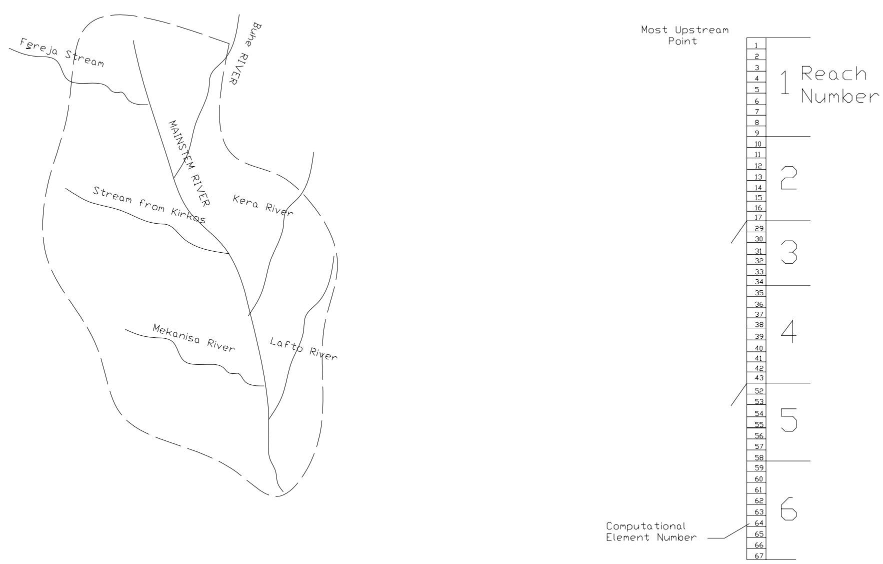
4.4.1 Spatial Discretization

As mentioned above the river is treated as a collection of 559 river segments, each having homogeneous hydro-geometric properties. Each river segment or collection of river segments, further divided in to a series of equal-length computational elements or control volumes.

Therefore, the 27.4 km (27400 m) long river is further discitiezed into a total of 1370 elemental cells of having equal length of 20 meters. These elemental cells assumed to have homogenous water quality. The river hydro-geometry parameters determined for each of the straight section of the river is converted for these elemental cells proportionally, (for example if a single 20 meters elemental cell is formed from two consecutive river segments, say 15 meters from the first and 5 m from the next; the hydro-geometry of the cell will take 75% from the first and 25% from the next).

With the above elemental cells discritization the stream was conceptualized as a string of completely mixed reactors--computational elements--- of having 20 meters length that are linked sequentially to one another via the mechanisms of transport and dispersion. The perennial rivers (Fereja, Buhe, stream from Kirkos, stream from Mekanisa and Lafto streams) that influenced the discharge rate of the river and made the river to be delineated into six different reaches. Fig 4.5 indicates the stream net work and computational elements of the LAR modeled studied.

Fig. 4. 5 Stream Network of Computional Elements and Reaches



4.4.2 Assumptions and Functional Modifications

The basic equation solved in the study was the one dimensional advection-dispersion mass transport equation as defined by (Eq.3.4). In the study, this general equation was modified based on the following assumptions:

Because M = VC, we can write

$$\frac{\partial M}{\partial t} = \frac{\partial (CV)}{\partial t} = V\frac{\partial C}{\partial t} + C\frac{\partial V}{\partial t} \quad (4.3a)$$

With steady state - non uniform river flow assumption, i.e. $\frac{\partial Q}{\partial t} = 0$, $\frac{\partial V}{\partial t} = 0$ and Eq.4.3a becomes:

$$\frac{\partial M}{\partial t} = V\frac{\partial C}{\partial t} \quad (4.3b)$$

Combining equations 3.4 and 4.3b and rearranging,

$$V\frac{\partial C}{\partial t} = \frac{\partial\left(A_c D_L \frac{\partial C}{\partial x}\right)}{\partial x}dx - \frac{\partial (A_c UC)}{\partial x}dx + V\frac{dC}{dt} + S \quad (4.4)$$

The terms in Eq. 4.4 represented as:

$$V\frac{\partial C}{\partial t} = Accumlation$$

$$\frac{\partial\left(A_c D_L \frac{\partial C}{\partial x}\right)}{\partial x}dx - \frac{\partial (A_c UC)}{\partial x}dx = Transport \ (dispersion \ \& \ Advection)$$

$$V\frac{dC}{dt} = Kinetics$$

$$S = External\_sources / sinks$$

Where

- V = Volume (L^3)
- X = distance (L)
- t = time (T)
- C = concentration (M L^{-3})
- Ac = cross-sectional area (L^2)
- DL = dispersion coefficient L^2 T^{-1})
- U= mean velocity (L T^{-1})

- S = External sources (positive) or sinks (negative) of the constituent (M T^{-1})

Fig. 4. 6 Flow Balance on the Discritized Elemental Volume of the River

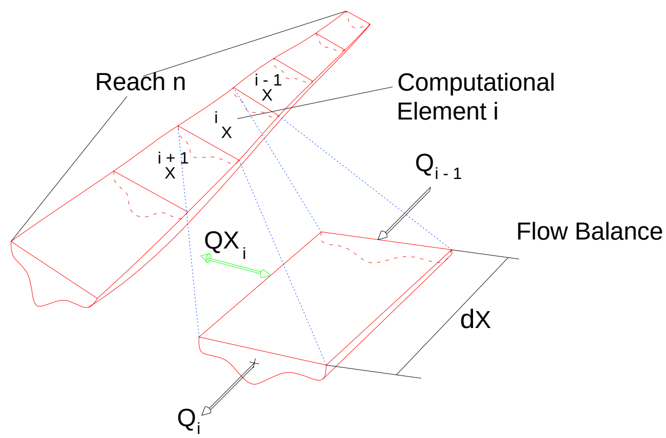
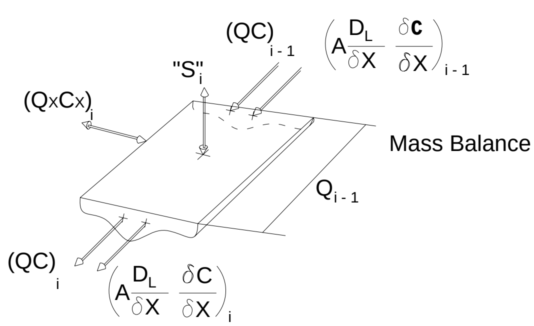


Fig. 4. 7 Mass Balance on the Discritized Elemental Volume of the River



4.4.3 Transport

As mentioned in the previous sections of the Thesis and as also indicated in Eq.4.4; transports consist of two components: advection and dispersion, the former specifies the movement of the constituents with water as it flows downstream. The later relates to the spreading of the constituent that occurs primarily due to shear.

4.4.3.1 Advection

In the study, a steady, non-uniform flow condition was assumed. The term steady flow indicates that flow does not vary temporally (there is no diversion or addition of flow rate in a specified time quantum). The term non uniform flow connotes that it varies spatially. For such a characterization a flow balance foe elemental cell *i* can be written as

$$Q_{i-1} \pm Q_{x,i} - Q_i = 0 \qquad (4.5)$$

where:

Q_{i-1} = flow from the upstream element

Q_i = outflow from the element

$Q_{x,i}$ = lateral flow into (positive) or out of (negative) the element

4.4.3.2 Dispersion

As presented in Chapter 3 and presented in section 4.3.4, the longitudinal dispersion coefficient of the LAR estimated using Eq.3.7 that compute the river dispersion coefficient as a function of the channel's characteristics.

4.4.3.3 Kinetics

The kinetics term depends on the type of chemical constituent to be modeled. Generally there are two types of contaminant constituents; conservative and reactive. In the conservative case, the term ***dC/dt*** is zero; thus the kinetic term will be zero. For the reactive constituents the term varies depending on the physical and/or bio-chemical kinetics the contaminant constituent undertakes in the river system.

4.5 Numerical Algorithm and Associated Issues

All the above discussions are aimed on providing the model framework for the LAR. How the model obtains solutions numerically (or the computational representation of the river) is presented.

Recalling Eq. 4.4 and dividing both the RHS and LHS of the equation with volume, V, V=Ac*dx

$$\frac{\partial C}{\partial t}=\frac{\partial\left(A_c D_L \frac{\partial C}{\partial x}\right)}{A_c \partial x}-\frac{\partial\left(A_c U C\right)}{A_c \partial x}+\frac{dC}{dt}+\frac{S}{V} \tag{4.6}$$

At each time step and for each constituent, Eq. 4.6 can be written n times, once for each of the n elemental volumes in the LAR system.

4.5.1 Fully Implicit Finite Difference Scheme Formulation

The finite difference scheme is formulated by considering the constituent concentration, C, at four points as shown in Fig. 4.9.

Three points were required at time l+1 to approximate the spatial derivatives. The temporal derivative was approximated at distance step i. Equation 4.6 can be written in finite difference form in three steps. First the advection and diffusion terms are differentiated once with respect to x gave:

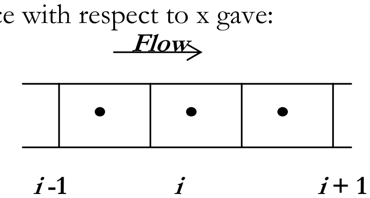


Fig 4. 8: The Elemental Cell Representation of the River (Discritized Spatially)

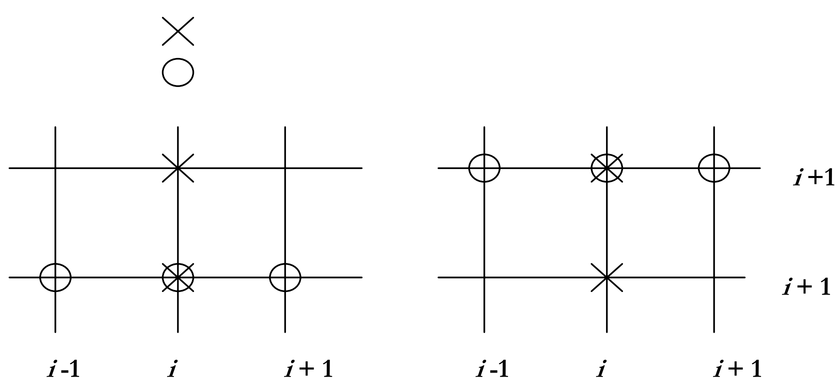


Fig 4. 9 The Classical Implicit Nodal Implicit Scheme Adopted in the Study

$$\frac{\partial C_i}{\partial t}=\frac{-\left(A_cD_L\frac{\partial C}{\partial x}\right)_{i-1}+\left(A_cD_L\frac{\partial C}{\partial x}\right)_i A_cD_L\frac{\partial C}{\partial x}}{V_i}+\frac{(A_cUC)_{i-1}+(A_cUC)_i}{V_i}+r_iC_i+\frac{S_i}{V_i} \qquad (4.7)$$

Then, expressing the spatial derivatives of the diffusion terms in finite difference resulted:

$$\frac{\partial C_i}{\partial t}=\frac{(A_cD_L)(C_{i+1}-C_i)}{V_i\Delta x_i}+\frac{(A_cD_L)(C_{i-1}-C_i)}{V_i\Delta x_i}+\frac{Q_{i-1}C_{i-1}-Q_iC_i}{V_i}+r_iC_i+\frac{S_i}{V_i} \qquad (4.8)$$

Finally, expressing the temporal derivative in fully implicit finite difference provided:

$$\frac{C_i^{l+1}-C_i^l}{\Delta t}=\frac{(A_cD_L)_{i,i+1}(C_{i+1}^{l+1}-C_i^{l+1})}{V_i\Delta x_i}+\frac{(A_cD_L)_{i-1,i}(C_{i-1}^{l+1}-C_i^{l+1})}{V_i\Delta x_i}+ \\ \frac{Q_{i-1}C_{i-1}^{l+1}-Q_iC_i^{l+1}}{V_i}+r_iC_i^{l+1}+\frac{S_i}{V_i} \qquad (4.9)$$

Collecting like terms of Eq. 4.9 then converted into algebraic equations of the form (Eq. 4.10), whose solution was C(x, t)

$$e_iC_{i-1}^{n+1}+f_iC_i^{n+1}+g_iC_{i+1}^{n+1}=z_i \qquad (4.10)$$

where

$$e_i=-\left[\left(A_cD_L\right)_{i-1}*\frac{\Delta t}{V_i\Delta x_i}+\frac{Q_{i-1}\Delta t}{V_i}\right] \qquad (4.11)$$

$$f_i=1+\left[[\left(A_cD_L\right)_{i-1}+(A_cD_L)_i]\frac{\Delta t}{V_i\Delta x_i}+\frac{Q_i\Delta t}{V_i}\right]-r_i\Delta t \qquad (4.12)$$

$$g_i=-\left[\left(A_cD_L\right)_i\frac{\Delta t}{V_i\Delta x_i}\right] \qquad (4.13)$$

$$z_i=C_i^n+\frac{S_i\Delta t}{V_i} \qquad (4.14)$$

4.5.2 Stability and Accuracy

Solving differential equations by discritizing that equation on a numerical grid has some restrictions. In all numerical schemes there are similar restrictions that limit the allowable spatial grid size and time step (Hemond and Fechner, 2000). Stability and accuracy are the main numerical solution scheme limitation issues. Stability connotes that errors are not amplified by the solution scheme. Hence an unstable solution is where errors ultimately 'swamp' the true solution. Accuracy deals with how well the solution scheme conforms to the true solution of the underlying differential equation (Chapra, 1997). In the study both issues were considered based on published criteria for stability and accuracy. Thus stability problem was addressed applying the fully implicit temporal discritization of the model equation (as presented above).

Depending the spatial discritization method used (backward difference or centered difference) numerical solution accuracy problems arises either due to numerical dispersion or positivity. Numerical dispersion is problem for the backward difference, while postivity is associated with the centered difference. These solution accuracy limitations are associated with the size of the elemental cell to be analyzed and the constraints are quantified often with the following formulation (Chapra, 1997):

$$\Delta X_c < \frac{D_l}{0.5 * U} \qquad (4.15)$$

where:

ΔX_c the size of the elemental cell

As described in Eq. 4.15, to avoid numerical dispersion and maintain postivity of solution the spatial discritization should be below $\frac{D_l}{0.5 * U}$ (Chapra, 1997).

Thus, in the study the river was discritiezed based on this criteria and the issue was also included in the program algorithm.

4.5.3 Segmentation around Point Sources

Finer segmentation is typically used to better capture the sharper gradients around point sources. Studies indicate that when a coarse scheme is used the concentration at the entry point of the point source can be underestimated (Chapra, 1997). Therefore, in the study the elemental cells located at point sources were analyzed by discritizing more finer than the other point source free elemental cells.

4.6 Method of Solution and Programming the Model

Equation 4.9 represent a set of simultaneous linear equations whose solution provides the values of C_i^{n+1} for all ***i's***.

A solution algorithm that can solve the set of linear equations of Eq. 4.10 iteratively for C_i^{n+1} using known values C_i^n and C_{i-1}^{n+1} as well as by guessing C_{i+1}^{n+1} at each of the 1371 nodes was the desired computer model.

In the study, due to its special capability of handling such matrix related mathematical algorithms, MATLAB computer language was used for solving this tri-diagonal matrix problem.

4.7 Preliminary Model Test

The developed general water quality model was tested with the aim of verifying it and to demonstrate;

- the accuracy of the developed model equation in describing the physical processes occurring in the river system, and
- the accuracy of the developed computer program for solving the model equations that make-up the mathematical model.

Therefore, the developed water quality model was tested in idealized conditions to compare its results to known analytical solutions. Thus, the following two scenarios were considered and analyzed.

Figure 4.10 shows the execution sequences of the developed MATLAB Computer program used for this raw model test study the model.

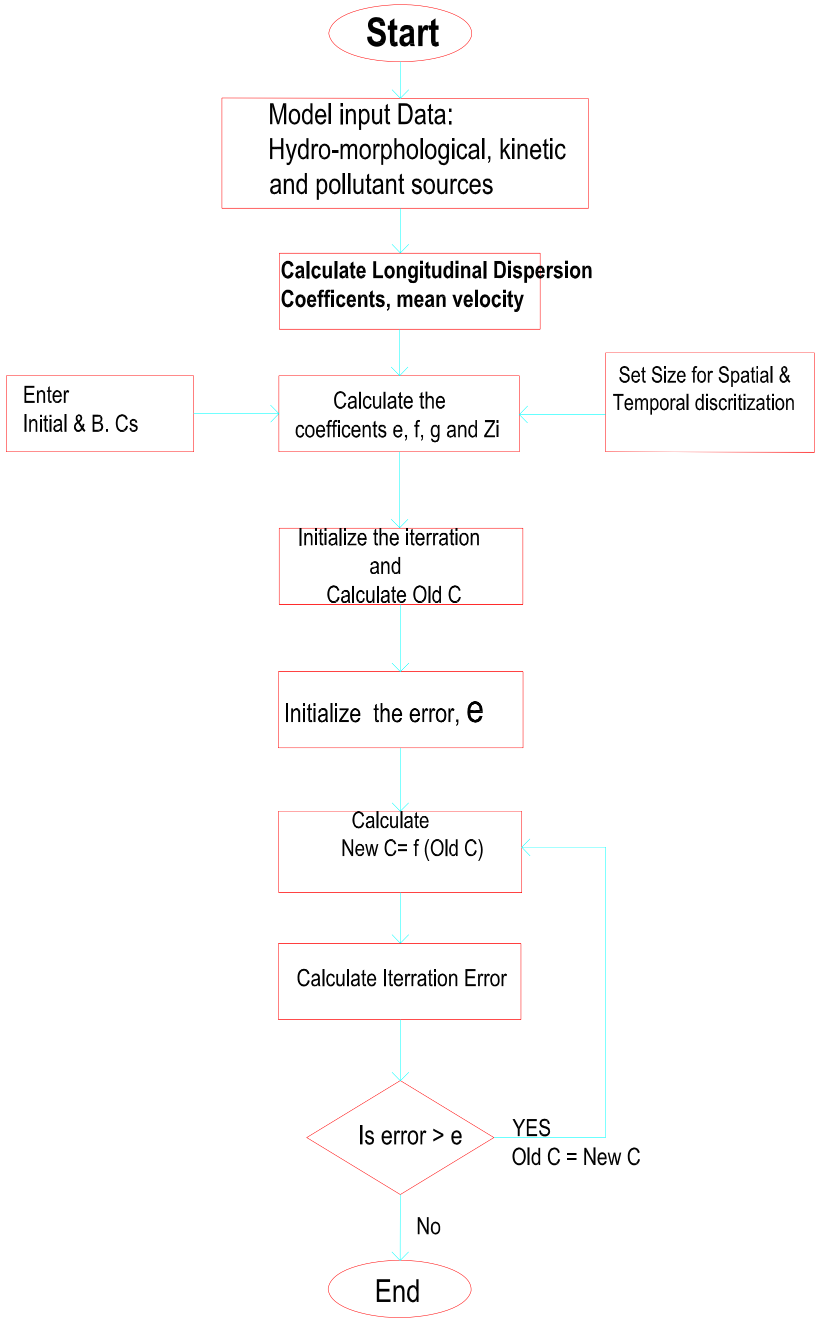


Fig 4. 10 Execution Procedure of the MATLAB Model Solution Programme

4.7.1 Case I: Instantaneous or "Impulse" Spills

For this case a highly persistent chemical accidentally discharged to the LAR was considered and the fate and transport of the chemical was analyzed. In the model, how far will the contaminant spread at different time intervals was analyzed and the model result was compared with the analytical solution result.

Model Input Data

It was assumed that the spill occurred at the month of October and the nearest location of the point source taken to be X= 468885 and Y= 1000515. This nodal point is located at nodal point 21 (with the previous 20 m size grid) and it is located at the first section of the river and this point has the following features:

- Mean bank width, W = 4.1 m
- Mean river depth, H = 0.11 m
- Mean River velocity, U= 0.61 m/sec
- Mean Discharge of the river, Q = 0.366 m^3/sec
- Slope, S = 0.0143

The total amount of the spilled contaminant assumed to a total mass of 12 kg. It was also assumed that the spill occurs instantaneously as a plane source, thus at time, t=0 the concentration of the contaminant will be maximum at point of discharge and is zero at other nodal points.

Analytical Solution

The analytical solution for this idealized advection-dispersion with out reaction (reaction=0) is given by (Chapra, 1997).

$$C(x,t) = \frac{m_p}{2 * \sqrt{\pi * D_L * t}} e^{-\frac{(x-Ut)^2}{4 * D_L * t}} \qquad (4.16)$$

Model Simulation

In formulating the numerical model algorithm, the size of the elemental cell where the point source assumed to enter was assumed to be 10 cm; i.e. ΔX_0=0.1 m; while the remaining section of the river discritized in equal 20 m lengths, ΔX_c=20 m. elemental cells. Accordingly, the model state variables (initial and boundary conditions) were formulated as follows:

Initial Condition

C(x=21,0) = 133 gm/lt, C(x<>21,0)=0

Boundary Conditions

C(0,t)=0

$$\frac{\partial C}{\partial x}\Big|_{X=L} = 0$$

Kinetics (dC/dt)

Conservative (non-reactive contaminant) was considered (dC/dt =0)

Model Results

The concentration of the point source measured for different time periods. The results calculated using the model are displayed in Fig. 4.11, 12, 13, 14.

As shown in the figures the peak of the spill spreads as time progresses and progressively decays due to dispersion. As it was shown in Fig 4.11, the peak point reaches about 90 mg/l at t= 1hrs and the point is located at nodal point 21. In Fig. 4.12, after 2 hrs time, the peak point reduced to 37 mg/l due to the dispersion of the chemical and this peak point moved to the 167th nodal point due to advection mass transport.

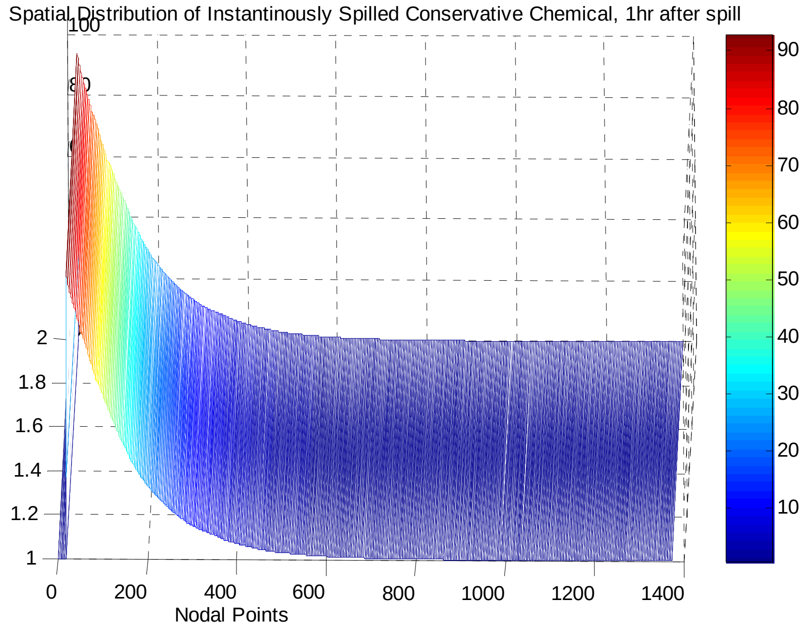


Fig. 4. 11 The spatial distribution of non-continuous point source after 1hrs

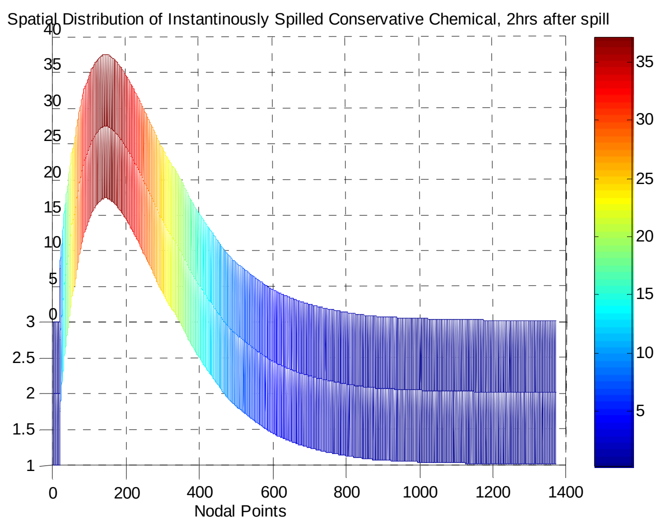


Fig. 4. 12 The spatial distribution of non-continuous point source after 2hrs

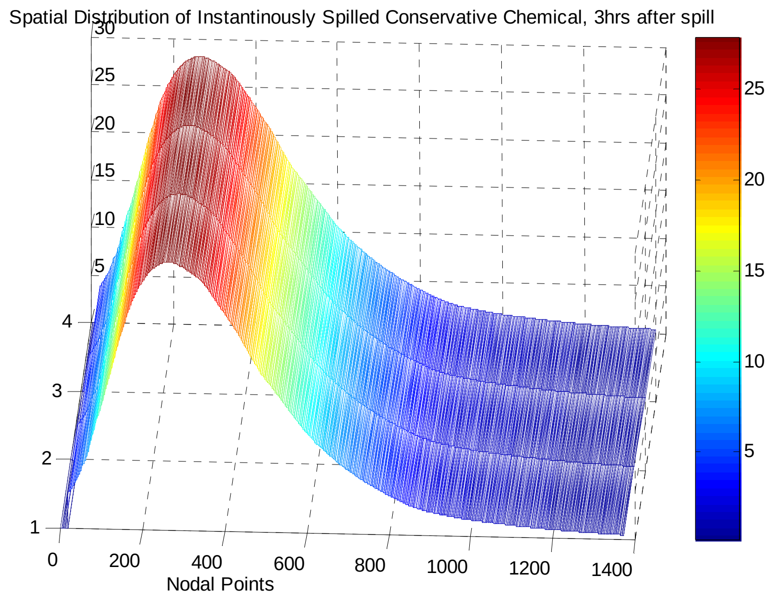


Fig. 4. 13 The spatial distribution of non-continuous point source after 3hrs

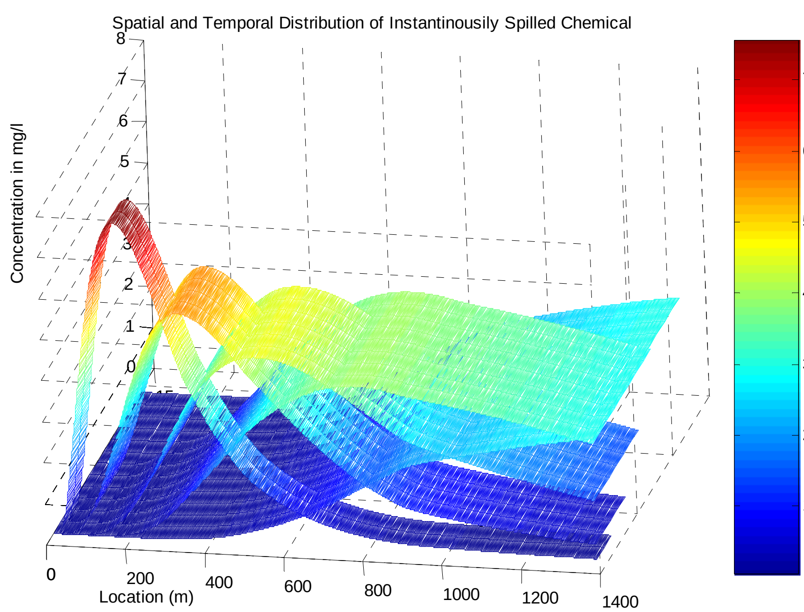


Fig. 4. 14 The spatial distribution of non-continuous point source at different times

4.7.2 Case II: Continuous Point Source Discharge

Model Input Data

It was assumed that the spill was occurred at the same month and the same location as above.

Therefore, the elemental cell at the point source will have the following features:

- Mean bank width, W = 4.1 m
- Mean river depth, H = 0.11 m
- Mean River velocity, U= 0.61 m/sec
- Mean Discharge of the river, Q = 0.366 m^3/sec
- Slope, S = 0.0143

The point source assumed to enter to the river as wastewater constituent of flow rate, Q= 1.6 l/sec of measured concentration, C=500 mg/l.

In formulating the numerical model algorithm for this case, the size of the first elemental cell where the point source assumed to enter to assumed to be 1 cm; i.e. ΔX_0=0.1 m; while the reaming section of the river assumed to be river discritized in equal 20 m lengths, ΔX_c=20 m. elemental cells.

Accordingly, the model state variables (initial and boundary conditions) were formulated as follows:

Initial Condition

C(x,0) = 0

Boundary Conditions

C(0,t)=0

$$\frac{\partial C}{\partial x}\Big|_{X=L} = 0$$

Kinetics (dC/dt)

Conservative (non-reactive contaminant) was considered (dC/dt =0)

Analytical Solution

The solution for this continuous source case is given by (Chapra, 1997).

$$C(x,t) = \frac{C_0}{2}\left[e^{\frac{Ux}{2D_L}(1-\Gamma)} erfc\left(\frac{x - Ut\Gamma}{2\sqrt{D_L t}} \right) + e^{\frac{Ux}{2D_L}(1+\Gamma)} erfc\left(\frac{x + Ut\Gamma}{2\sqrt{D_L t}} \right) \right] \tag{4.17}$$

where:

$$\Gamma = \sqrt{1 + 4\eta} \tag{4.18}$$

$$\eta = \frac{\kappa D_L}{U^2} \tag{4.19}$$

.

$$erfc(b) = 1 - \left(\frac{2}{\pi}\int_0^b e^{-\beta^2} d\beta\right) \tag{4.20}$$

But as a conservative contaminant was considered for this preliminary model test case; Eq. 4.19 is zero (because k=0). Thus, $\Gamma = 1$ and Eq.4.17 reduced to:

$$C(x,t) = \frac{C_0}{2}\left[erfc\left(\frac{x - Ut}{2\sqrt{D_L t}} \right) + e^{\frac{Ux}{D_L}} erfc\left(\frac{x + Ut}{2\sqrt{D_L t}} \right) \right] \tag{4.21}$$

As it was shown in Fig. 4.15, the concentration of the conservative chemical reaches a constant concentration level. With this continuous point source case, a transition approaches a constant pattern, which is an asymptotic shape in which a zero concentration gradient reached with the upstream. The time required for reaching this constant concentration point varies from location to location.

A simulation of the continuous point source concentration to time at different locations of the river is shown in Fig. 4.16. Such curves are referred to as "breakthrough" curves and they are used extensively in both surface and ground water problems context (Chapra, 1997). One of the important uses of these breakthrough curves is in determining the rivers flow and transport properties, particularly for determining the mean advective flow velocity and longitudinal dispersion coefficient of rivers.

As displayed in Fig. 4.16, the breakthrough curves can be used for estimating the time required for reaching the constant concentration point at specific point downstream from the continuous point source location.

Fig 4.17 displays the one dimensional concentration distribution of the conservative contaminant observed from top view after different times.

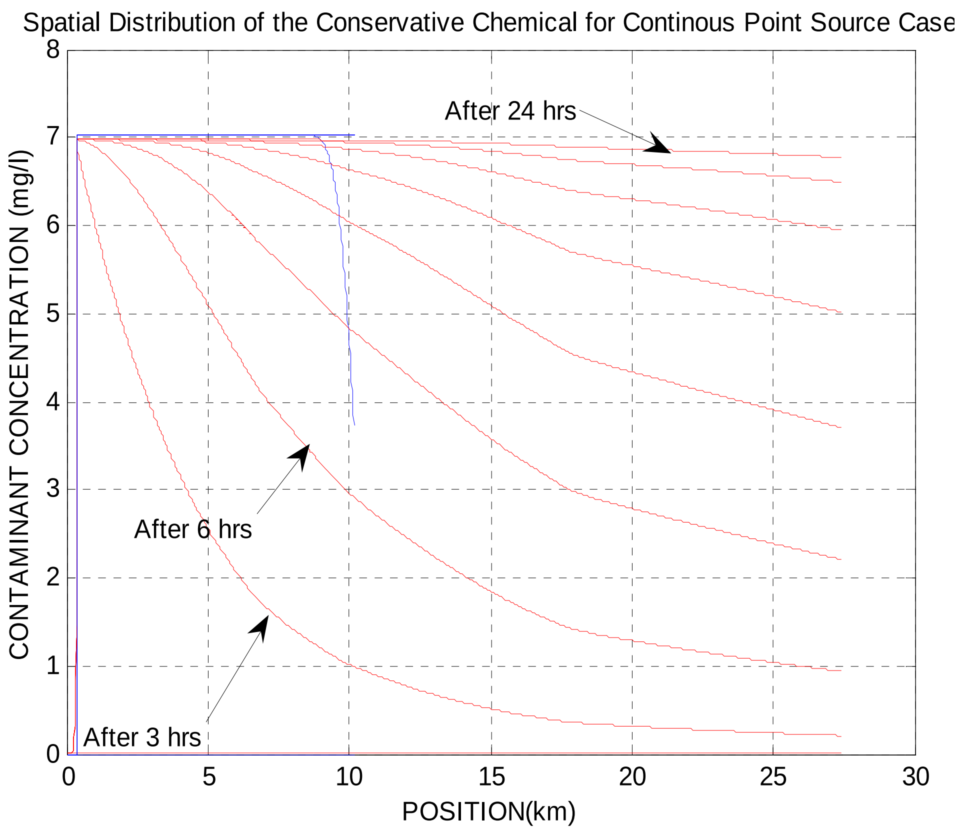


Fig. 4.15 Spatial Distribution of Concentration of the continuous point source pollutant measured after different times

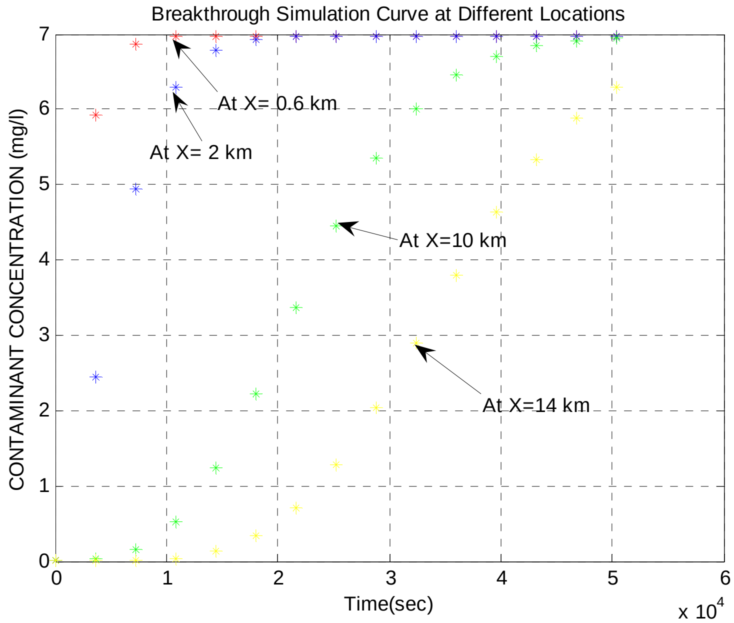


Fig. 4.16 Concentration Breakthrough curve of the continuously discharged conservative chemical at different locations

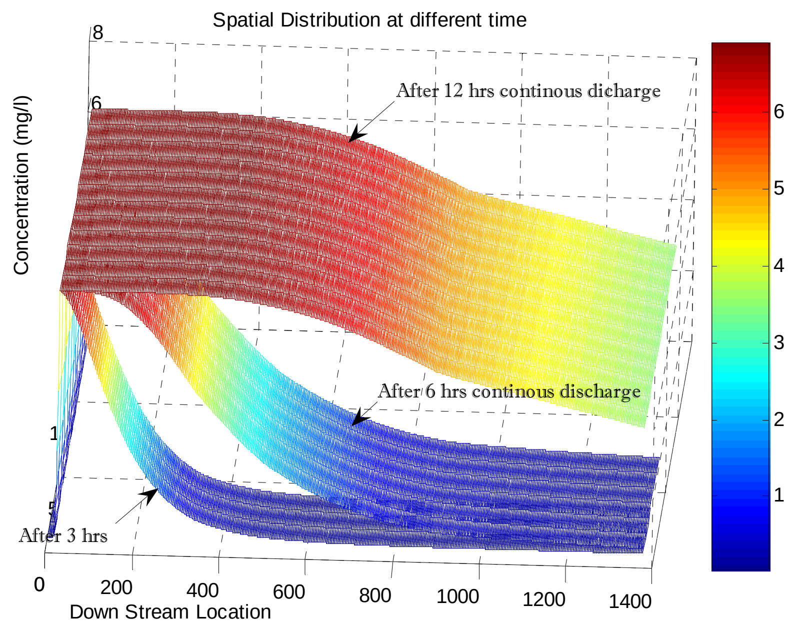


Fig. 4.17 Top view concentration profile of the continuously discharged conservative chemical at different times

CHAPTER 5 MODEL APPLICATION, CASE STUDY FOR BOD AND DO

5.1 Overview

As mentioned in the above sections; this research work primarily aimed on developing analytical tool that can support industrial pollution control plans and operations on the LAR. Therefore, apart from the preliminary model verification, which was conducted on hypothetically created point sources; two of the common water quality indicators; BOD and DO were selected as a case study to demonstrate the functionality and capability of the model.

Therefore, the developed general water quality model was calibrated for simulating and predicting the effect of industrial discharged wastewater effluent on the level of BOD and DO. There was an attempt made by Nigussie (1998) for modeling BOD and DO in the river system using the modified Streeter – Phelps equations. However, due to the complexity of the river system and the inherent drawbacks of the Streeter – Phelps equation in handling hydro-geometric variation along a river and addressing non point pollutant sources along the computational domain, resulted inconsistencies. As an example, the spatial variation of the different hydro-morphological features of the river that can affect transport of contaminants was not considered in the model. Lack of flexibility for different scenarios (like inconsideration of non-point source distributed diffusing pollutants) was the other drawback observed on this model.

5.2 Theoretical Background

5.2.1 Problem Formulation

A steady state condition was considered for modeling the BOD-DO in the LAR. In this model formulation due consideration was given to the problem to be addressed and the available water quality data for calibrating the model. Therefore, the general model Equation 4.6 was reformulated for a steady state condition:

$$0 = \frac{\partial\left(A_c D_L \frac{\partial C}{\partial x}\right)}{A_c \partial x} - \frac{\partial\left(A_c U C\right)}{A_c \partial x} + \frac{dC}{dt} + \frac{S}{V} \qquad (5.1)$$

Dividing the kinetics in to two separate terms

$$\frac{dC}{dt} = rC + P \tag{5.2}$$

In which the first term on the right denotes those reactions that are linearly dependent on concentration (like biodegradation), and the second term denotes internal constituent sources and sinks (like sedimentation).

Thus, collecting like terms and simplification, an equation similar to Equation 4.1, but with the following modified coefficients for e_i , f_i , g_i and, Z_i was obtained.

$$e_i = -\left[\frac{(A_c D_L)_{i-1}}{V_i \Delta x_i} + \frac{Q_{i-1}}{V_i}\right] \tag{5.3}$$

$$f_i = \left[\frac{(A_c D_L)_i}{V_i \Delta x_i} + \frac{(A_c D_L)_{i-1}}{V_i \Delta x_i} + \frac{Q_i}{V_i} - r_i\right] \tag{5.4}$$

$$g_i = -\left[\frac{(A_c D_L)_i}{V_i \Delta x_i}\right] \tag{5.5}$$

$$Z_i = \frac{S_i}{V_i} + P_i \tag{5.6}$$

As can be seen from the above four equations, except the reaction term (*r and P)* and the point source term (*S*),all the other terms are the hydro-geometry parameters of the river. These terms were presented in the previous sections. The kinetics of BOD-DO of a river system is presented in sub-sections below.

5.2.2 Kinetics of DO

The sources of DO in a water body include re-aeration from the atmosphere, photosynthetic oxygen production from aquatic plants, denitrification and DO inputs while sinks include oxidation of carbonaceous and nitrogenous material, sediment oxygen demand and respiration by aquatic plants (Chapra, 1997).

In the study, atmospheric reaeration was the only DO source considered. On the other hand biochemical oxidations of both carbonaceous and nitrogenous material as well as river bed sediment oxygen demand were the sinks of DO considered in the model.

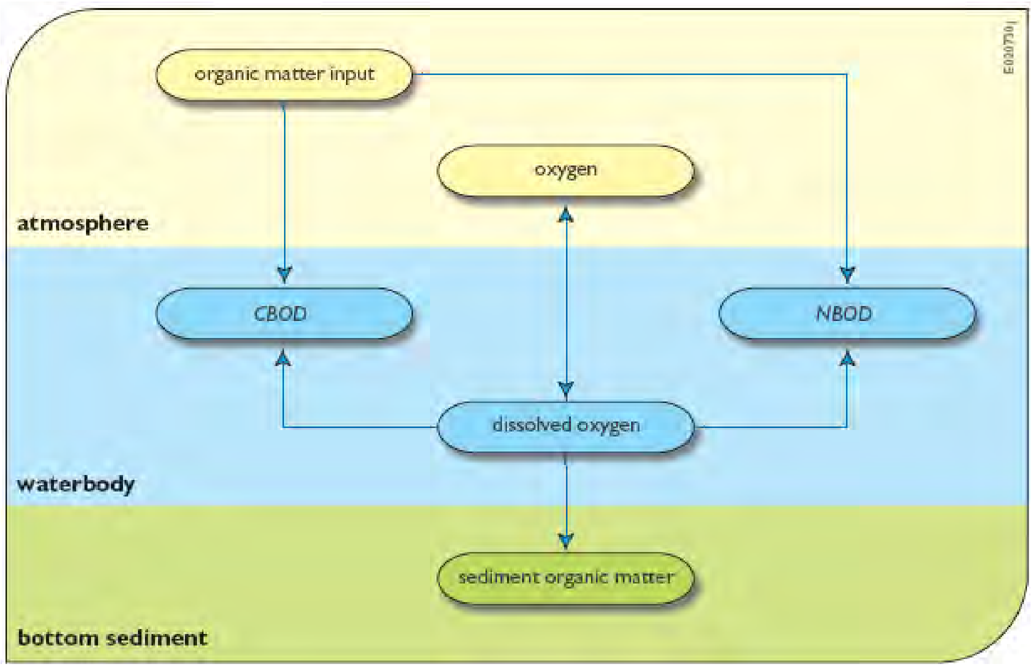


Fig. 5.1 The Dissolved Oxygen Interactions in water body, showing the decay of carbonaceous, nitrogenous and sediment oxygen demands and water body reaeration.

(Adopted from Water Resources System Planning and Management ISBN92-3-103998-UNESCO 2005 Page 391)

Thus, the kinetics of DO represented mathematically as:

$$\frac{dDO}{dt} = K_2(DO_s - DO) - K_1 L - \frac{K_4}{H} - \alpha_5 \beta_1 N_1 \qquad (5.7)$$

Where:

DO-dissolved oxygen concentration (mg/l)

K_2-rearation rate (d^{-1})

DOs – dissolved oxygen saturation concentration (mg/l)

K_4-Sedment oxygen demand (g m^{-2} d^{-1})

a_5-the rate of oxygen uptake per unit of ammonia nitrogen oxidation, mg-O/mg-N

b_1(Kn) - ammonia oxidation rate, d^{-1}

N_1- ammonia nitrogen concentration, mg-N/l

The saturation concentration, DOs, of oxygen in water is a function of the water temperature salinity (chloride concentration, Cl (g/m3)) and altitude (pressure) (Brown and Barnwell, 1987). Assuming that temperature is the significant factor for DOsat concentration in the LAR; Elmore and Hayes' (1960) expression for the DO saturation concentration, DOsat (mg/l), as a function of temperature (T, °C) and fitted by Chapra (1997) was used in the model:

$$DO_s = 14.47 - 0.3369T + 0.0035T^2 \quad (5.8)$$

Even though there is a typical range value for determination of K_2, in this model the value of the re-aeration rate was calculated internally in the model using Churchill et.al (1962) equation that relates U (mean velocity) and H (depth) of the river at each nodal as follows:

$$K_2 = 5.03 * \frac{U^{0.969}}{H^{1.673}} \quad (5.9)$$

Average literature values for rate of oxygen uptake per unit of ammonia nitrogen oxidation; a_5 =3.43 was taken in all section of the river and ammonia oxidation rate b_1 was taken, the value was corrected for each nodal point during the calibration of the model.

Value for the sediment oxygen demand rate (K_4) was determined for each nodal point based on the pollution statues of the river (based on previous studies) and ranged between 1 and 10 g m^{-2} d^{-1} and allowed to be calibrated.

5.2.3 Kinetics of Carbonaceous BOD

A first order reaction assumption best describes de-oxygenation of ultimate carbonaceous BOD in a stream (Brown and Barnwell, 1987). In the study the same assumption was applied. Beside this oxygen demanding related removal of CBOD, the study also takes into account additional CBOD removal due to sedimentation, which do not exert an oxygen demand.

Thus, the kinetics for removal of COBD represented mathematically by:

$$\frac{dL}{dt} = -k_1 L - k_3 L$$

Where:

$$L = \text{the concentration of ultimate carbonaceous BOD, mg/lt} \qquad (5.10)$$

$$k_1 = \text{BOD decomposition rate} \left(d^{-1}\right)$$

$$k_3 = \text{the rate of loss of Carbonaceous BOD due to setting} \left(d^{-1}\right)$$

As the model input data was expressed in the 5-day BOD (Appendix C), these 5-day BOD value was converted to ultimate BOD. For the first order de-oxygenation assumption, the conversion represented as (Chapra, 1997):

$$L = \frac{BOD_5}{\left(1 - \exp\left(5 * K_{1_{20}}\right)\right)}$$

Where:

$$BOD_5 = 5\, days\, biochemical\, oxygen\, demand, mg/lt \qquad (5.11)$$

$$k_1 = BOD\, decomposition\, rate \left(d^{-1}\right)$$

K_1; BOD decomposition rate and K_3; the rate of loss of carbonaceous BOD due to settling were the two parametric values of requirement. In the model, literature average values were taken and manipulated during the calibration based on observed BOD values. Typical ranges of these reaction coefficients and the nodal values used in this study were attached in Appendices.

5.2.4 Temperature Dependence of Kinetic Terms

Except a_5, rate of oxygen uptake per unit of ammonia nitrogen oxidation, all the other kinetic rate coefficients are temperature dependent and data were represented for 20 ^{O}C condition. These coefficients were input at the given 20 ^{O}C condition and are then internally corrected in the model using the following relation:

$$X_t = X_{20} * \theta^{(T-20)} \qquad (5.12)$$

where

Xt-The value of the coefficient at the local temperature (T)

X20-The value of the coefficient at the standard temperature (20Oc)

Θ-An empirical constant for each reaction coefficient

The value of the temperature correction factor was obtained from literature as shown in Appendix-A2 (C).

5.3 Model Calibration

5.3.1 General

The above literature values and empirically calculated rate constants and the longitudinal dispersion coefficients of the river calculated in the previous chapter of the paper were the calibrated model input parameters.

For calibration of the model input parameters, the modified Streeter – Phelps equation for determination of DO deficit, Eq. 5.13, was used. The numerical model used for modeling DO in river was used.

$$D(x) = D(0)e_a - \left(\frac{K1+K3}{K_2-(K_1+K_3)} Lo\right)(e_c - e_a) + \left(\frac{Kn}{K_2-K_n} No\right)(e_n - e_a) + \frac{S}{K_2 H}(1-e_a) \qquad (5.13)$$

Where:

- D(x) = predicted dissolved oxygen deficit at the river’s temperature, mg/l
- D(0) = initial dissolved oxygen deficit, mg/l
- Lo = initial ultimate CBOD at the beginning of each reach or sub reach, mg/l

- No = initial NBOD, at the beginning of each reach or sub reach, mg/l
- S = sediment oxygen demand, mg/l; = K4/H
- K1 = deoxygenation coefficient for CBOD at the river's temperature, day-1;
- K3 = overall CBOD loss due settling, day-1;
- Kn = deoxygenation coefficient for NBOD at the river's temperature, day-1;
- e_c= exp(-(K_1+K_3)t)
- e_a= exp(-(K_2)t)
- e_n= exp(-(K_n)t)
- H = depth of flow, m
- V = velocity of flow, m/s.

On the other hand the DO deficit can be determined using the numerical method, first by determining the DO iteratively and deducting the result from the saturation DO value. The coefficients e_i , f_i g_i and Z_i for DO will become:

$$e_i = -\left[\frac{(A_c D_L)_{i-1}}{V_i \Delta x_i} + \frac{Q_{i-1}}{V_i}\right] \tag{5.14}$$

$$f_i = \left[\frac{(A_c D_L)_i}{V_i \Delta x_i} + \frac{(A_c D_L)_{i-1}}{V_i \Delta x_i} + \frac{Q_i}{V_i} + K_2\right] \tag{5.15}$$

$$g_i = -\left[\frac{(A_c D_L)_i}{V_i \Delta x_i}\right] \tag{5.16}$$

$$Z_i = K_2 DOS - K_1 L_i - 3.43 K_n N_i \tag{5.17}$$

Therefore, iterative and optimization MATLAB programs were developed. The developed model program determines the DO iteratively, determines the DO deficit using Eq. (5-13) and optimizes the difference between the results by adjusting the 7 model input parameters (i.e. Dl, K1, K2, K3, K4, Kn and Kc,20).

The procedure adopted for the model calibration process is shown in Fig 5.2.

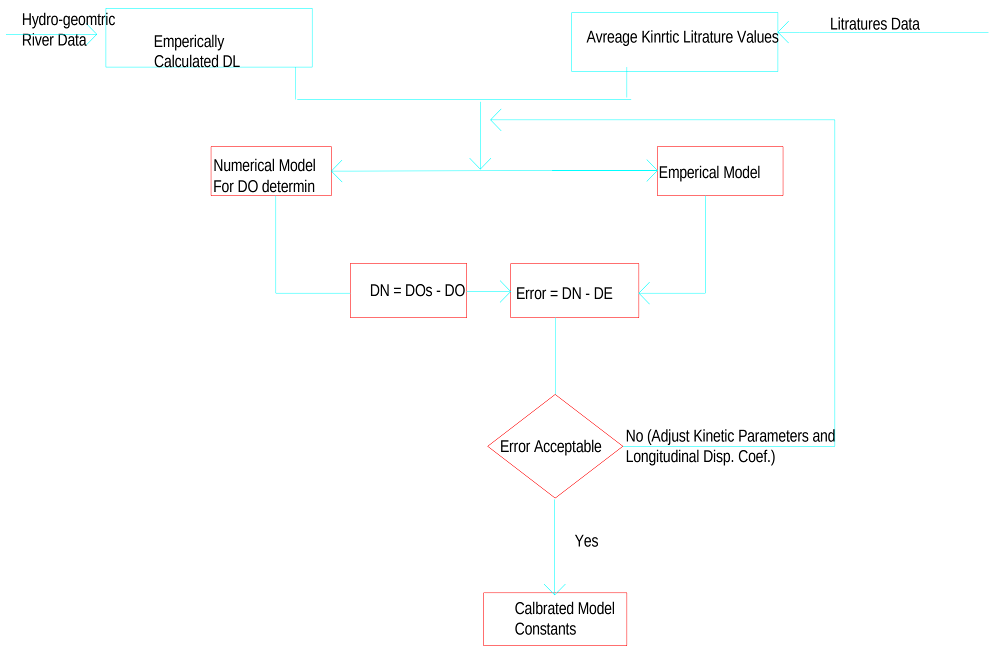


Fig. 5. 2 Schematic Description of the Model Calibration Process

5.3.2 Data Organization

5.3.2.1 Location of Industrial Pollutants

Table 5.1 describes industries that can be considered as potential point source pollutants of the LAR (Mohamed, 2002).

Initially, the study was planned to include all the point source industrial pollutants, however the time and financial constraint for collecting model calibration data as well as lack of secondary data that fits the model objective, limited between the second point source industrial pollutant (Edible Oil Factories) and the 6th industrial pollutant (Addis Ababa Abattoirs –inclusively). In addition to this, as the wastewater discharge from National Tobacco is insignificant only the four industrial pollutants were considered in calibrating the model. Beside the four industrial pollutants, the perennial tributaries of the LAR in the calibrated section were also considered as a point source in calibrating the model parameters.

5.3.2.2 Reaches and Sub-Reaches of the River

Based on the location of these six point source pollutants, the calibrated section of the river was divided into six sub-reaches. The classification of the river in sub reaches was undertaken with the objective of utilizing the capability of Eq. 5.13, and to fit the model with the structure of the secondary water quality data available for the calibration work. Therefore, the river section classification undertook during the water quality data collection was adopted with some modifications.

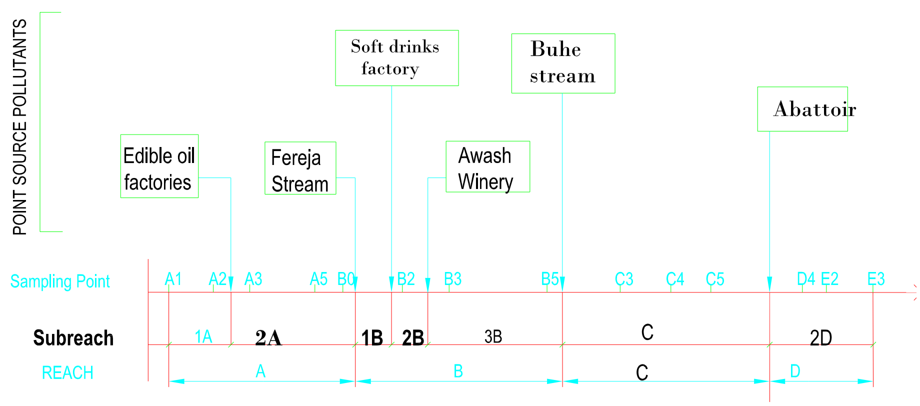


Fig. 5. 3 Reaches and Sub-Reaches of the calibrated section of the river

No	Name of Point Source	Location	
		X (Easting)	Y (Northing)
1	Ethiopia Marble Factory	468800	1000708

2	Edible Oil Factories	468764.2	998690.7
3	East Africa Bottling	469974.026	996239.091
4	Awash Winery	469970.196	995967.146
5	National Tobacco	470781.907	994821.198
6	Addis Ababa Abettors	471969	993240
7	National Alcohol and Liquor Factory (Mekanisa Branch)	4711855.463	992528.99
8	Ethio-Pickling and Tanning Factory	472393.965	989855.233
9	Waliya Tannery	473317.52	989150.444

Table 5. 1 Name and Location of Industrial Point Sources Considered in the Study

The calibrated section of the river is shown in Fig. 5.4.

5.3.2.3 Point Source Discharge Quality and Quantity

Fig. 5.5 displays interaction of the six sub-reaches with the main river route.

The core for using Eq. 5.13, beside the rate constants and hydrological data, is the concentration of the CBOD, NBOD and DO deficit at the head of the river sub reach. A material balance between the point source and the waste load from upstream reach was conducted and the initial CBOD (Lo), NBOD (No) and DO deficit (Do) was calculated for each sub reach.

The flow rates of the wastewater discharge from each of the point source industrial pollutants and concentration of BOD, DO and NH_3-N in each industrial effluent and the tributaries were obtained from Nigussie's (1998) work and attached in Appendix part of the Thesis.

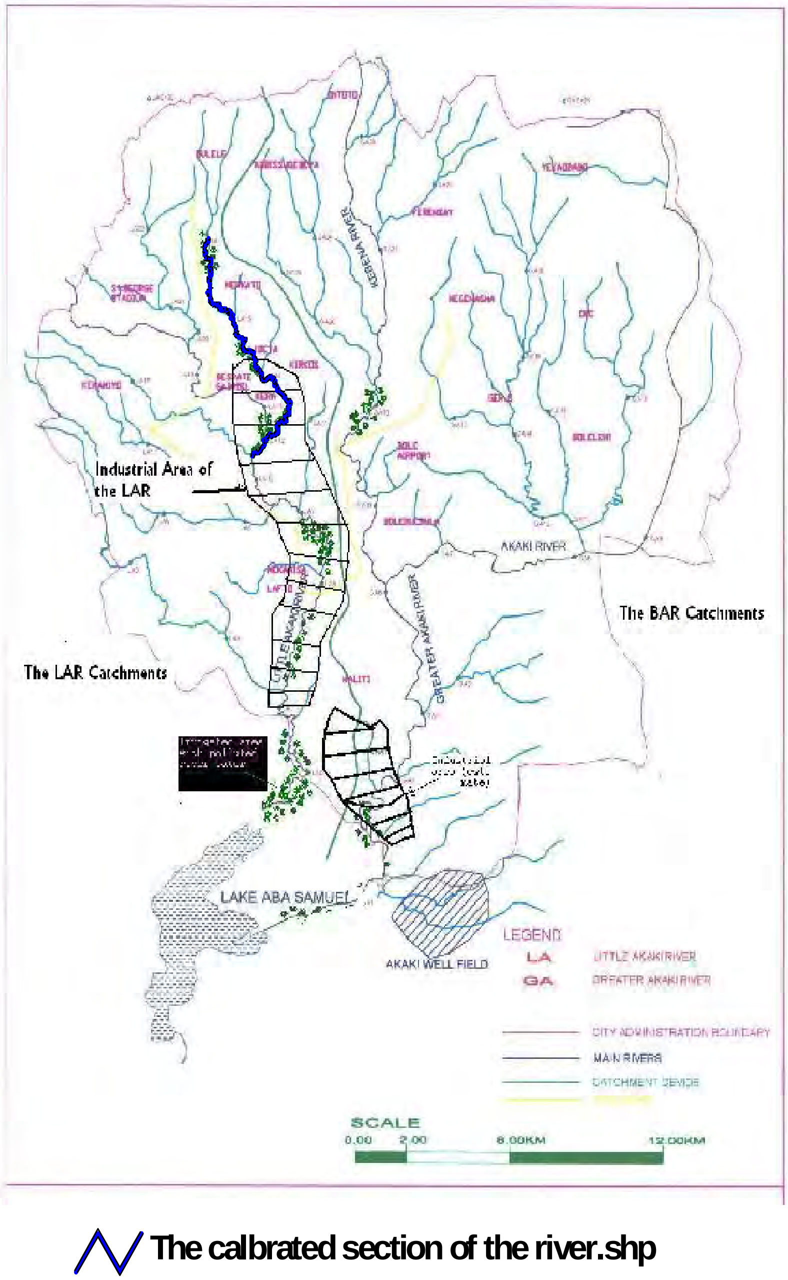


Fig. 5. 4 The Calibrated section of the LAR

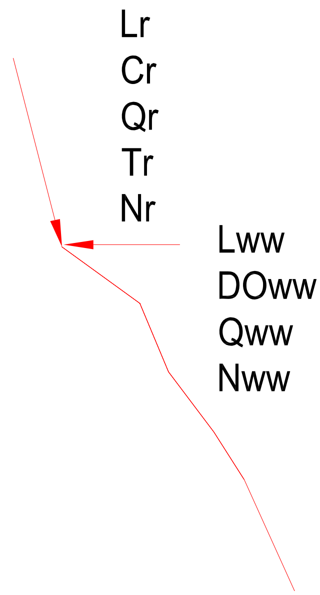


Fig. 5. 5 Schematic description of the sub reaches with point DO demanding point sources (Conceptual Representation of the Model Calbration)

5.3.3 The Model Calibration Programme

As mentioned before the model calibration programme comprises an iterative and optimization model programme. The MATLAB function file DATA CALBRATOR (Appendix D-2a), loads all hydrological data and the literature kinetic values, calculates the numerical model equation estimated coefficients, and solves the DO at each nodal point iteratively for each sub reach. The DO result deducted from DOs to find the DO deficit at each nodal point. On the other hand the empirical equation, Eq. 5.13, determines the DO deficit directly.

The m-file MAIN DATA CALBRATOR (Appendix D-2b) uses the built in MATLAB optimization function, fsolve. This optimization function calls the calibrator; the calibrator use the initial empirically calculated longitudinal dispersion coefficient and kinetic literature values and calculates the DO deficit using the numerical and analytical relations were then compared to each other and the error was calculated. The function fsolve do its optimization routine to minimize the error by varying the 7 model input parameters to be calibrated.

Sub Reach	Total Length (m)	Calculated Water Quality Values (mg/l)			
		BOD	NBOD	DO	DO-deficit
2A	3480	31.35	2.6	6.9	3.406
1B	400	16.243	9.235	3.92	6.617
2B	320	15.4	9.41	3.62	6.686
3B	2480	128.26	20.264	1.4	8.906
C	3800	55.45	19.22	3.8	6.284
2D	2300	172.34	20.3	0.585	8.882

Table 5. 2 Calculated Water Quality Values at the head sub reaches

5.3.4 Calibration Results

Calibrated longitudinal dispersion coefficient of the river and the kinetic parameters that influence the fate of BOD-DO in the river system were displayed in the Appendix-A.

Fig. 5.6, 5.7 and 5.8 shows the curve fit between the model results and the empirical solution at three different optimization steps for each of the six sub reaches.

As we can see from the figures, initially using the literature average values of the kinetic rate constants and the empirically calculated longitudinal dispersion coefficients the model simulation and the simulation using the modified Streeter – Phelps equation shows discrepancy. Despite of the similar model in put parameters used and the favorable condition to model situation using the empirical equation, this discrepancy most importantly associated with the use of inadequate model input parameters. As we can see from the results, there is both under and over estimation of the DO deficit using the model.

Fig. 5. 6 Initial Curve Fittings Using Average Literature Values

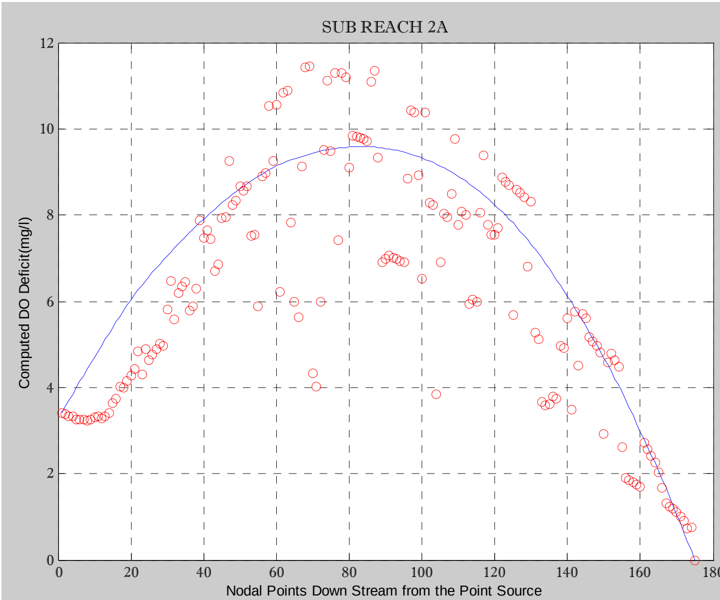


Fig. 5. 6a: For Sub-Reach 2A

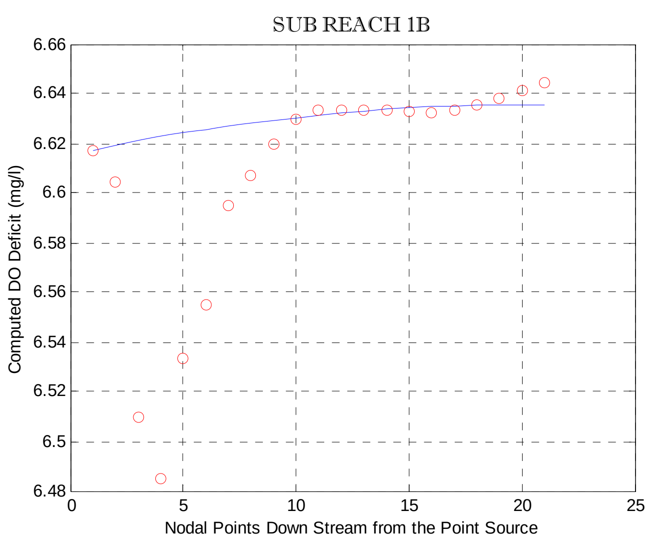


Fig. 5. 6b: For Sub-Reach 1B

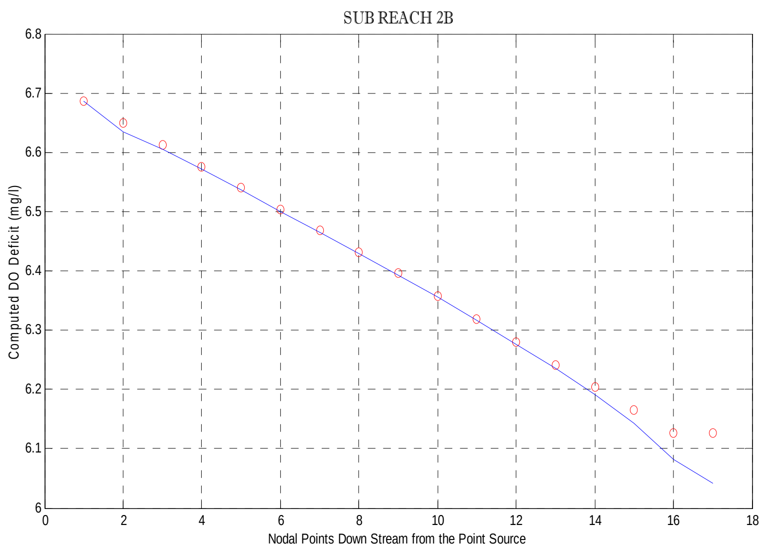


Fig. 5. 6C: For Sub-Reach 2B

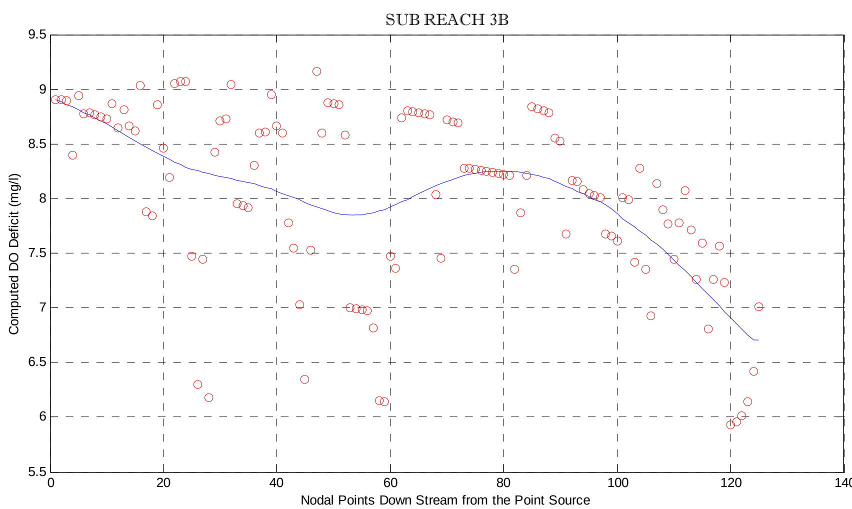


Fig. 5. 6d: For Sub-Reach 3B

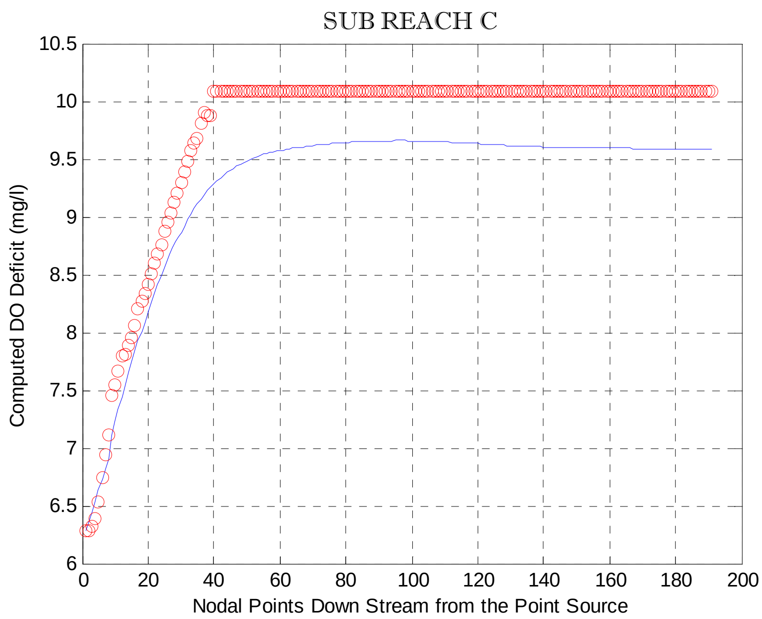


Fig. 5. 6e For Sub-Reach C

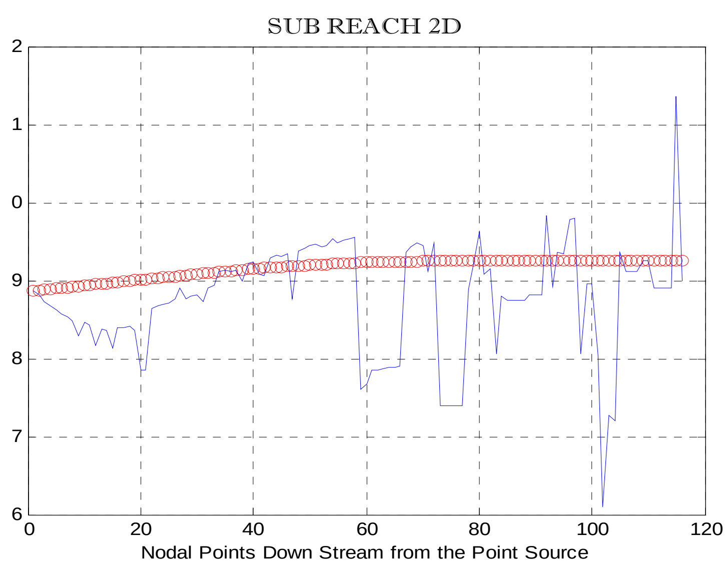


Fig. 5. 6f For Sub-Reach 2D

Fig. 5. 7 Improved Curve Fittings After Adjusting the Parameters to be Calibrated

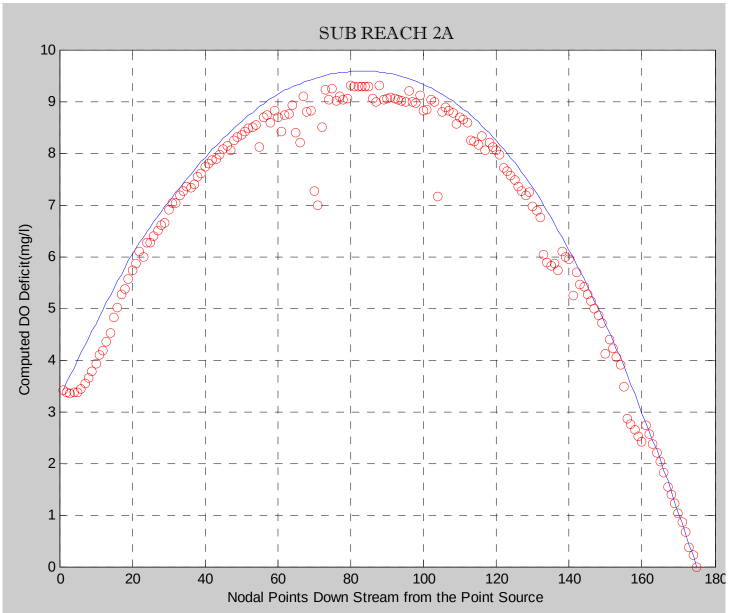


Fig. 5. 7a: For Sub-Reach 2A

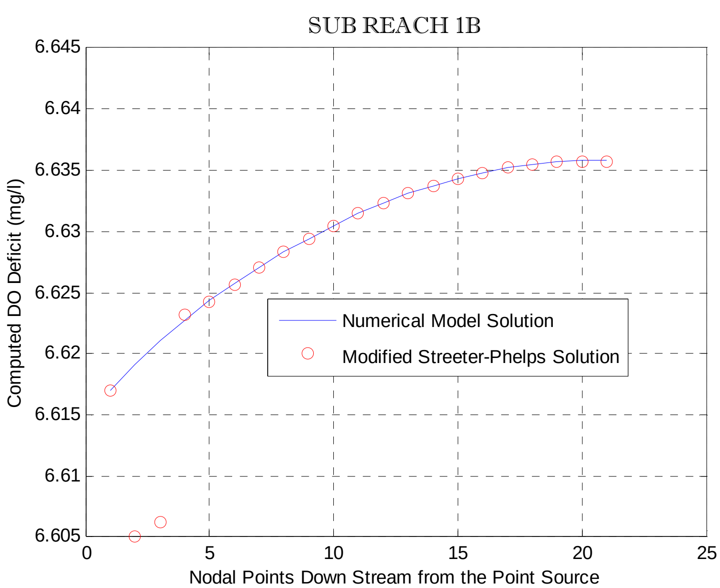


Fig. 5. 7b: For Sub-Reach 1B

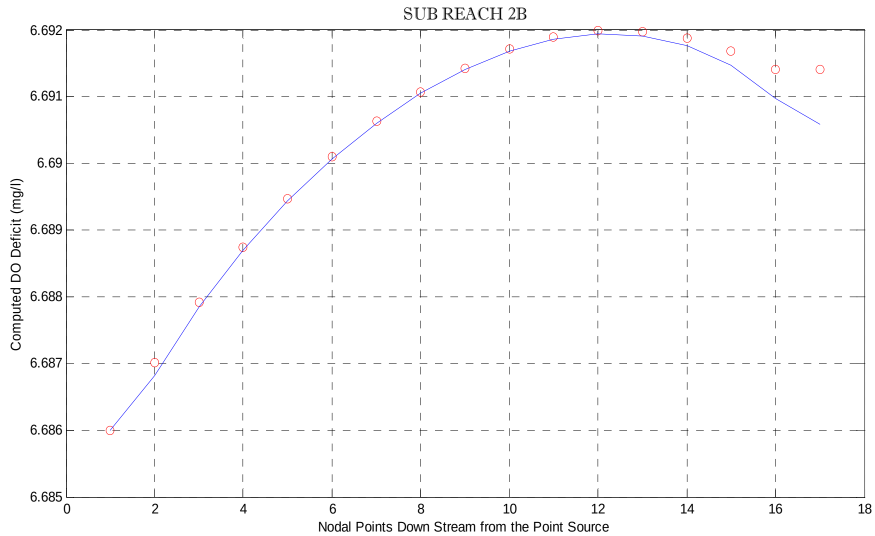


Fig. 5. 7C: For Sub-Reach 2B

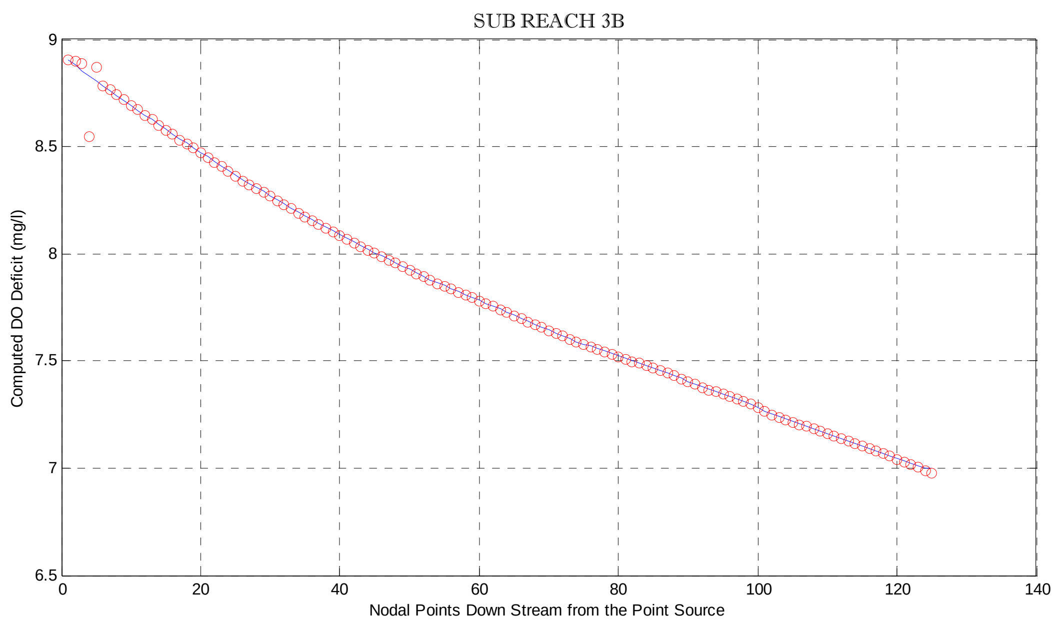


Fig. 5. 7d: For Sub-Reach 3B

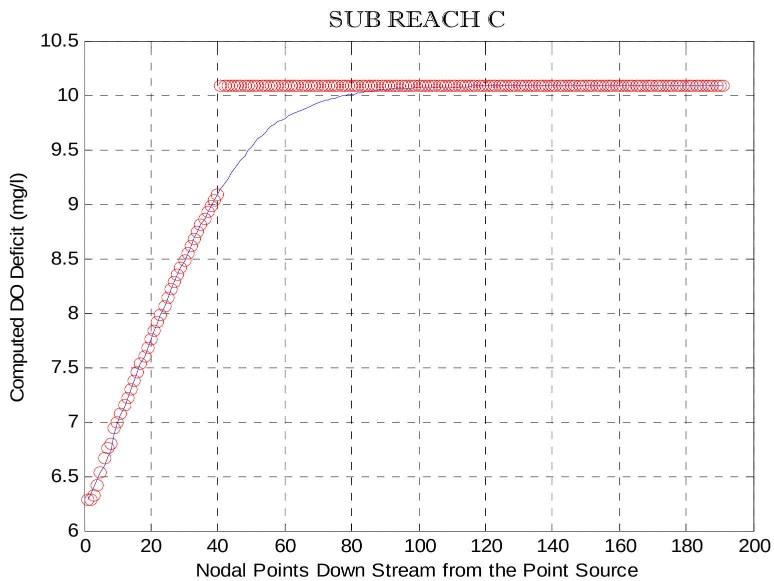


Fig. 5. 7e: For Sub-Reach C

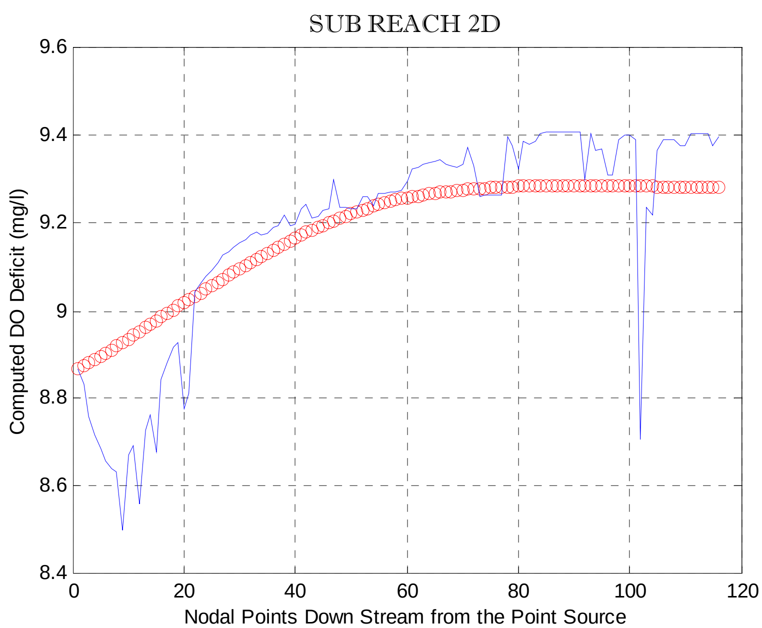


Fig. 5. 7f: For Sub-Reach 2D

The developed calibration model tends to minimize the difference between the numerical model simulation result and the result from the modified Streeter – Phelps equation result by varying the model input parameters to be calibrated. As it was shown on the improved curve fitting graphs as it was observed during the simulation study work, the initially observed discrepancies curves were improved.

The final curve fit results, below represent the numerical model simulation and the modified Streeter – Phelps equation result for predicting the DO deficit caused by industries and tributaries. The simulation at this stage of the calibration study uses the values of the finally calibrated model input parameters. As it was shown in Fig. 5.8 the curve fit graphs prevail that except for the minor discrepancy observed on sub reach C; in all of the other 5 sub reaches the simulation results are in good agreement.

However, depending on the length of the sub reaches and the sub reach complexity for representing it mathematically; the total time (the number of iteration) required for reaching this final result varies from sub reach to sub reach. The other important issue in relation to this calibration study is the initialization of the numerical model for iteration. Particularly, for the longest sub reaches; the iteration should be started by assigning a random concentration values, otherwise the calibration work can take 6-10 hrs iteration time even using high speed computers.

For this calibration study, the performance of the calibration was measured by calculating the absolute error value of the difference between the results obtained from the simulations. For this a sub-program was included within the main calibration program. At the end of each iteration step of the calibration process, this sub-program calculates the difference between the simulations at each nodal point and displays the result spatially. In the study these absolute error value were used as measure of the performance in the model calibration. Fig. 5.9 shows the spatial distribution of these calculated absolute error value results at the final calibration stage of the model.

Fig. 5. 8 Final Curve Fittings After Using Calibrated Model Parameters

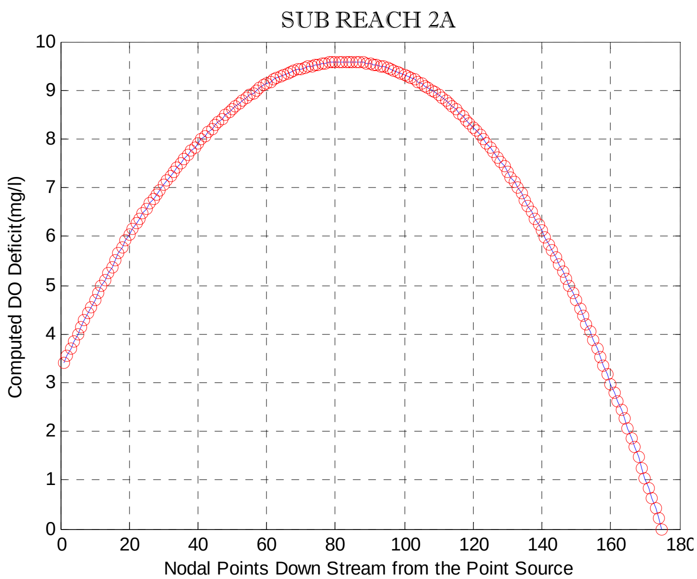


Fig. 5. 8 a: For Sub-Reach 2A

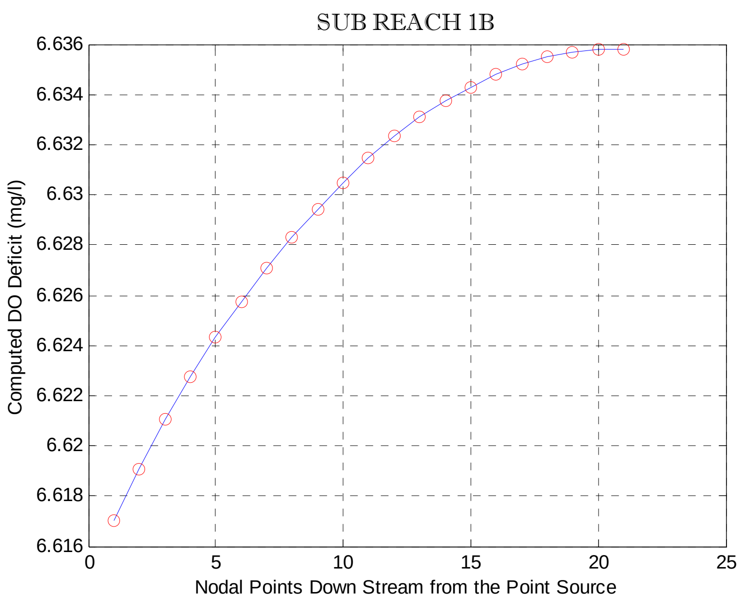


Fig. 5. 8 b: For Sub-Reach 1B

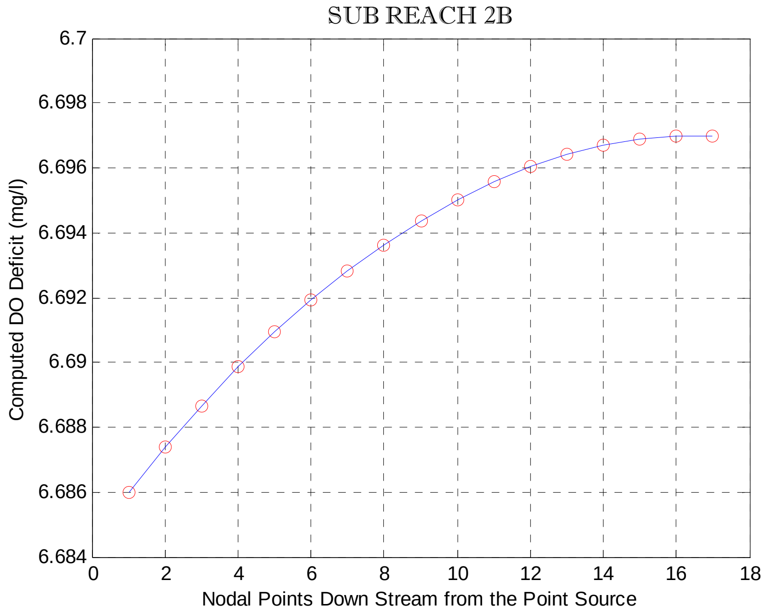


Fig. 5. 8 c: For Sub-Reach 2B

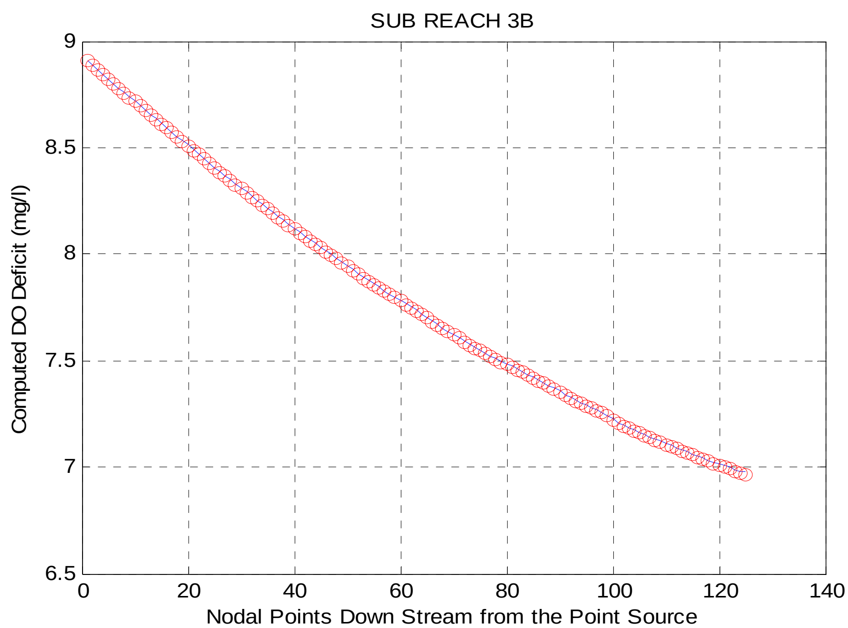


Fig. 5. 8 d: For Sub-Reach 3B

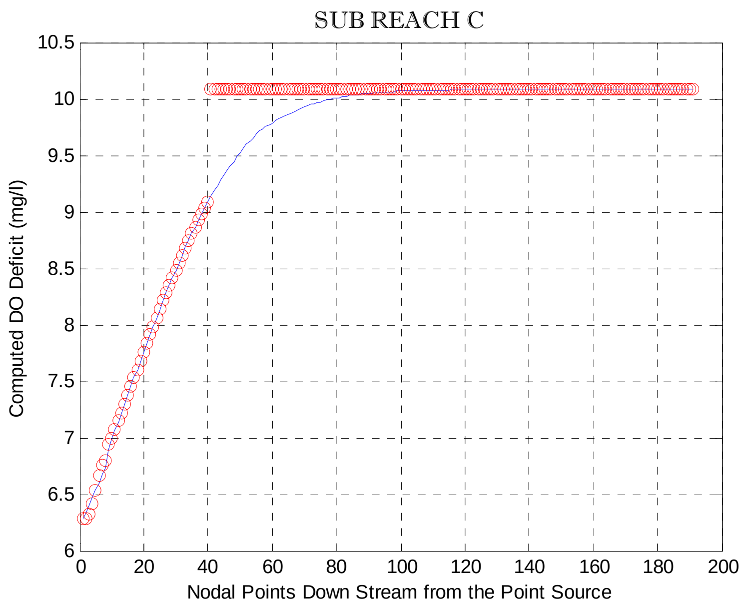


Fig. 5. 8 e: For Sub-Reach C

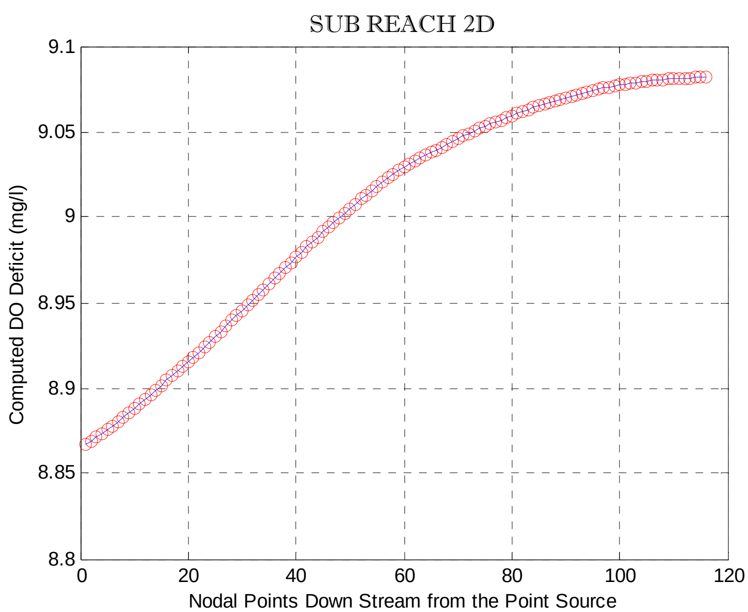


Fig. 5. 8 f: For Sub-Reach 2D

Fig. 5. 9 Absolute Error Distribution and Model Calibration Performance Evaluation

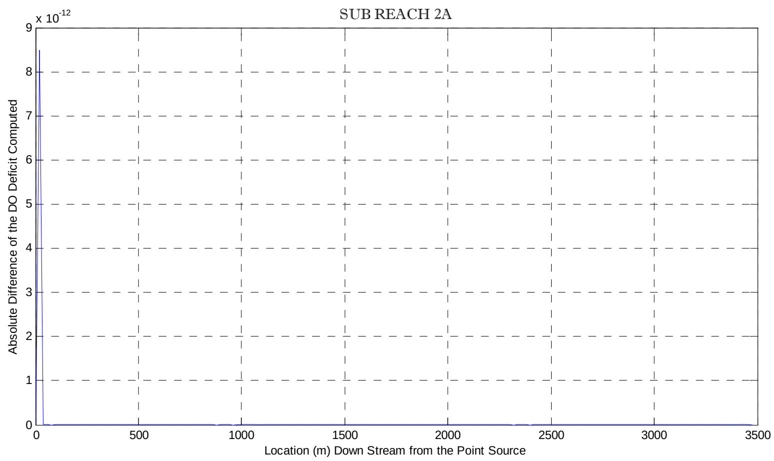


Fig. 5. 9 a: For Sub-Reach 2A

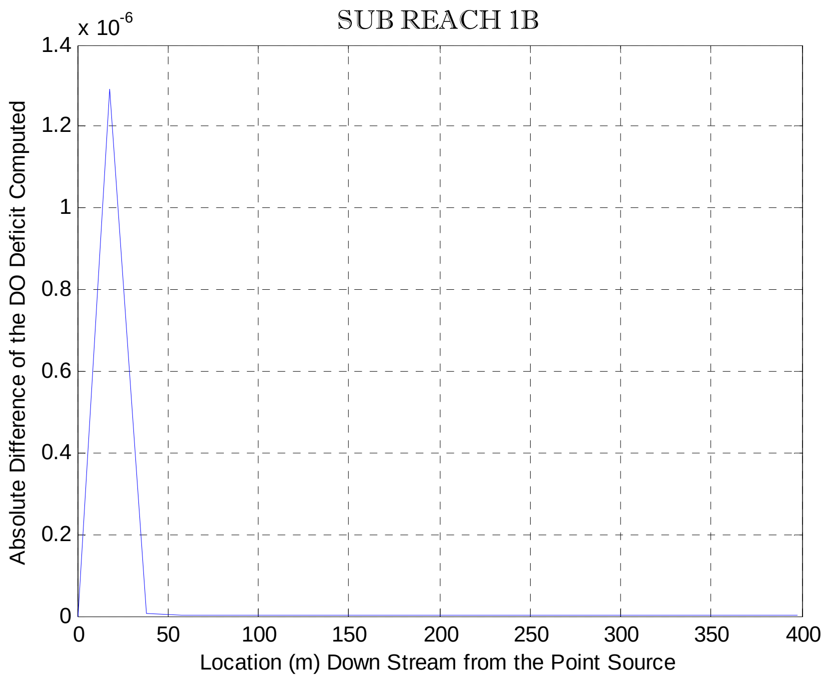


Fig. 5. 9 b: For Sub-Reach 1B

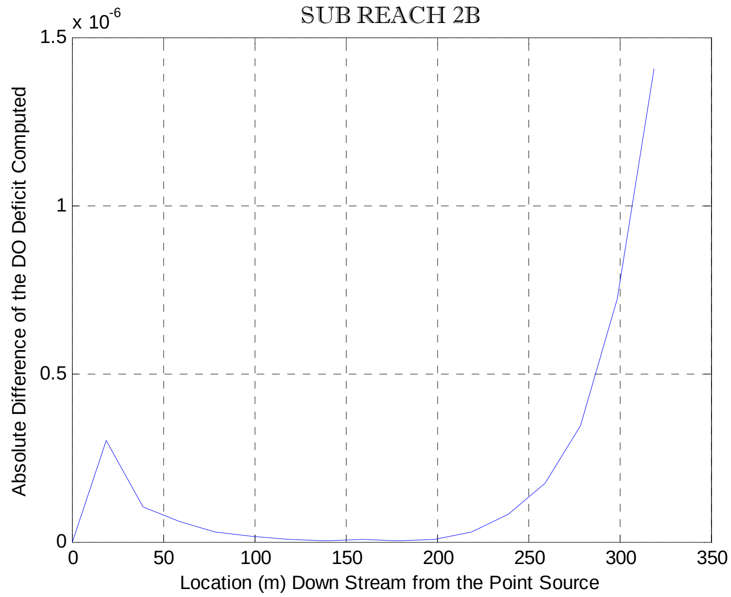


Fig. 5. 9 c: For Sub-Reach 2B

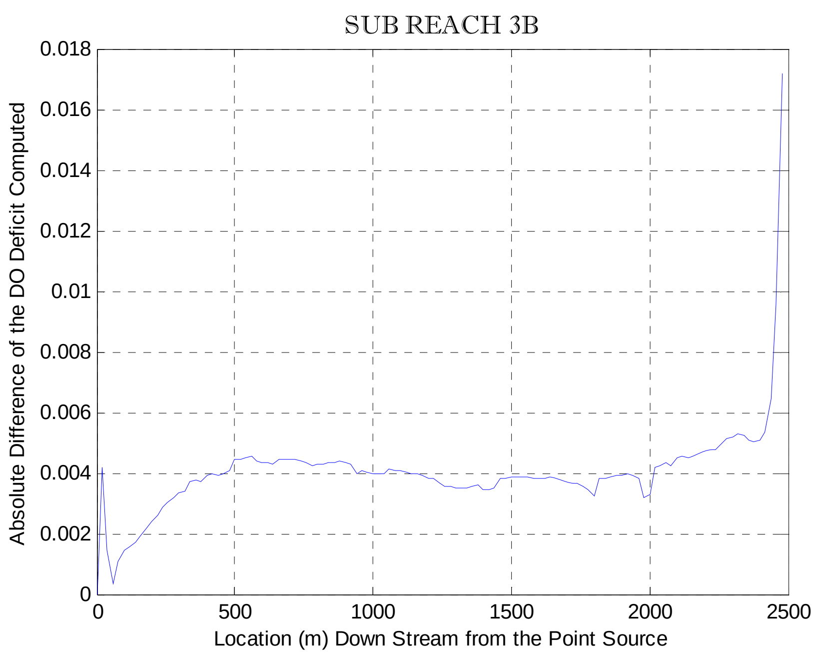


Fig. 5. 9 d: For Sub-Reach 3B

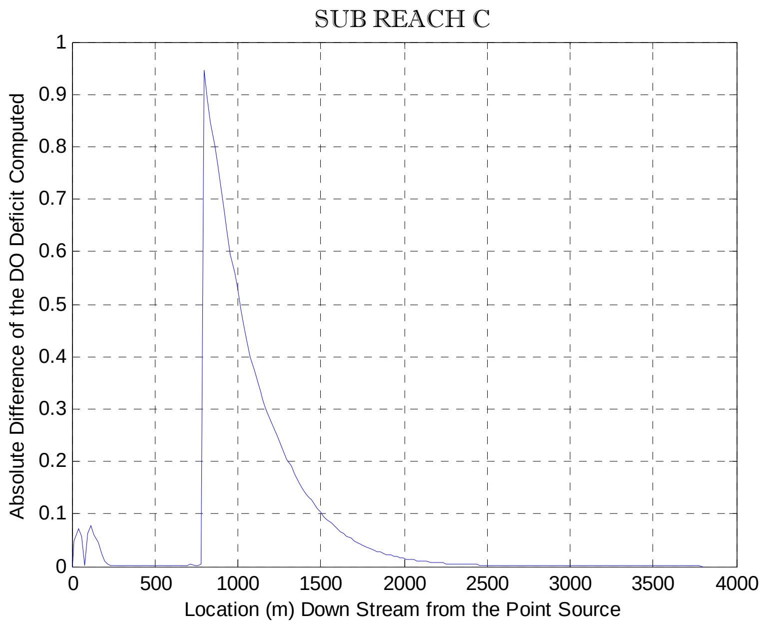


Fig. 5. 9 e: For Sub-Reach C

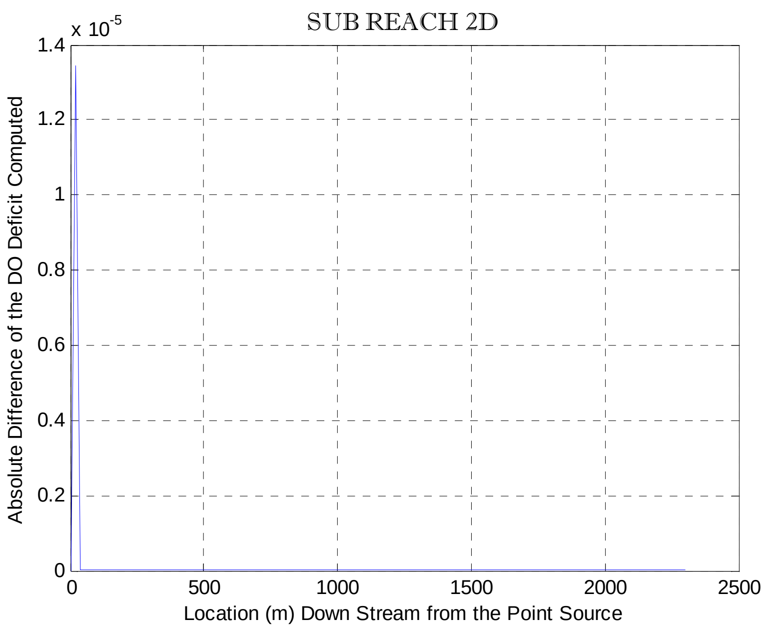


Fig. 5. 9 f: For Sub-Reach 2D

These model calibration performance measurement results indicate that, except for the case in sub reach C, the value ranges from 1E-05 to 1E-12. The value for sub reach C is with in a range of 0 to 1. In addition to this, it was also observed that maximum value prevailed at the start of the sub reaches, where the boundary conditions were assigned constant. In this constant DO value allocation the empirical model under estimates effect of dispersion and a higher error value may result with the numerically predicted one. This might be the main reason for the observed higher error value in sub reach C, where the DO deficit is constant after some sections.

5.4 Model Application Example

One of the drawbacks of the Streeter – Phelps equation is its incapability for determining non-point source caused DO deficit and the effect of diffusive CBOD on the river water quality. As part of the study work, the calibrated model input parameters were used for determination of the background DO deficit (Db) of the river and the non point sources distributed CBOD wastes.

5.4.1 Predicting Db

The total Streeter – Phelps equation that consider non point source caused DO deficit is given by the following equation (Chapra, 1997):

$$D(x) = D(0)e_a - \left(\frac{K_1 + K_3}{K_2 - (K_1 + K_3)} L(x)\right)(e_c - e_a) + \left(\frac{K_n}{K_2 - K_n} N(x)\right)(e_n - e_a) + \frac{S}{K_2 H}(1 - e_a) + D_b \qquad (5.17)$$

where

- Db = background dissolved oxygen deficit, mg/l;

Similar to the model calibration, for predicting the background DO deficit, iterative and optimization model programmes were used. The MATLAB function file Db_PREDICTOR (Appendix D-3a) loads the calibrated parameters, all hydrological data, and solves the DO at each nodal point iteratively for each sub reach using measured DO at different nodal points. The DO result deducted from DOs to find the DO deficit at each nodal point. On the other hand, the total Streeter-Phelps's equation, Eq. 5.17 determines the DO deficit directly assuming Db to be zero.

The m-file MAIN Db_PREDICTOR (Appendix D-3b) uses the built in MATLAB optimization function, fsolve. This function calls the predictor, the predictor use the measured DO values as boundary condition and determines the nodal values; then, the result would be deducted from DOs to determine the DO deficit at each nodal point. The result from Eq. 5.17 and the numerical result compared to each other, and the error, are calculated. The optimization function fsolve do its optimization routine to minimize the error by varying the background DO deficit.

In this background DO deficit prediction, intermediate measured DO values per each sub reach, including the boundary conditions, was used for determining the distribution of the DO in the river system.

Fig. 5.10 shows the correlation analysis between the model prediction for DO and the measured DO based water quality data targeted values for each sub reaches.

From the correlation analysis result, it was observed that the model predicted DO deficit is in a good agreement with the targeted DO deficits which are calculated using the secondary water quality data. As it was shown in Fig. 5.10; these predicted and targeted values are in a good agreement for all the sub reaches considered in the study.

As it was displayed in the figures the correlation between these targeted and model predicted values can be fitted linearly. All these correlation analysis results displayed in this paper were reached after a number of model iteration steps.

Depending on the length of the sub reach (i.e. the number of nodal points to be analyzed) by the model, the number of iterations required to reach these final correlation result vary from sub reach to sub reach. For example; the required final correlation result for sub reach 2B, the shortest sub reach; was reached after 5 iteration steps; while up to 30 steps were required for the longest sub reach C.

As it was mentioned above, the fundamental objective of this model application example was to use the model for predicting the concentration of the non point source related background DO deficits at different locations of the river. Thus, Fig. 5.11

shows the spatial distribution of these non point source related DO deficit in each sub reaches.

Fig. 5.10 Correlation Analysis for Prediction of Background DO Deficit

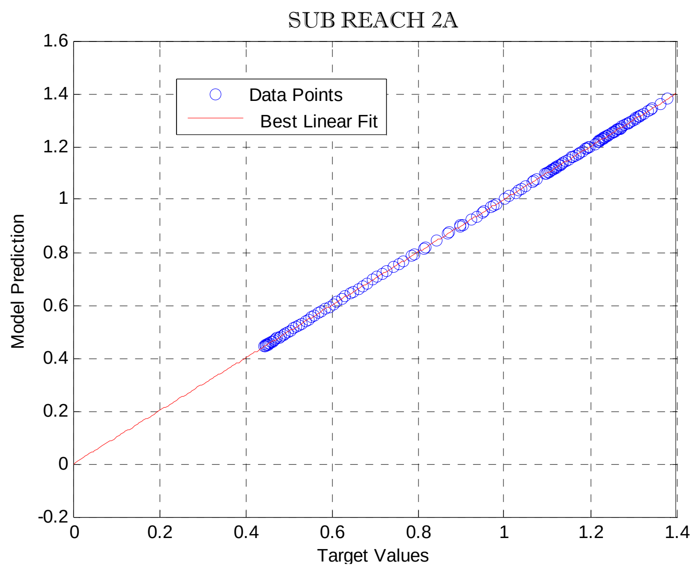


Fig. 5. 10a: For Sub-Reach 2A

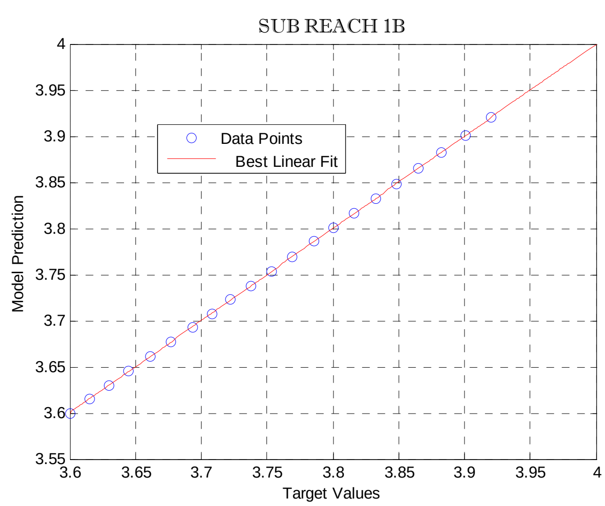


Fig. 5. 10b: For Sub-Reach 1B

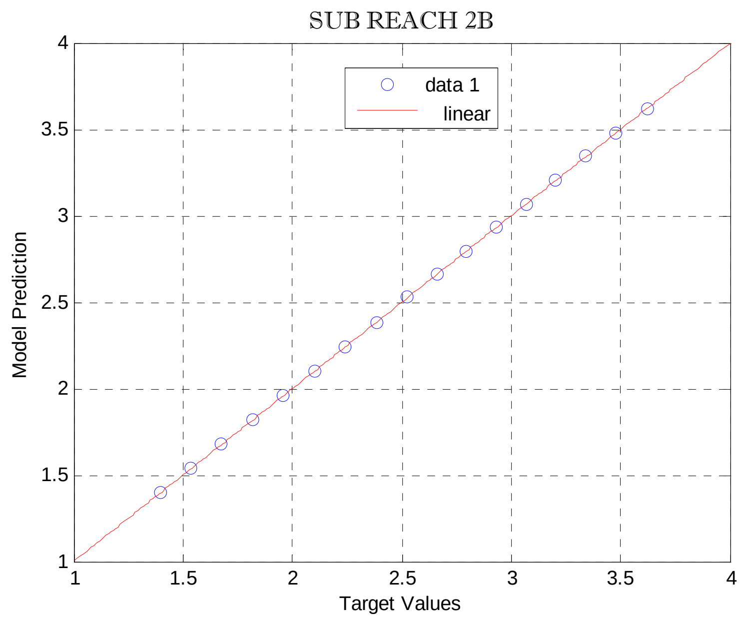


Fig. 5. 10c: For Sub-Reach 2B

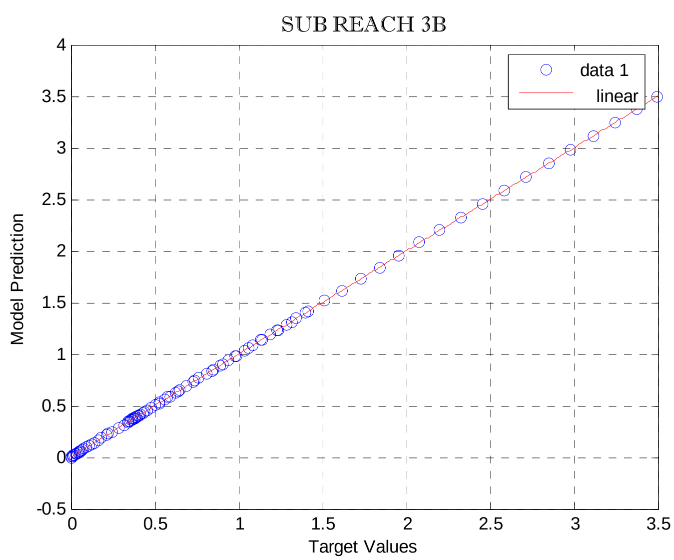


Fig. 5. 10d: For Sub-Reach 3B

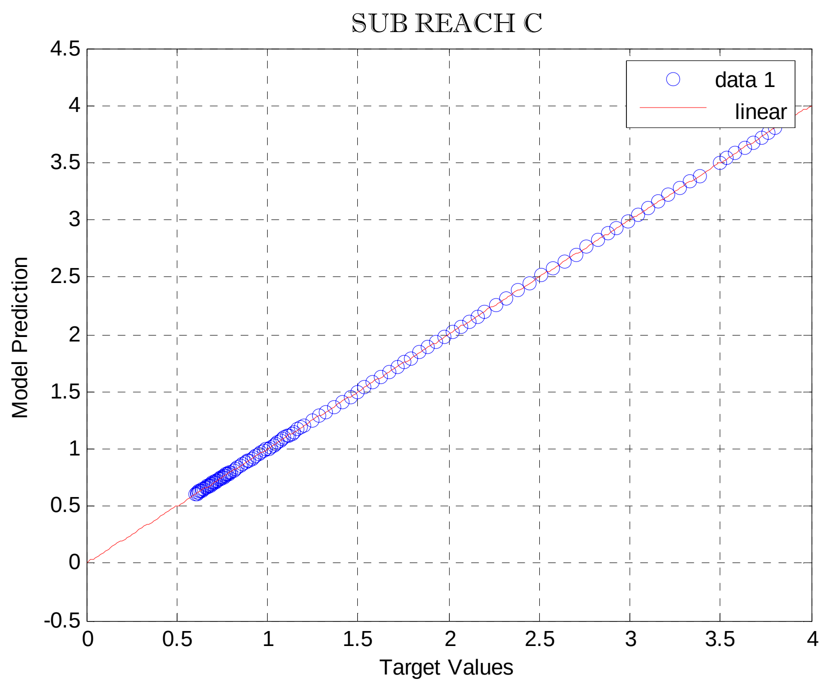


Fig. 5. 10e: For Sub-Reach C

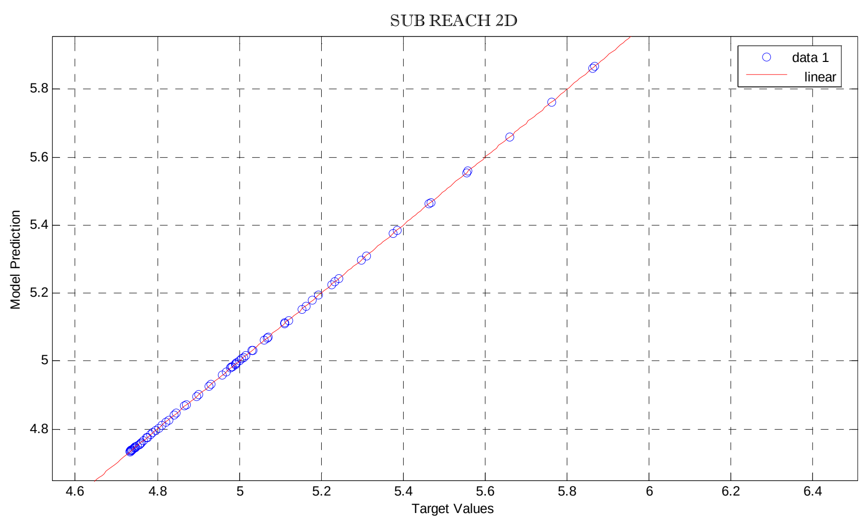


Fig. 5. 10f: For Sub-Reach 2D

Fig. 5.11 Spatial Distribution of the Background DO deficit in the LAR

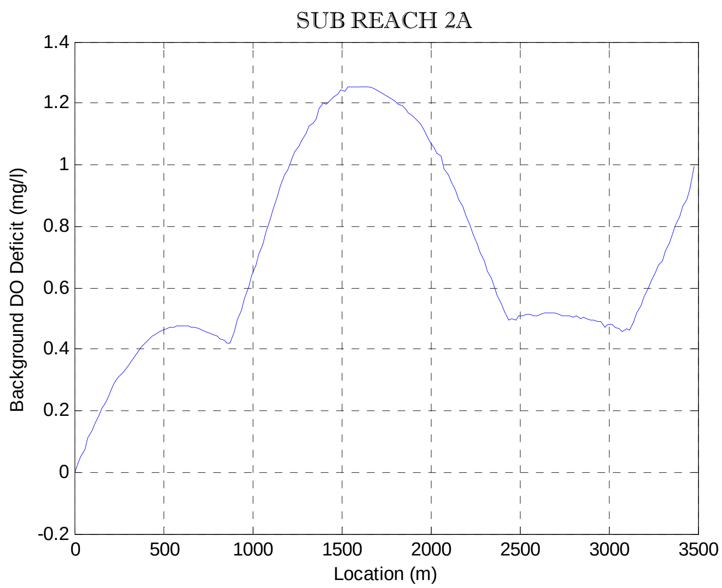


Fig. 5. 11a: For Sub-Reach 2A

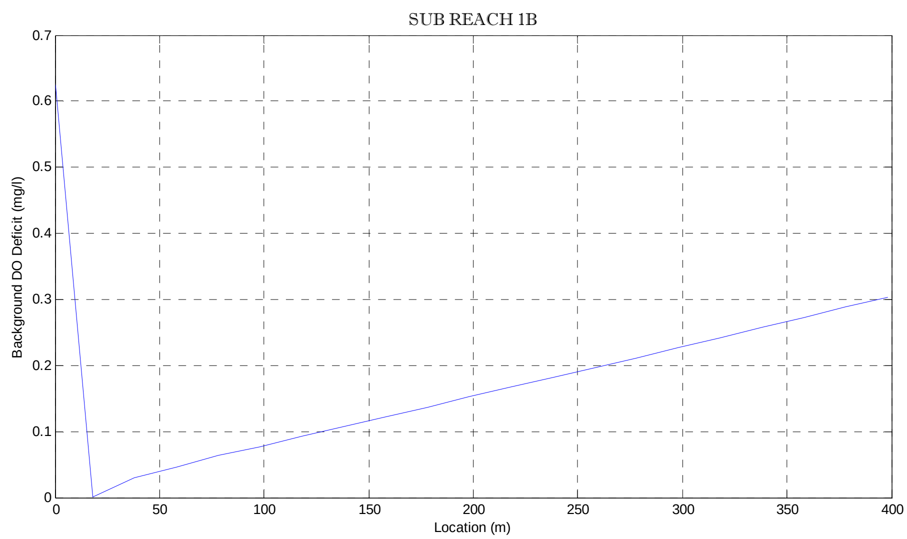


Fig. 5. 11b: For Sub-Reach 1B

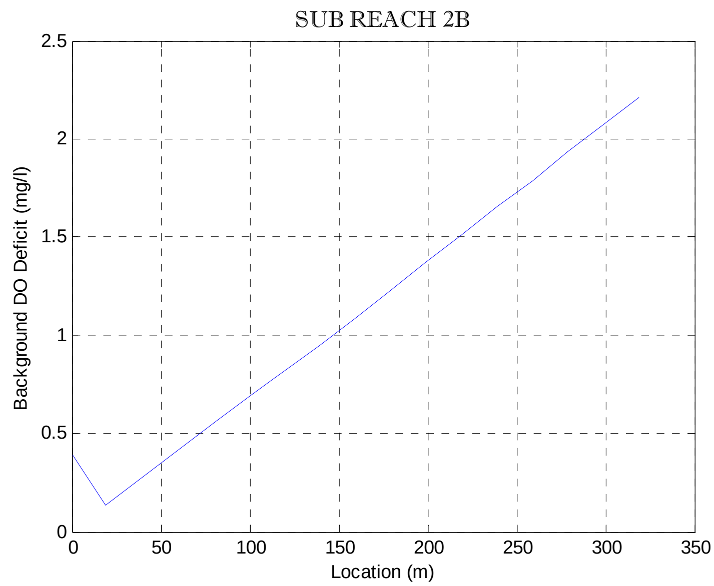


Fig. 5. 11c: For Sub-Reach 2B

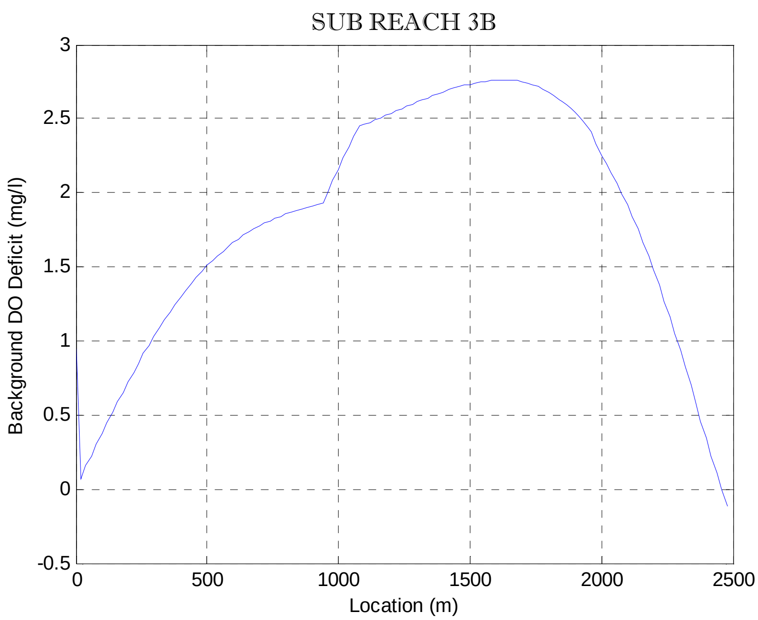


Fig. 5. 11d: For Sub-Reach 3B

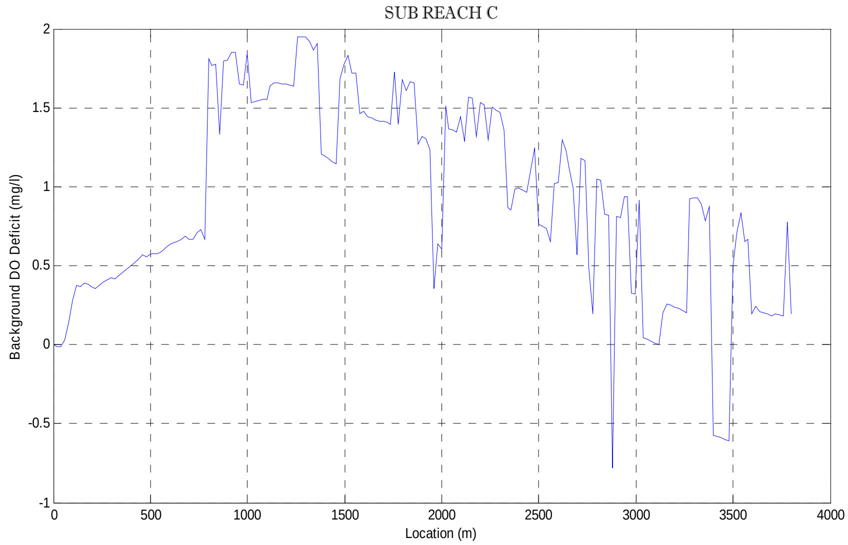


Fig. 5. 11e: For Sub-Reach C

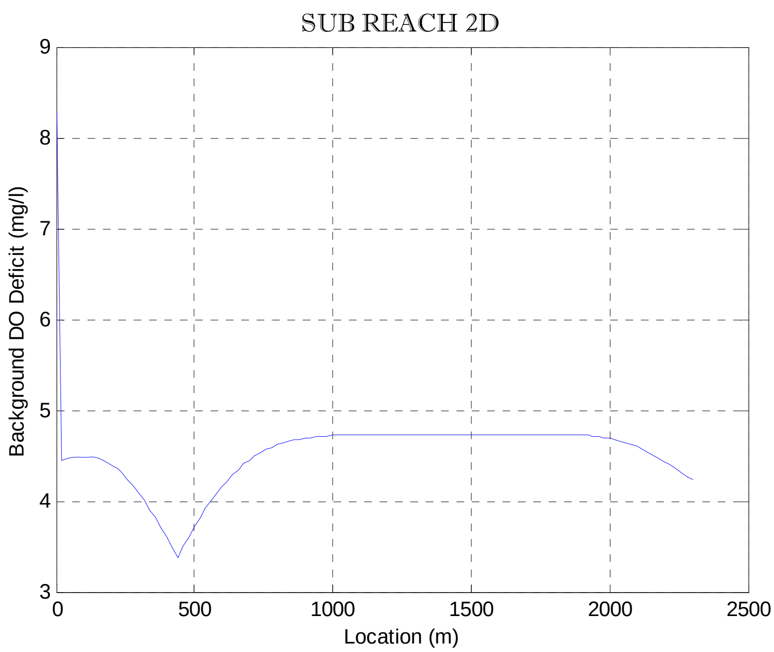


Fig. 5. 11f: For Sub-Reach 2D

As it was shown in the study results, the highest Db value is obtained in the sub reach 3B and 2D. While the lowest is in sub reach the starting part of sub 2A. The finding is in a good agreement with water quality assessment and monitoring reports prepared by Federal Environmental Protection Authority, Regional Environmental Protection Offices and other study papers. In this Db prediction, one important point to be considered is the water quality data to be used for the model prediction. The location where this data represents the river water quality is one important factor. The data should be in between two known point sources, as it represents the effect of upstream point source pollutant and non-point source pollutants.

In the study, for those sub-reaches having intermediate water quality data, the elemental cell where the upstream point source pollutant enters the river was considered as the first node and the intermediates were assigned to the corresponding node based on their location, while the last node was assigned to the cell just before the next point source. For the shortest sub reaches, sub reach 1B and 2B, in which intermediate water quality data were not used. Thus, values for the first and the last nodes were assigned using material balance calculations. The distance between sampling sites for collecting water quality data is the other important factor, particularly for the accuracy and immediate convergence of the model solution. Even though, it was not possible to identify the optimum sampling distance between the sampling sites, from the models behavior it is worth to mention that using data collected within short distances provides more reliable results. However, the allocation optimum distances between sampling sites require further analysis, including the pollution state of the river and economical aspects.

5.4.2 Prediction Distributed Non-Point Source CBOD

Non point source distributed CBOD loadings enter river system in three common ways as shown in Fig. 5.12 (Chapra, 1997). In the study, the line load; i.e. in which the loads were parameterized per length of the river.

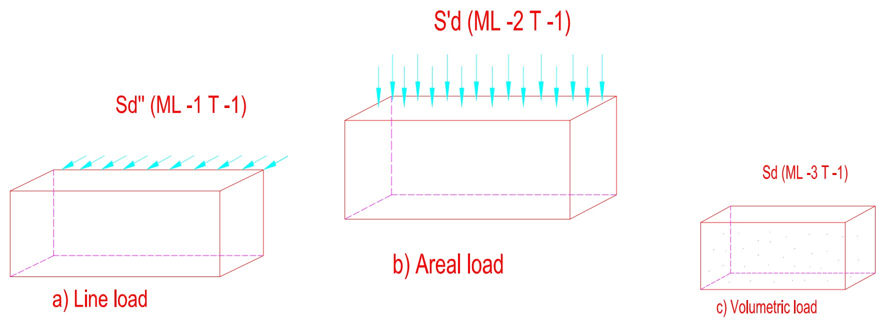


Fig. 5.12 Ways in which distributed loads enter one-dimensional water bodies

(Adopted from Chapra (1997))

The total Streeter – Phelps equation that considers distributed non point sources that introduce BOD in to a system is given by the following equation (Chapra, 1997):

$$L = L_o e^{-(K1+K3)t} + \frac{S_d}{(K1+K3)}(1-e^{-(K1+K3)t}) \qquad (5.18)$$

In the determination of this distributed non point source CBOD, the general 1-D numerical model equation (Eq. 5.1) was modified for BOD and the coefficients e_i , f_i g_i and Z_i for BOD will become:

$$e_i = -\left[\frac{(A_c D_L)_{i-1}}{V_i \Delta x_i} + \frac{Q_{i-1}}{V_i}\right] \qquad (5.19)$$

$$f_i = \left[\frac{(A_c D_L)_i}{V_i \Delta x_i} + \frac{(A_c D_L)_{i-1}}{V_i \Delta x_i} + \frac{Q_i}{V_i} + K1 + K3\right] \qquad (5.20)$$

$$g_i = -\left[\frac{(A_c D_L)_i}{V_i \Delta x_i}\right] \qquad (5.21)$$

$$Z_i = (S_L / ac) \qquad (5.22)$$

The MATLAB function file CBOD_PREDICTOR (Appendix D-4a), loads the calibrated parameters and all hydrological data findings, the numerical model equation coefficients, and solves the BOD at each nodal point iteratively for each sub reach using measured BOD at different nodal points. The BOD result converted to equivalent CBOD using Eq. 5.11 to find the CBOD at each nodal point. On the other hand the empirical equation, Eq. 5.18 determines the CBOD directly assuming SL to be zero.

The m-file MAIN CBOD_PREDICTOR (Appendix D-4b) uses the built in MATLAB optimization function, fsolve. fsolve calls the predictor, the predictor use the measured BOD values as boundary condition and determines the nodal values, the result would be converted the equivalent CBOD at each nodal point. The result from Eq. 5.18 and the numerical result then compared to each other and the error, which is the difference between the two values are then calculated. fsolve do its optimization routine to minimize the error by varying the distributed non-point source CBOD.

Fig. 5.13 shows the correlation analysis between the model prediction for CBOD and the measured CBOD based water quality data targeted values for each sub reaches.

Generally, the results obtained from correlation analysis study for predicting distributed non point source CBOD loads is satisfactory. However, the good agreement obtained in the prediction of the background DO deficit above was not obtained in this case.

Fig 5.14 displays the spatial distribution of distributed non point source CBOD line loadings (SL) in each sub reaches.

Fig. 5.13 Correlation Analysis for Prediction of Distributed Non Point Source CBOD Loads

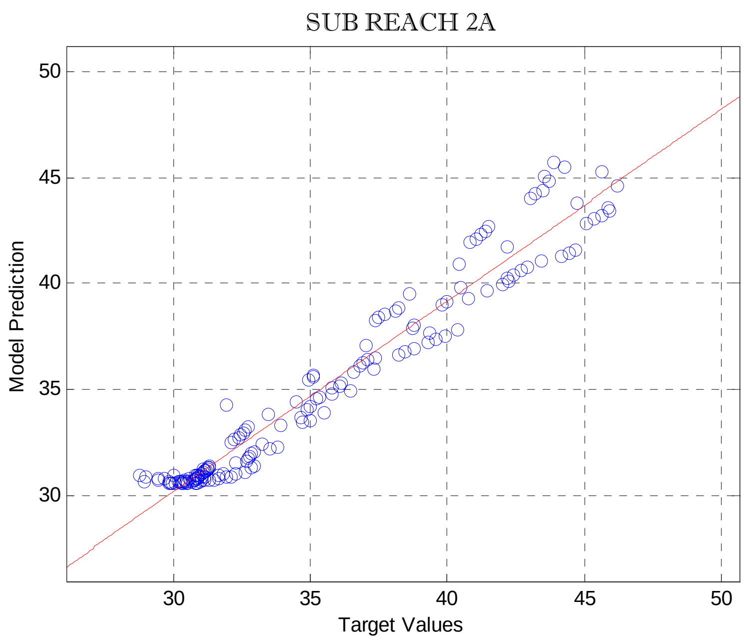


Fig. 5. 13 a: For Sub-Reach 2A

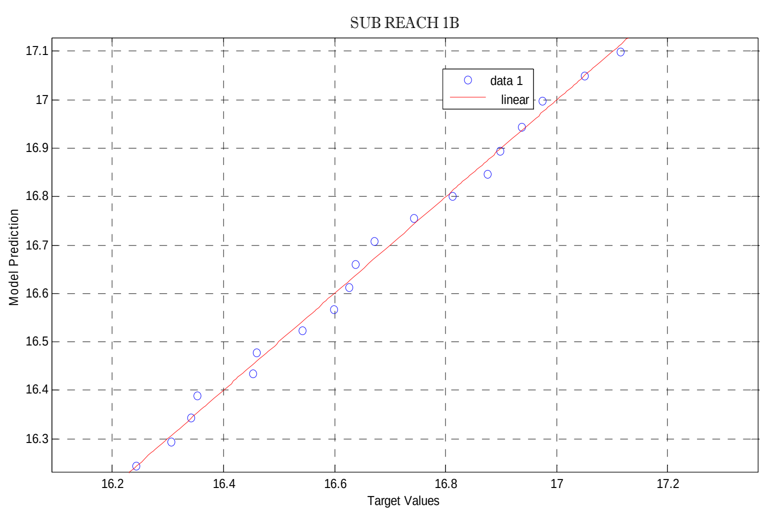


Fig. 5. 13 b: For Sub-Reach 1B

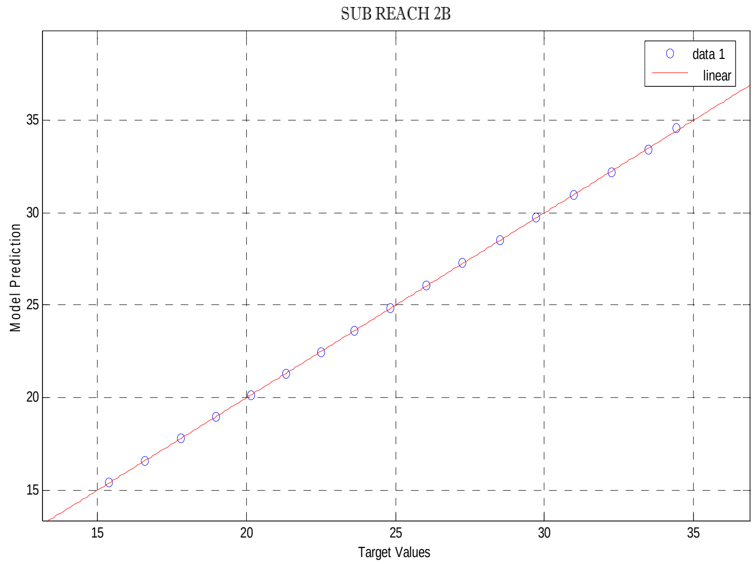


Fig. 5. 13 c: For Sub-Reach 2B

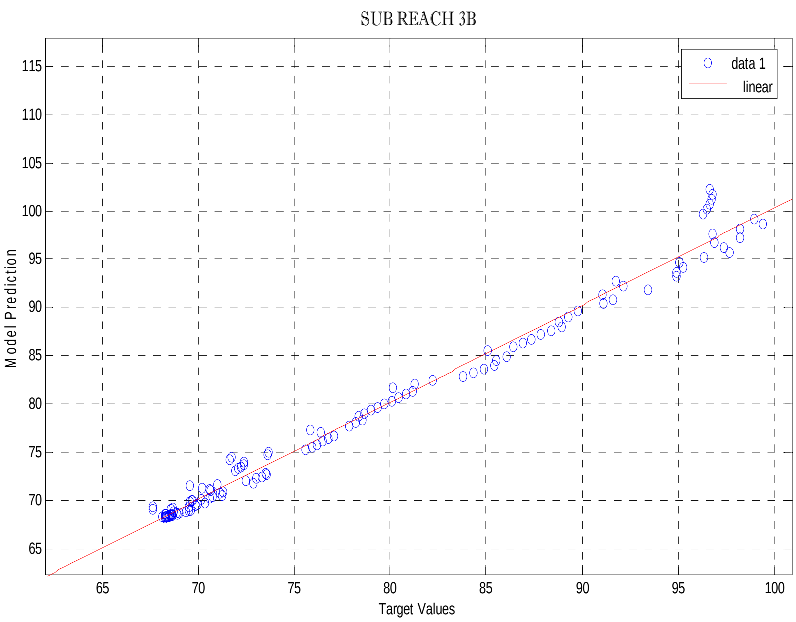


Fig. 5. 13 d: For Sub-Reach 3B

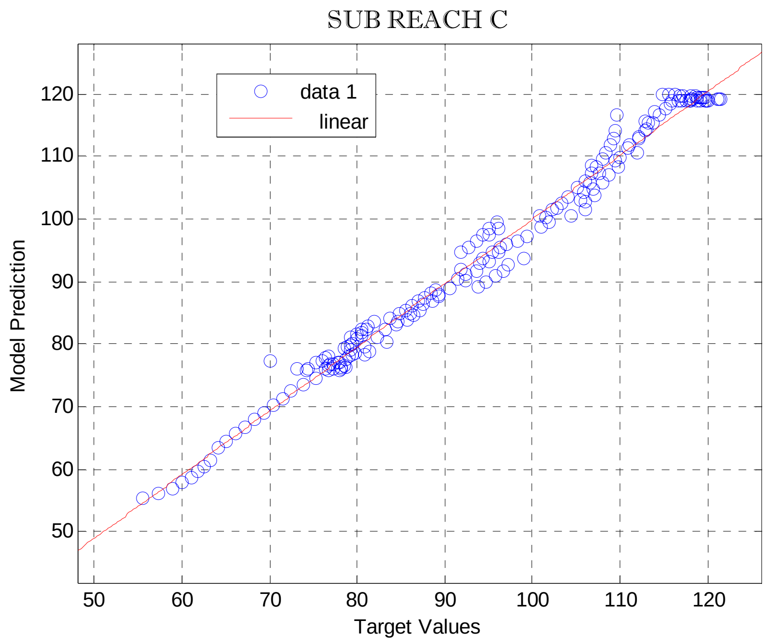


Fig. 5. 13 e: For Sub-Reach C

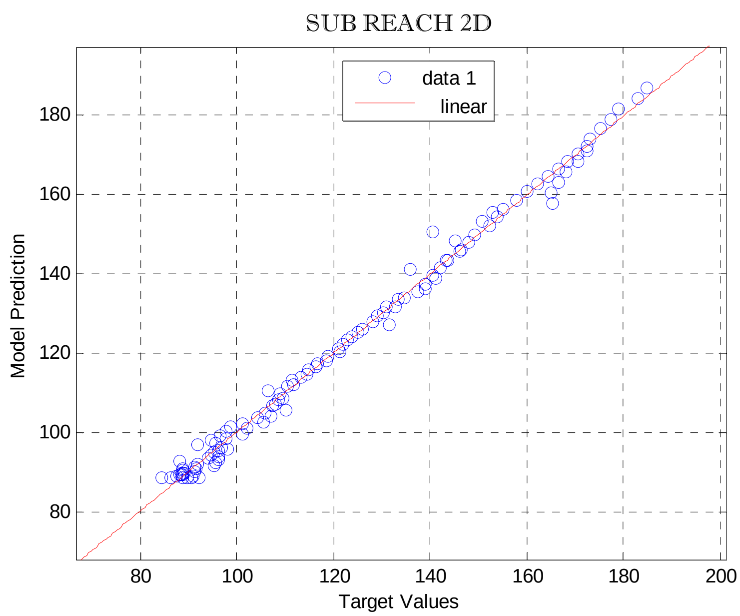


Fig. 5. 13 f: For Sub-Reach 2D

Fig. 5.14 Spatial Distribution of the non point source CBOD loads in the LAR

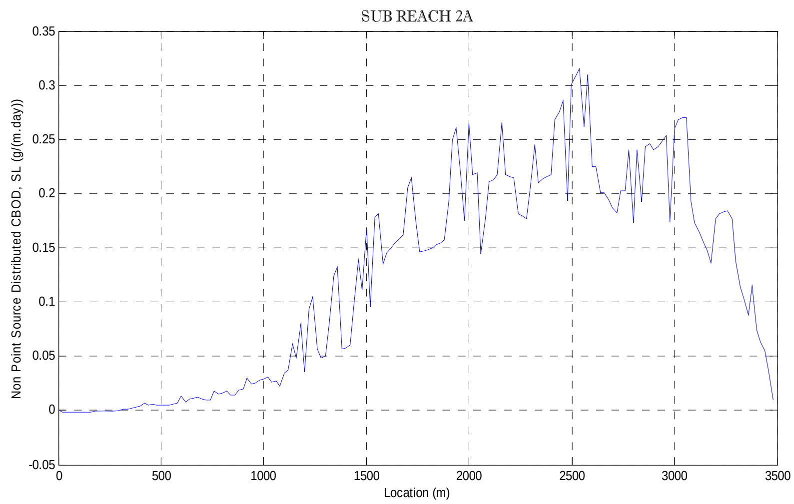


Fig. 5. 14a: For Sub-Reach 2A

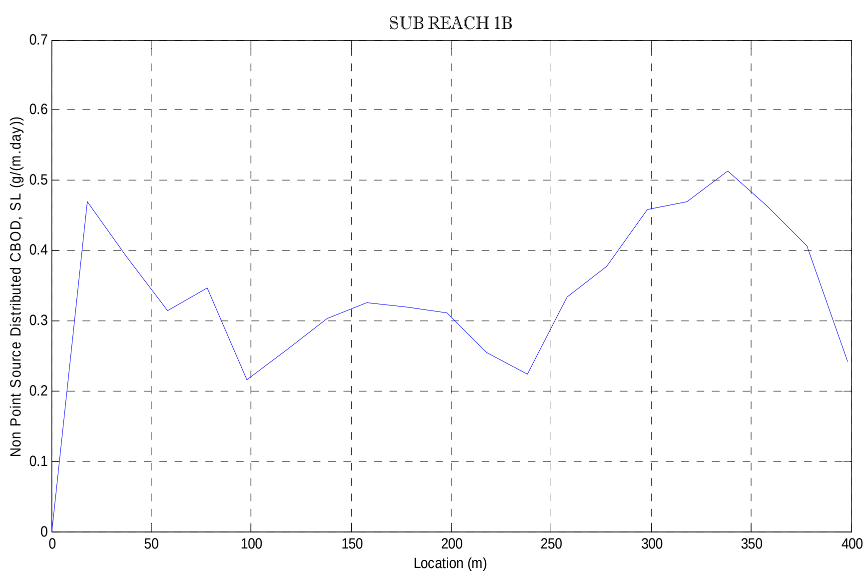


Fig. 5. 14b: For Sub-Reach 1B

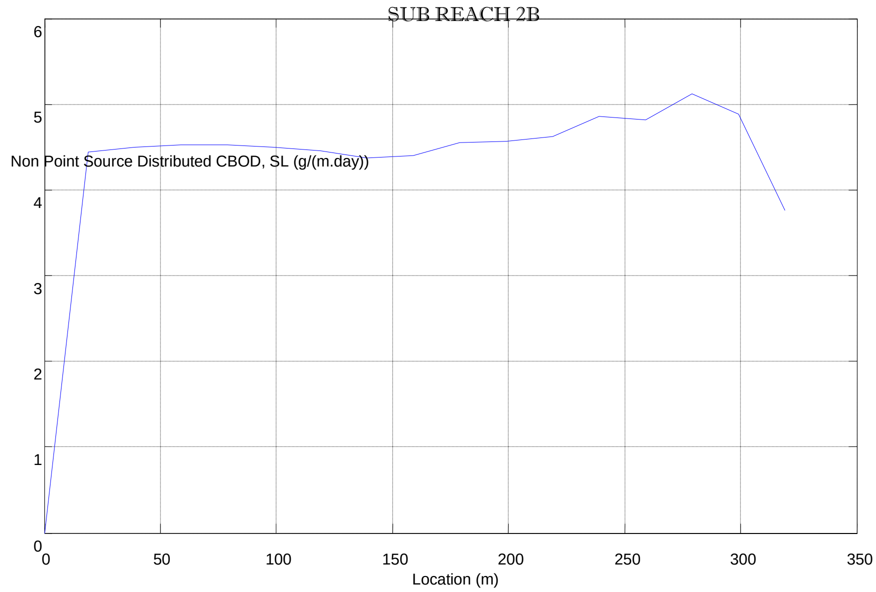


Fig. 5. 14c: For Sub-Reach 2B

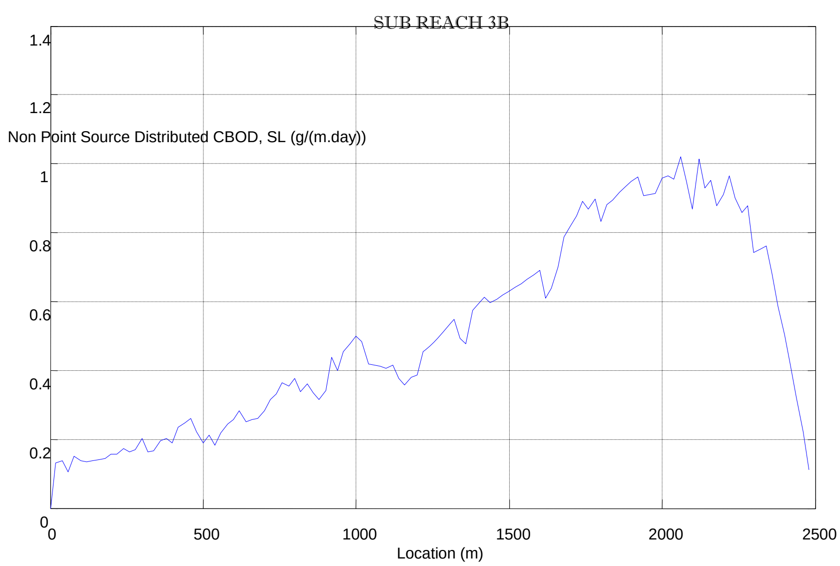


Fig. 5. 14d: For Sub-Reach 3B

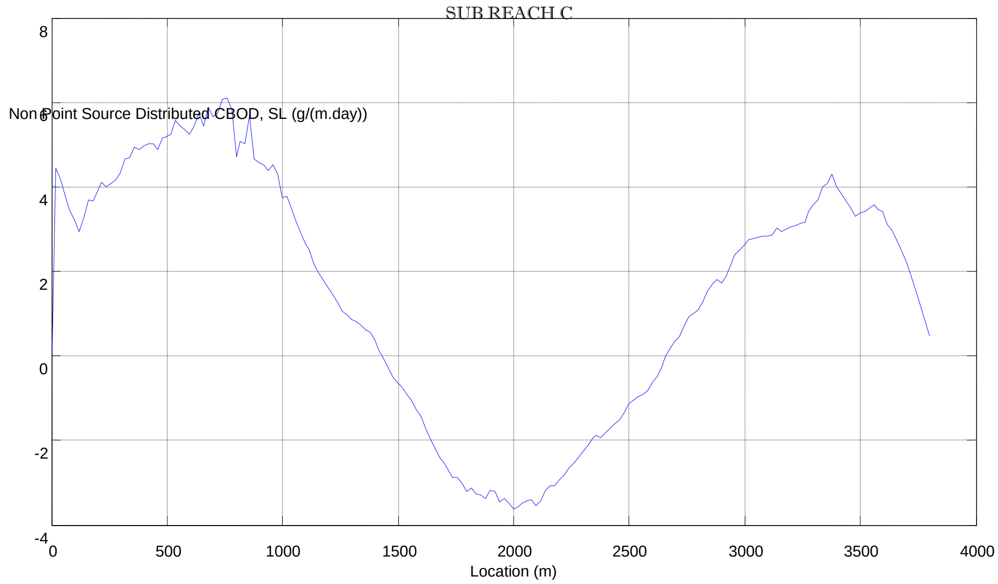


Fig. 5. 14e: For Sub-Reach C

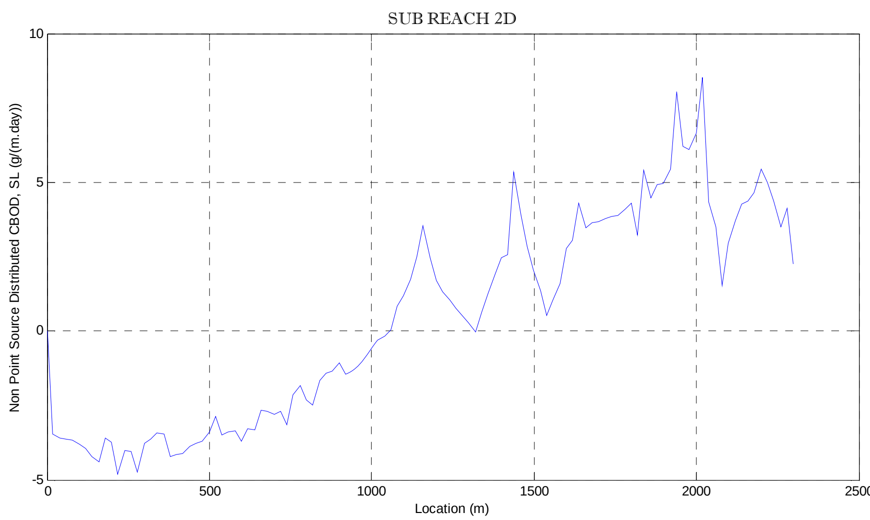


Fig. 5. 14f: For Sub-Reach 2D

Those issues discussed in Db prediction are also important issues in using the model for the prediction of distributed non point source CBOD loads in the river. Particularly, as it was observed during the study work, the spatial distribution of water quality sampling sites has significant influence on reliability of the predicted CBOD values. Identification of river locations with devoid DO is the other important point to be considered for using the model.

5.5 Model Demonstration as Decision Making Tool

5.5.1 Overview

The previous two sub sections, demonstrated the capability of the model for predicting non point source related pollutants in the river system based on limited river water quality data. The results obtained from these model application examples, were used for extending the model applicability to be used as decision making tool. Thus, the developed BOD-DO model was further enhanced for use as decision making tool and its application was demonstrated. For the purpose of this research work, the model was used to analyze two provisional environmental standards from the LAR perspective.

The provisional industrial wastewater discharge standard; 'Standards for Industrial Pollution Control in Ethiopia' which was Prepared by FEPA and UNIDO under the Ecologically Sustainable Industrial Development (ESID) Project; provisions emission limit values for discharges to surface water. BOD level in the industrial wastewater discharges is among these provisionally limited values in this industrial wastewater discharge standard. On the other hand, the ambient environmental quality standards which were set by FEPA with a goal of safeguarding public health and protecting the environment allow a maximum 5 ppm BOD in surface water sources like the LAR.

In the study, the effectiveness of the provisioned BOD level in the industrial pollution control standard in achieving the allowable maximum 5 ppm BOD ambient environmental quality standards was evaluated from the actual LAR and the efficiency of the policy response for restoring the healthy functioning of the LAR was assessed.

5.5.2 Model Structure and Inputs

Equation 5.1, the general one-dimensional equation developed for LAR was used for developing this demonstration model. For this an iterative program was developed using MATLAB (Appendix: D-5) for determining BOD at each elemental cells.

The predicted non point source distributed CBOD loads and the BOD loadings from tributaries were considered without modification (i.e. the no action scenario on other situations was considered). The industrial BOD point source term which was used in the previous models were replaced with the provisional BOD standards.

Thus, Eq. 5.22 the BOD model coefficient zi term was modified as shown in Eq. 5.23, while the other model coefficients remain the same.

$$Z_i = (S_L / ac) + S_p / v \qquad (5.23)$$

where:

Sp is the point source BOD loading (gm day^{-1})

S_L The predicted non point source distributed BOD loading (gm day^{-1} m^{-1})

Fig. 5.15 shows the model predicted BOD level in the river both without the implementation of the provisional standard (blue line) and if the standard is implemented (red line).

Table 5.3 displays the summery of the Sp value used for the model demonstration.

As displayed in the graph, the implementation of the provisional will have a significant effect in reducing the BOD level in the river. However, this model demonstration result asserts that, only the implementation of this industrial pollution control standard could not restore the healthy functioning of the river and also can not be achieved the maximum 5 ppm BOD level surface water quality standard provisioned by the authority.

Table 5. 3 Point Source BOD Loadings (with the provisional Emission Limit)

Point Source	Nodal Point	Provisional BOD	Point Source BOD
Edible Oil Factories	3	80	12,442
Tributary - One	178	-	471,744 *
Soft Drink Factories	199	80	20,045
Awash Winery	216	60	8,294.4
Tributary - Two	341	-	1,587,168 *
Abattoir	532	80	60,134

* There is a seasonal variation on the values.

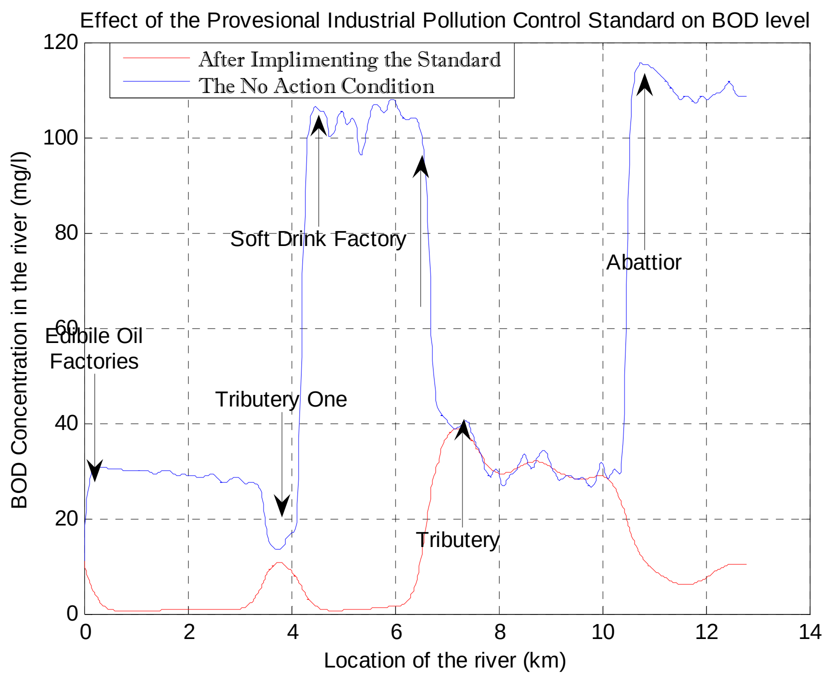


Fig. 5.15 Effect of industrial wastewater discharges on the BOD level before and after the implementation of the provisional industrial pollution control standards

CHAPTER 6 DISCUSSION AND INTERPRETATION OF THE MODEL

6.1 The General LAR Water Quality Model

Generally, with the available data and the study assumptions, the developed general water quality model is capable for simulating the fate and transport of contaminant transport in the 27.4 km section of the LAR. This can be attested from the preliminary model test and the BOD-DO model application study results.

The graphs displaying the transport of the conservative chemical in the river system were in good agreement with the theoretical condition. As indicated in the non-continuous point source pollutant case; the peak concentration point of the chemical travels in the flow direction of the river due to the advection mass transport; while this peak concentration point progressively decays due to the dispersion mass transport.

As displayed in the model simulation; for the continuous point source case, the down stream concentration of the conservative chemical in the river increases in successive times and reaches steady state. Both dispersive and advective mass transport conditions were prevailed in the preliminary model test simulation result.

6.2 The Model Calibration Results

Generally, the value of the calibrated model input parameters are within the range of known literature values and resembles theoretical facts. Further more the DO deficit calculated using the model and the modified Streeter – Phelps equation is in a good agreement at the end of the calibration stage. This can be attested from both Fig. 5.8 and the absolute error performance measurement graphs (Fig. 5.9)

The significant calibration error is observed in Sub reach C. This might be due to the high pollution condition of the river in this sub reach. It is possible this section of the river is devoid of oxygen. Thus, at this point biodegradable wastes undergo oxidation an aerobically.

For this an aerobic condition oxidation of CBOD and NBOD can no longer proceed at the assumed first order decay, rather it will be limited by the rate at which oxygen passes across the air water interface via re-aeration. Once the oxygen is totally depleted, the CBOD and NBOD oxidation becomes zero - order. Consequently as with all zero - order reactions, the CBOD and NBOD are reduced linearly (not exponentially as of the assumption). Therefore, it is possible that the results from the numerical and analytical method can be different and exhibits high absolute error value between them. The other important findings of the calibration study is the spatial variation of these model input parameters.

The calibration results have revealed a significant spatial variation on the longitudinal dispersion coefficient D_L. Though, the degree of variation is less as compared to the former one; there is also spatial variation on air-water oxygen transfer (re-aeration) rate, K_2 and the settling rate of CBOD, K_3 within a sub reach, while the value of the oxidation rate of CBOD, K_1 and the rate of sediment oxygen demand, K_4 changes (varies) from sub reach to sub reach.

The significant spatial variation of the longitudinal dispersion coefficient might be the high dependence of the parameter to the hydro-morphological properties of the river. Most importantly, the longitudinal dispersion coefficients of rivers are highly affected by the mean flow velocity of the river, which is highly variable with the depth and slope (topography of the river). The longitudinal dispersion coefficient of in most section of the river lies within the average range value of 6 – 10 m^2/sec. There are river sections, where the value is higher than 20m^2/sec. This exaggerated value may be due to some of the in accuracies that arises from the estimation of the depth and width of the river. As the parameters directly affects the parameter in using the Deng's et. Al. (2001) empirical equation and also indirectly causes discrepancy for determination of the mean flow velocity of the river. Particularly the rectangular river cross section assumption might be one error enhancing factor.

The spatial variation of the rate of DO re-aeration, is might be due to the topography of the river bed and the spatial variation of the river depth. As presented in section (5) of the paper, the empirical equation used for initial K_2 estimation indicates the direct dependence of the value with mean flow velocity and depth of the river.

Generally, the value of K_2 for the LAR is within a higher value range (more than 50 day^{-1}) one possible explanation for the situation is the high gradient, the higher flow velocity and the shallow condition of the river. Thus high drop conditions and riffles that are related to these conditions may enhance rate of re-aeration in the river.

The variation of the CBOD settling rate, K_3 can arise due to the spatial variation of the river depth, which is one of the controlling factors for the settling rate of any suspended solid including CBOD. Generally, the value of K_3 agrees with literature values and ranges between 0.2 – 0.4 day^{-1}.

The variation of the sediment oxygen demand, K_4 from sub reach to sub reach might be associated with the pollution condition of the river. The situation can be attested from the calibration results. As it was observed near the start of sub reach 2A, where the urban structure and the land use activities were limited during the sampling period, the value of the calculated K_4 value is below 5.0 gm m^{-2} day^{-1}, while it reaches the maximum literature value range (10 gm m^{-2} $day^{-1)}$ in sub reach 3B, C and 2D; where there is a high pollution condition due to high population density and the impact of upstream industrial pollution is significant.

An oxidation rate of NBOD, K_n of up to 6 day^{-1} was calculated in some sections of the river, though the majority river section falls within 1.0 up to 5.0 day^{-1} value. The value of K_n almost consistent and higher than 1.0 day^{-1} which agrees with a stated literature value ranges, (i.e. 0.1 – 0.5 day^{-1} for deeper waters and greater than 1.0 day^{-1} for shallower streams).

6.3 Model Application Examples

6.3.1 Predictions of the Background DO Deficit

Generally, the correlation analysis graphs (Fig. 5.11) indicates that the model predicted DO in the river is in a good agreement with the water quality analysis based target values. This capability of the model for predicting non-point sources related background deficit demonstrates the capacity of the model to be used as a tool for different purposes including the water quality assessment and monitoring works. The model needs limited water quality data sets that can serve as a boundary condition for the numerical model. As it was described in the model programs, the model uses the calibrated data and determines the spatial distribution of the DO in the river iteratively by using the measured DO values as boundary conditions. Thus, the spatial location of the river water quality data, to be used as boundary condition, and the pre-set error value for the execution of the program will have a significant contribution for the prediction accuracy. In the study, for the short sub reaches; up to a 1E-12 error value was used for the prediction of the Db in sub reach 1B and 2B. On the other hand, with available computer capacity a 1E-05 value was the possible minimum error value achieved for sub reaches 2A, 3B, C and 2D. Thus, for accuracy and immediate convergence of the model solution, using data collected within short distances provides more reliable results. However, the allocation optimum distances between sampling sites require further analysis, including the pollution state of the river and economical aspects.

In addition to this, in order to use this Db prediction model, the water quality data to be used for model prediction should be in between two known point sources, since the data represents the effect of upstream point source pollutant and non-point source pollutants. In the study, for those sub-reaches having intermediate water quality data, the elemental cell where the upstream point source pollutant enters the river was considered as the first node and the intermediates were assigned to the corresponding node based on their location, while the last node was assigned to the cell just before the next point source. For the shortest sub reaches, sub reach 1B and 2B, in which intermediate water quality data were not used. Thus, values for the first and the last nodes were assigned using material balance calculations.

The other important finding of this application example is spatial distribution of the background DO deficit. The highest Db value is obtained in the sub reach 3B and 2D. While the lowest at the starting part of sub reach 2A. The finding is in a good agreement with water quality assessment and monitoring reports prepared by FEPA, EPO and other study papers. However, there are also some unreliable negative Db values predicted by the model. Negative Db value is prevailed at the end section of sub reach 3B and between the middle and end section of sub reach C. An aerobic oxidation condition might be one of the possible causes for this unexpected result. This unrealistic value might also arise from the models Db prediction method. In the Db calculation, the model uses the measured DO values as boundary condition and the measured CBOD and NBOD and iteratively computes the nodal DO concentration. This nodal concentration determination might be a source of error for spatial allocation of Db values by distributing nodal values to neighboring nodes. Thus, the model might be over estimating some of the nodal points, while under estimating others. Therefore, the best way to express the predicted Db and get a more comprehensive result is by summing up the spatially distributed Db values and assigning within a limited spatial ranges (like within 1 km distance). But if the total sum up of the predicted Db is below zero, it is an indicator for the mal functionality of the model.

6.3.2 Predictions of Non-point Source Distributed CBOD

As we can see from the sub reach's correlation analysis graph (Fig. 5.13) the model predicted CBOD in the river is in a good agreement with the water quality analysis based target values for sub reaches 1B and 2B. Even though, the result is not good as the two sub reaches; with the available water quality data sets and other constraints, the result for the other sub reaches is also satisfactory. As it was observed during the execution of the model programs, the main factor for convergence of the model solution is the number of iteration and the error value for numerical computation of the model equations. The good correlation results for sub reach 1B and 2B were achieved after 1000 fsolve iteration process. But the longer distance and the high number of the nodal points to be solved in the other four sub reaches do not allowed to run the program for more than 100 iterations with available computer capacity.

As it was seen in Fig. 5.14, the highest non point source distributed CBOD value was observed in sub reach C, 2B and 2D. Despite of its high Db value, the level of distributed non point source CBOD in sub reach 3B is not significant. Even though it was expected that the two model out puts to give a correlated result between two, a significant discrepancy was prevailed. This is because; the high Db level in the sub reach might be caused due to the type of the distributed non point source waste discharge. Even though it was not possible to identify in this study, the higher Db level might be due to the presence of high non point source distributed NBOD waste in the area.

The other important, issue related to this CBOD analysis result is the negative SL values prevailed in sub reach C and D. The situation might be a justification for the above points. As it was mentioned in the paper, anaerobic oxidation condition was the proposed cause for the observed discrepancy for some of the study results in these sub reaches. Thus, for the anaerobic oxidation condition the decay of CBOD is linearly related to the product of the directly K_2 and the saturation DO rather than the available mass of CBOD. This might be the reason why, a negative SL value prevailed at nodal points with high CBOD amount.

6.4 Model Demonstration as Decision Making Tool

Planning efficient policy responses for controlling industrial pollution of the LAR and monitoring the operations of the pollution control activities would be among the main components of the proposed 'Programme on Sustainable Consumption and Production in The Akaki River'. As it was shown on the model demonstration result, the developed model is capable to support the above mentioned tasks of the programme. For example, as mentioned in the previous chapter of the paper; since implementing the provisional industrial pollution control standard could not be a solution by itself for restoring the healthy functioning of the rivers; planners and decision makers will be informed to investigate additional environmental management strategies.

Beside this generalized information, it was also possible to use the model for identification of prioritized areas for targeting interventions and to plan sustainable environmental management strategies. For example, as it was shown on the demonstration model simulation result; in the no action scenario, the BOD level of the river is high at all sections of the river. The simulation after the implementation of the provisional standard indicates a significant BOD level reduction at river sections where industries are the significant pollutant sources, while a minor (no) improvement conditions was observed in river sections where non point sources and tributaries are the significant cause for the pollution condition of the river.

CHAPTER 7 CONCLUSION AND RECOMMENDATIONS

7.1 Summary and Conclusions

A general one – dimensional computer based mechanistic water quality model has been developed for the 27.4 km long section of the LAR. This general water quality model has been calibrated for part of the river (which covers about 12.780 km length) by taking BOD and DO as water quality indictors. The practical applicability of the model to be used as decision making has been demonstrated by evaluating the efficiency of the provisional industrial pollution control standard in restoring the BOD level of the LAR to the maximum 5 mg/l BOD level provisioned by the Country's ambient environmental quality standard.

Beside the fundamental objective of the research work, (i.e. mathematical modeling of the cause and effect relationship between point source pollutants and the water quality of the LAR); in the study the spatial distribution of non-point source related CBOD and DO deficit related pollutants has been identified and their effect in the LAR water quality was also modeled.

Therefore, based on the overall findings and the study results the following conclusions are presented:

- The general water quality model reasonably represents the fate and transport of any contaminant transport in the 27.4 km long section of the river system.
- The preliminary tested water quality model represents the overall mixing characteristics of the LAR system based on the reasonable agreement between the analytical results.
- The value of the calibrated kinetic parameters for BOD-DO modeling, are within a range of literature values
- The calibrated BOD-DO model results showed reasonable agreement with the observed data based target values.

- The calibrated BOD-DO model is not only capable for predicting point source industrial pollutants, but also can be used for estimating distributed non point source caused background DO deficit, as well as non point source distributed CBOD wastes.
- As currently the model is calibrated for the highly polluted section of the river, the water quality model provides a reasonable predictive tool for monitoring the water quality state of the river using BOD-DO as water quality indicators.

The developed water quality model will have versatile applications; particularly as supporting tool for Integrated Industrial Pollution Control on the Little Akaki River. Generally the model can be used as decision making tool in the following areas:

- In assessing the present industrial pollution situation and to create a data base that will facilitate information exchange between different stakeholders.
- provides bases for targeted industrial environmental management in the area.
- To monitor, collect and process data in order to evaluate applicable industrial environmental management plans and operations in the area. .
- To support decision-making with a view to the future identification, analysis and evaluation of alternative allocations, policies or plans related to industrial developments in the area as well as strategic environmental management options.

Here it is also worth to mention the possible limitations of the study work. In developing the general water quality model, as much as possible recent model inputs were used. However, for calibrating the model, the water quality data and the industrial wastewater discharges model input data were collected in previous time. Thus, this time gap might be a possible limitation for representing the river water quality condition at the time of this study work. Particularly for the cases like changes on the land use pattern of the basin and industrial wastewater quality and quantity modifications might have an effect on the predicted CBOD and Db values as well as the kinetic terms. In the study, calibration of the whole 27.4 km long section of the LAR was not possible, hence reliable secondary water quality was available for limited section of the river.

But these gaps of the study are not the study technical weakness; rather they are limitations which arisen from financial and time constraints. It was not possible to collect river water quality data from the river; hence the budget allocated for the study work was not enough even to cover basic study costs. Attempt was made to generate extra fund from different organizations, but it was not possible to get at the required time frame.

In summery; the developed water quality model will have significant contribution for mitigating surface water quality degradation problems in the Akaki River Basin in general and for controlling industrial pollutions of the LAR in particular. The study would be a spring board for developing a comprehensive analytical tool for integrated river basin management options in the area. Particularly, the model's theoretical framework and the numerical method used for solving the model equation makes the developed computer program easy for use and flexible for updating and modifications.

7.2 Recommendations for Future Works

Recommendations were given for improvement of the developed water quality model and additional research works for wider application of the model.

The following are the main model improvement issues recommended in the study:

- It is known that research works of this kind are open-ended and needs improvement time to time. Therefore, it is recommended to improve the model by:

  (i) model-based design of the experimental set-up,

(ii) high-frequency sampling at sufficient locations including the assessment of mixing and dispersion effects, and

(iii) biological, chemical and physical studies that follow the conversions taking place in a representative sample of river water.

Initial model improvement intervention is recommended in the determination of model transfer functions and model constants. Thus, the following are recommended model improvement issues:

- Correlating the stream hydro-geometric properties of the river by collecting seasonal field data and measured mean flow velocity
- Determine the longitudinal dispersion coefficient of the river using tracer tests. A tracer test at a low flow condition best represents the longitudinal dispersion coefficient for addressing waste water discharge related water quality problems.
- Performing the model calibration using laboratory measured rate constants and systematically collected water quality data as well as measured wastewater quality and quantity data of point source pollutants

From other institutions experience, studies of this kind require the coordination and participation of different stakeholders. It is also known that studies of this kind are used for research, education, improved communication, knowledge transfer, regulatory applications such as catchment planning, and improved data collection. Therefore, in order to maximize the benefits of the study, establishment of a centralized and well organized institutional framework that comprises research institutions, regulators, academicians, etc is recommended.

Recommended future research works for a wider application of this study work are listed as follows:

- Development of a more comprehensive generalized water quality model, or separate detailed models for different quality constituents. The current model has a generalized water quality model that can provide adequate estimations particularly for simulating the transport of chemicals in the river system However, if intensive on-site data are available, more comprehensive models can be developed to provide detailed analysis of the fate and transport of contaminants.
- Development of an interactive geo-referenced water quality model that provide platform for integrating spatial factors that affect the water quality model. Given the variability of the river morphology and the stream velocity along the reach, several rate constants were found to be space-dependent. Thus spatial representation of the physical parameters that affect the transport of chemicals in the river system makes the model more comprehensive. The possibility of integrating MATLAB with GIS and MATLAB's capability for processing geographical data through the Matlab Mapping Toolbox™ makes the recommendation feasible.
- The developed water quality model covers one of the Akaki River sub-catchments (the LAR) and also only industrial pollution were analyzed. However, in order to use the model for the proposed use; as a decision making tool for the Programme on Sustainable Consumption and Production in The Akaki River, it is recommended to develop the model to a watershed level by considering other factors including ground-surface water interaction, land use pattern, socio-economic issues, etc.

REFERENCES

1. Adane Bekele (1999), Surface Water and Groundwater Pollution Problems in the Upper Awash River Basin, Ethiopia, Master Thesis. University of Turku, Finland.

2. Andre Marquette (2005), Modeling of Chemical Fate and Transport in the Environment. Master Thesis. Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College, Louisiana, USA.

3. Agzew Nigussie (1998), Evaluation of Water Quality and Suggested Improvement Measures, The Case of the Little Akaki River, Addis Ababa Ethiopa. Master Thesis. Royal Institute of Technology, Environmental Engineering and Sustainable Infrastructure Programme, Stokoholm.

4. Asit K.Biswas (1981), Models for Water Quality Management. McGraw Hill Series in Water Resources and Environmental Engineering, USA

5. A.Bruce Bishop, Rangeson Narayana, William J.Grenney, Paul E.Punger (1997), Goal Programming Model for Water Quality Planning, Journal of Environmental Engineering ASCE, Vol. April 103, 1997

6. Bedford, K.W., R.M. Sykes, and C. Libicki, "Dynamic Advective Water Quality Model for Rivers," Journal of Environmental Engineering Division, American Society of Civil Engineers, Vol 109, No. 3, pp 535-554, 1983.

7. Brown. L. C. and T. 0. Barnwell, "The Enhanced Stream Water Quality Models QUAL2E and QUAL2E-UNCAS: Documentation and User Manual," Report # EPA/600/3- 87/007, Environmental Research Laboratory, Office of Research and Development, U. S. Environmental Protection Agency. Athens, Georgia, 1987

8. Bruce E.Logan (1999), Environnemental Transport Proceses, The Pennsylvania State University, USA; University of Park, PA

9. D.C. Singhal, N.K. Goel, D.K. Srivastava, Ranvir Singh, Himanshu Joshi, B.S. Mathur (1997), Emerging Trends in Hydrology, University of Roorkee, Roorkee-247 667, India

10. Desta M. Oct. 1990. Industrial Waste Management in Ethiopia, Addis Ababa, Ethiopia

11. Desta Mebratu, Robi Redda, (May 2005), First Draft Documents for the Programme on Sustainable Consumption and Production in the Akaki River, Addis Ababa, Ethiopia.

12. Dirk Muschalla, (2001), Urban storm-water drainage system in the central Part of Addis Ababa: Present state and proposals for the improvements Institute of Hydraulic and Water Resources Engineering Darmstadt University of Technology In co-operation with the Water Resources Research Group At the Department of Civil Engineering Faculty of Technology, Addis Ababa University, Darmstadt, May 2001

13. EPA, (1997), Environmental Policy of Ethiopia. Environmental Protection Authority of Ethiopian in Collaboration with Ministry of Economic Development and Cooperation, Addis Ababa – Ethiopia, April 2, 1997.

14. Geza Jolankai, (1997), Basic River Water Quality Models-Computer Aided Learning (CAL) Programme on Water Quality Modeling (WQMCAL Version 1.1). IHP-VI Technical Documents in Hydrology, UNESCO, Paris

15. George E.P.Box, Wiliam G.Hunter, J.Stuart Hunter (1978), Statistics for An Experimenters: An Introduction to Design, Data Analysis, and Model Building, John Wiley & Sons, Canada

16. Gowda, T.P., "Water Quality Prediction in Mixing Zones of Rivers," Journal of Environmental Engineering, 110(4), 751, 1984.

17. Hemond, H. F. & Fechner-Levy, E. J. (2000), Chemical Fate and Transport in the Environment, Academic Press, San Diego, CA.

Formatted: Bullets and Numbering

18. M.A. Mohamed (2002), Industrial Pollution and Its Impact on the Little Akaki River. Master Thesis. Faculty of Engineering Loughborough University. UK.

19. Oromia EPO, Assessment of Socio-economic Impacts of Akaki River Pollution, Adama, 2004.

20. Ralph A. Wurbs (July 1994), COMPUTER MODELS FOR WATER RESOURCES PLANNING AND MANAGEMENT Texas A&M University Department of Civil and Engineering Environmental, Ocean and Water Resources Division College Station, Texas

21. Samuel Melaku Abegaz (2005), Investigation of Input and Distribution of Polluting Elements in Tinishu Akaki River, Ethiopia, Based on the determination by ICP-MS, Ph.D. Paper. Laboratory of Analytical Chemistry Institute for Nuclear Sciences, UNIVERSITEIT GENT

22. Steven C.Chapra (1997), Surface Water Quality Modeling. WCB/McGraw Hill, USA.

23. Teklehaimanot R.R., Toxic Risk Evaluation of the Awash River Basin, Ethiopia. M.Sc-Environmental Sciences, Wageningen University, Wageningen, The Netherlands, 2003.

24. T.Alemayhu, D.Legesse, T.Ayenew, Y.Tadesse, S.Waltenigus, N.Mohamed (Sep. 2005), Hydrology, Water Quality and the Degree of Groundwater Vulnerability to pollution in Addis Ababa, Ethiopia.

25. Tewei Dai and John W. Labadie (1997), Integration of Water Quantity/Quality in River Basin Network Flow Modeling. Master Thesis. Department of Civil Engineering Colorado State University. USA

26. Thomann, R.V., "Mathematical Model for Dissolved Oxygen," Journal of Sanitary Engineering, ASCE, Vol. 89, No. 5, 1963.

27. www.epa.goviwatertrain: A CD-based version of EPA's online watershed management training. Module on Watershed Modeling.

28. www.cap.net.org: Water Resources Management and Integrated Water Resources Management Plans.

29. www.lms.ihe.nl online course on 'Integrated River Basin Management' UNESCO-IHE, Netherlands, Delft.

30. Zeyakobe Belete and Zeru Girmay (1999), Industries and Akaki River. Seminar on Akaki River Pollution, ENDA.

APPENDICES

Appendix-A: Summery of the Calibrated Model Parameters

A-1: Sub Reach 2A

Nodal Point Location X	Nodal Point Location Y	Spatial Location (m) From	Spatial Location (m) To	DL (m2/sec)	K1 (d^{-1})	K2 (d^{-1})	K3 (d^{-1})	K4 (gm d^{-1} m^{-2})	Kn (d^{-1})	Kr20 (d^{-1})
468917.3	999189.1	0	20	6.0	2.4	74.9	0.4	3.9	1.6	2.1
468900.3	999180	20	40	6.0	2.4	74.9	0.4	3.9	1.6	2.1
468880.9	999176	40	60	6.0	2.3	74.9	0.4	3.9	1.6	2.1
468868.5	999163.4	60	80	5.5	2.3	72.3	0.4	3.9	1.6	2.1
468869	999143.5	80	100	6.8	2.5	89.2	0.4	3.9	1.6	2.2
468869.6	999123.6	100	120	6.8	2.5	89.2	0.4	3.9	1.6	2.2
468874.4	999104.4	120	140	6.4	2.4	87.2	0.4	3.9	1.6	2.2
468870.3	999085	140	160	7.2	2.5	91.2	0.4	3.9	1.6	2.2
468865	999066.1	160	180	7.2	2.5	91.2	0.4	3.9	1.6	2.2
468852.1	999051	180	200	7.2	2.5	91.2	0.4	3.9	1.6	2.2
468839.2	999035.8	200	220	7.3	2.5	91.8	0.4	3.9	1.6	2.2
468826.3	999020.6	220	240	7.6	3.2	92.5	0.4	4.1	1.8	2.2
468813.4	999005.5	240	260	7.6	3.2	93.1	0.4	4.1	1.8	2.2
468802.8	998989.5	260	280	7.6	3.2	93.8	0.4	4.1	1.8	2.2
468803.5	998969.6	280	300	6.7	2.3	88.6	0.4	3.8	1.6	2.2
468796.7	998952.6	300	320	6.7	2.3	88.6	0.4	3.8	1.6	2.2
468783.1	998938.1	320	340	6.1	1.4	75.6	0.4	3.6	1.3	2.1
468769.4	998923.6	340	360	6.7	2.2	87.9	0.4	3.8	1.5	2.2
468755.8	998909.1	360	380	6.7	2.2	87.9	0.4	3.8	1.5	2.2
468742.1	998894.6	380	400	8.0	2.1	87.9	0.4	3.8	1.5	2.2
468740.9	998875.5	400	420	8.0	2.1	87.9	0.4	3.8	1.5	2.2
468741.7	998855.6	420	440	6.9	1.0	73.1	0.4	3.5	1.2	2.1
468742.5	998835.7	440	460	9.9	3.7	68.2	0.4	4.2	1.9	2.2
468743.3	998815.9	460	480	7.9	2.0	87.2	0.4	3.8	1.5	2.2
468744.1	998796	480	500	9.3	3.3	87.2	0.4	4.1	1.8	2.2
468753	998779.1	500	520	9.3	3.3	87.2	0.4	4.1	1.8	2.2
468765.5	998763.7	520	540	9.3	3.3	87.2	0.4	4.1	1.8	2.2
468778.1	998748.3	540	560	9.3	3.3	87.2	0.4	4.1	1.8	2.2
468790.7	998732.9	560	580	10.4	3.7	87.9	0.4	4.2	2.0	2.2
468793.1	998718.1	580	600	8.0	1.9	87.9	0.4	3.7	1.5	2.2
468778.6	998704.4	600	620	6.9	0.9	73.1	0.4	3.5	1.2	2.1
468764.2	998690.7	620	640	9.0	3.1	58.3	0.4	4.1	1.8	2.2
468749.7	998677	640	660	8.7	2.2	43.5	0.4	3.8	1.5	2.2
468742.7	998663.8	660	680	8.6	2.2	91.2	0.4	3.8	1.5	2.2

468758.6	998651.9	680	700	8.9	2.3	53.8	0.4	3.8	1.6	2.2
468774.6	998640	700	720	10.3	3.7	59.6	0.4	4.2	2.0	2.2
468789.8	998627.8	720	740	10.3	3.7	65.4	0.4	4.2	2.0	2.2
468786.8	998608.1	740	760	9.1	3.2	71.1	0.4	4.1	1.8	2.2
468783.8	998588.5	760	780	7.2	1.1	75.0	0.4	3.6	1.3	2.1
468780.8	998568.8	780	800	7.6	1.9	86.6	0.4	3.7	1.5	2.2
468777.7	998549.1	800	820	7.6	1.9	86.6	0.4	3.7	1.5	2.2
468774.7	998529.5	820	840	8.8	2.4	81.9	0.4	3.9	1.6	2.2
468786.1	998519.6	840	860	9.6	3.5	82.8	0.4	4.2	1.9	2.2
468805.5	998515.2	860	880	9.4	3.3	83.7	0.4	4.1	1.8	2.2
468824.9	998510.9	880	900	8.5	2.2	84.6	0.4	3.8	1.5	2.2
468844.3	998506.5	900	920	8.8	2.3	91.9	0.4	3.8	1.6	2.2
468863.7	998502.1	920	940	7.2	1.1	74.4	0.4	3.6	1.3	2.1
468883.2	998497.8	940	960	8.7	2.2	91.2	0.4	3.8	1.5	2.2
468902.6	998493.4	960	980	8.7	2.2	91.2	0.4	3.8	1.5	2.2
468922	998489.1	980	1000	7.9	1.9	87.9	0.4	3.7	1.5	2.2
468940.8	998483.2	1000	1020	8.4	2.1	90.0	0.4	3.8	1.5	2.2
468958.3	998473.7	1020	1040	8.4	2.1	90.9	0.4	3.8	1.5	2.2
468975.8	998464.2	1040	1060	9.4	3.1	91.8	0.4	4.0	1.8	2.2
468983.5	998445.9	1060	1080	9.5	3.1	92.7	0.4	4.0	1.8	2.2
468991.1	998427.5	1080	1100	11.7	4.8	93.6	0.3	4.6	2.2	2.3
468998.8	998409.1	1100	1120	8.6	1.9	94.5	0.4	3.7	1.5	2.2
469006.4	998390.7	1120	1140	8.6	1.8	95.4	0.4	3.7	1.4	2.2
469006.8	998372.3	1140	1160	7.3	0.8	75.0	0.4	3.5	1.2	2.1
468999.7	998353.7	1160	1180	8.2	1.5	89.3	0.4	3.6	1.3	2.2
468992.5	998335.1	1180	1200	9.1	0.8	76.3	0.4	3.5	1.1	2.1
468979.3	998321.6	1200	1220	12.7	4.0	81.4	0.3	4.3	2.0	2.3
468962.4	998311	1220	1240	8.9	0.6	82.0	0.4	3.4	1.1	2.1
468945.5	998300.4	1240	1260	9.0	0.6	82.7	0.4	3.4	1.1	2.1
468933.8	998286.8	1260	1280	11.2	2.4	83.3	0.4	3.8	1.6	2.2
468932.2	998266.9	1280	1300	13.3	3.9	83.9	0.3	4.3	2.0	2.3
468930.5	998247.1	1300	1320	14.3	4.3	84.5	0.3	4.5	2.1	2.3
468928.9	998227.3	1320	1340	10.7	1.6	85.1	0.4	3.6	1.4	2.2
468927.3	998207.4	1340	1360	8.4	0.6	85.8	0.4	3.4	1.1	2.1
468943.2	998198.4	1360	1380	8.4	0.7	86.4	0.5	3.4	1.1	2.1
468961.7	998191	1380	1400	15.5	5.5	87.0	0.3	5.0	2.4	2.5
468972.3	998175.3	1400	1420	16.7	5.9	87.6	0.2	5.2	2.6	2.5
468980.6	998157.2	1420	1440	13.1	3.9	88.2	0.3	4.3	2.0	2.3
468988.8	998139.1	1440	1460	10.0	1.5	88.9	0.4	3.6	1.3	2.2
468997.1	998121	1460	1480	9.1	0.9	89.5	0.4	3.5	1.2	2.1
469005.4	998102.9	1480	1500	10.0	1.6	90.1	0.4	3.6	1.4	2.2

469004.7	998090.3	1500	1520	8.8	0.8	90.7	0.4	3.5	1.2	2.1
468984.8	998089.3	1520	1540	12.0	2.9	91.3	0.4	4.0	1.7	2.2
468967.9	998083.2	1540	1560	8.8	0.9	74.4	0.4	3.5	1.2	2.1
468964.6	998064.5	1560	1580	8.9	1.0	75.0	0.4	3.5	1.2	2.1
468952.8	998050	1580	1600	10.6	2.0	92.5	0.4	3.7	1.5	2.2
468952.8	998030.1	1600	1620	9.2	1.6	85.9	0.4	3.6	1.4	2.2
468960.5	998014.7	1620	1640	9.2	1.6	85.9	0.4	3.6	1.4	2.2
468977.9	998005	1640	1660	9.2	1.7	85.9	0.4	3.6	1.4	2.2
468993	997993	1660	1680	9.2	1.7	85.9	0.4	3.7	1.4	2.2
469001.4	997975.7	1680	1700	9.2	1.7	85.9	0.4	3.7	1.4	2.2
468990.5	997963.2	1700	1720	8.7	1.2	74.3	0.4	3.6	1.3	2.1
468970.8	997960.3	1720	1740	8.4	1.1	76.7	0.4	3.6	1.3	2.1
468951.6	997955.8	1740	1760	9.6	1.9	74.3	0.4	3.7	1.5	2.2
468933.2	997948.1	1760	1780	12.2	3.4	72.0	0.3	4.2	1.9	2.2
468923.4	997933.3	1780	1800	12.0	3.3	72.0	0.3	4.1	1.9	2.2
468929.7	997914.5	1800	1820	11.7	3.2	71.1	0.3	4.1	1.8	2.2
468941.1	997898.2	1820	1840	11.7	3.2	70.2	0.3	4.1	1.8	2.2
468958.3	997888.9	1840	1860	11.7	3.2	69.3	0.3	4.1	1.8	2.2
468955.1	997874.8	1860	1880	11.7	3.1	68.3	0.3	4.1	1.8	2.2
468938.3	997864.1	1880	1900	11.7	3.1	67.4	0.4	4.1	1.8	2.2
468923.1	997852	1900	1920	9.9	1.9	66.5	0.4	3.7	1.4	2.2
468914.9	997833.9	1920	1940	9.1	1.2	65.6	0.4	3.6	1.3	2.1
468906.7	997815.7	1940	1960	9.1	1.2	75.6	0.4	3.6	1.3	2.1
468898.4	997797.6	1960	1980	9.4	1.7	87.3	0.4	3.7	1.4	2.2
468893.2	997779	1980	2000	12.1	3.1	113.8	0.3	4.1	1.8	2.2
468897.1	997760	2000	2020	8.8	1.2	74.3	0.4	3.6	1.3	2.1
468911.9	997746.7	2020	2040	10.3	2.0	91.2	0.4	3.7	1.5	2.2
468923.4	997730.9	2040	2060	10.3	2.0	91.2	0.4	3.8	1.5	2.2
468931.5	997712.8	2060	2080	14.7	5.6	173.4	0.1	5.1	2.5	2.5
468939.7	997694.6	2080	2100	10.7	2.7	106.1	0.4	3.9	1.7	2.2
468941.7	997675.3	2100	2120	10.4	2.1	91.9	0.4	3.8	1.5	2.2
468940.8	997655.4	2120	2140	10.4	2.1	91.9	0.4	3.8	1.5	2.2
468944.2	997636.1	2140	2160	9.3	1.8	86.6	0.4	3.7	1.4	2.2
468949.4	997616.9	2160	2180	8.9	1.3	75.0	0.4	3.6	1.3	2.1
468950.6	997597.1	2180	2200	10.4	2.1	91.9	0.4	3.8	1.5	2.2
468948.5	997577.5	2200	2220	9.7	2.0	88.6	0.4	3.7	1.5	2.2
468948.5	997558.6	2220	2240	9.7	2.0	88.6	0.4	3.7	1.5	2.2
468956.7	997540.4	2240	2260	12.1	3.4	87.7	0.3	4.2	1.9	2.2
468961	997521.3	2260	2280	11.8	3.3	87.9	0.3	4.1	1.8	2.2

468955.9	997502.1	2280	2300	11.8	3.3	88.1	0.3	4.1	1.8	2.2
468950.6	997482.9	2300	2320	9.2	1.9	88.3	0.4	3.7	1.5	2.2
468944.5	997464	2320	2340	8.7	1.4	88.5	0.4	3.6	1.3	2.1
468934.9	997446.6	2340	2360	9.4	2.0	87.2	0.4	3.7	1.5	2.2
468924.6	997429.6	2360	2380	9.8	2.1	88.6	0.4	3.8	1.5	2.2
468910.2	997416.1	2380	2400	9.7	2.0	87.9	0.4	3.7	1.5	2.2
468899.4	997402.7	2400	2420	9.2	1.8	85.9	0.4	3.7	1.4	2.2
468908	997385.3	2420	2440	8.8	1.3	74.3	0.5	3.6	1.3	2.1
468920.3	997372.5	2440	2460	8.8	1.3	74.3	0.5	3.6	1.3	2.1
468908.7	997358.4	2460	2480	8.7	1.2	67.6	0.5	3.6	1.3	2.1
468889.2	997362.3	2480	2500	11.1	2.9	62.3	0.4	4.0	1.7	2.2
468869.7	997366.2	2500	2520	8.6	1.1	57.1	0.5	3.5	1.2	2.1
468862.6	997353.9	2520	2540	8.6	1.1	51.9	0.5	3.5	1.2	2.1
468876.8	997340	2540	2560	8.6	1.1	73.7	0.5	3.5	1.2	2.1
468891.1	997326.1	2560	2580	9.8	1.7	88.6	0.4	3.7	1.4	2.2
468905.3	997312.2	2580	2600	8.4	1.1	73.1	0.5	3.5	1.2	2.1
468919.5	997298.3	2600	2620	11.3	2.6	77.8	0.4	3.9	1.6	2.2
468931.1	997282.9	2620	2640	11.5	2.7	77.5	0.4	3.9	1.7	2.2
468935.3	997263.5	2640	2660	14.3	4.1	77.2	0.2	4.5	2.1	2.3
468942.5	997245.2	2660	2680	14.5	4.1	76.9	0.2	4.5	2.1	2.3
468952.7	997228.1	2680	2700	14.2	4.0	76.6	0.2	4.4	2.0	2.3
468948.7	997210.5	2700	2720	13.2	3.6	76.3	0.3	4.3	1.9	2.3
468939.8	997192.7	2720	2740	13.2	3.6	75.9	0.3	4.3	1.9	2.3
468940.5	997176.2	2740	2760	10.8	2.3	75.6	0.4	3.8	1.5	2.2
468953.7	997161.3	2760	2780	10.8	2.3	75.3	0.4	3.8	1.5	2.2
468966.9	997146.4	2780	2800	10.6	1.7	75.0	0.5	3.7	1.4	2.2
468980	997131.4	2800	2820	13.7	3.7	74.7	0.2	4.3	2.0	2.3
468993.2	997116.5	2820	2840	9.8	1.4	74.3	0.5	3.6	1.3	2.2
469006.4	997101.6	2840	2860	11.2	2.3	74.0	0.4	3.8	1.5	2.2
469013.1	997091.1	2860	2880	9.3	1.3	73.7	0.5	3.5	1.3	2.2
468994.4	997097.8	2880	2900	9.4	1.2	73.4	0.5	3.5	1.2	2.2
468975.7	997104.6	2900	2920	10.2	1.5	91.3	0.5	3.6	1.3	2.2
468957.3	997110.5	2920	2940	10.2	1.4	91.3	0.5	3.6	1.3	2.2
468947.7	997093.1	2940	2960	10.2	1.4	91.3	0.5	3.5	1.3	2.2
468946.2	997078.4	2960	2980	10.4	1.4	91.9	0.5	3.5	1.3	2.2
468964.6	997070.9	2980	3000	13.8	3.5	92.6	0.3	4.2	1.9	2.3
468983	997063.3	3000	3020	10.5	1.3	93.2	0.5	3.5	1.3	2.2
468987.2	997043.8	3020	3040	9.2	1.0	93.9	0.5	3.4	1.2	2.2
468996.3	997027.3	3040	3060	9.2	1.0	94.5	0.5	3.4	1.2	2.2

469013.9	997018	3060	3080	9.2	1.0	95.2	0.5	3.4	1.2	2.2
469031.5	997008.7	3080	3100	13.7	3.0	95.8	0.3	4.0	1.7	2.3
469046.8	996997.5	3100	3120	16.3	4.2	96.5	0.2	4.6	2.1	2.5
469051.8	996978.3	3120	3140	16.3	4.1	71.5	0.2	4.5	2.1	2.5
469061.6	996966.7	3140	3160	16.3	4.0	66.0	0.3	4.5	2.0	2.5
469081.1	996970.7	3160	3180	16.3	4.0	73.4	0.3	4.5	2.0	2.5
469100.6	996974.8	3180	3200	16.3	3.9	72.2	0.3	4.4	2.0	2.5
469119.5	996970.6	3200	3220	10.7	1.2	73.2	0.5	3.4	1.2	2.2
469138.3	996964	3220	3240	10.7	1.2	74.1	0.5	3.4	1.2	2.2
469157	996957.3	3240	3260	10.7	1.1	75.1	0.5	3.4	1.2	2.2
469176.1	996961.6	3260	3280	9.8	1.1	76.1	0.5	3.3	1.2	2.2
469195.1	996967.3	3280	3300	10.5	1.2	77.0	0.5	3.4	1.2	2.2
469214.2	996972.8	3300	3320	12.0	2.1	78.0	0.5	3.7	1.4	2.3
469234	996970.8	3320	3340	15.0	3.5	79.0	0.3	4.2	1.9	2.5
469248.5	996958	3340	3360	15.0	3.4	79.9	0.4	4.2	1.8	2.5
469261.3	996955.3	3360	3380	14.3	3.2	80.9	0.4	4.1	1.7	2.5
469272.8	996971.5	3380	3400	11.5	1.3	81.9	0.5	3.4	1.2	2.2
469284.3	996987.8	3400	3420	15.0	3.1	82.8	0.4	4.1	1.7	2.5
469298.6	996997.4	3420	3440	16.2	3.3	83.8	0.4	4.1	1.8	2.5
469314.3	996991.7	3440	3460	12.6	1.8	84.8	0.5	3.5	1.3	2.3
469310	996972.3	3460	3480	14.9	2.7	85.7	0.5	3.8	1.6	2.5
469305.7	996952.8	3480	3500	8.0	2.7	86.7	0.7	3.1	0.9	2.1

A-2: Sub Reach 1B

Nodal Point Location		Spatial Location (m)		DL	K1			K4		
X	Y	From	To	(m2/ sec)	(d^{-1})	K2 (d^{-1})	K3 (d^{-1})	(gm d^{-1} m^{-2})	Kn (d^{-1})	Kr20 (d^{-1})
469301.5	996933.4	0	20	8.2	2.4	63.4	0.4	6.6	0.2	2.1
469292.5	996916.9	20	40	8.2	3.9	61.6	0.4	8.7	9.0	2.1
469287	996902.4	40	60	7.1	3.4	61.7	0.4	8.1	8.5	1.9
469295.9	996884.6	60	80	6.5	3.3	61.7	0.4	8.1	8.5	1.9
469303.8	996866.3	80	100	13.9	3.3	61.8	0.4	8.5	7.9	2.1
469315.9	996850.9	100	120	7.9	3.3	61.7	0.4	8.2	8.3	1.9
469330.1	996837	120	140	15.3	3.3	61.9	0.4	8.6	7.7	2.2
469348.6	996829.8	140	160	11.3	3.3	61.8	0.4	8.4	8.1	2.0
469367.1	996822.4	160	180	7.6	3.3	61.7	0.4	8.1	8.4	1.9
469384.7	996814.1	180	200	6.5	3.3	61.7	0.4	8.1	8.5	1.9
469391.1	996795.3	200	220	8.6	3.3	61.8	0.4	8.2	8.3	1.9
469401.6	996780.8	220	240	14.3	3.3	61.9	0.4	8.6	7.7	2.2
469420.8	996775.6	240	260	16.1	3.3	61.9	0.4	8.6	7.7	2.2
469432.1	996787.9	260	280	11.1	3.3	61.8	0.4	8.4	8.1	2.0
469441.1	996805.7	280	300	6.6	3.3	61.8	0.4	8.1	8.5	1.9
469459.8	996809.8	300	320	6.6	3.4	61.8	0.4	8.1	8.5	1.9
469469.6	996792.5	320	340	6.5	3.4	61.8	0.4	8.1	8.6	1.9
469479.3	996775.1	340	360	8.4	3.3	61.9	0.4	8.2	8.4	1.9
469488.3	996789.7	360	380	8.4	3.3	61.9	0.4	8.2	8.5	1.9
469497.1	996807.5	380	400	8.5	3.3	62.0	0.4	8.2	8.5	1.9
469506	996825.4	400	420	6.7	3.3	62.1	0.4	8.1	8.6	1.9

A-3: Sub Reach 2B

Nodal Point Location		Spatial Location (m)			K1			K4		
X	Y	From	To	DL (m2/sec)	(d^{-1})	K2 (d^{-1})	K3 (d^{-1})	(gm d^{-1} m^{-2})	Kn (d^{-1})	Kr20 (d^{-1})
469514.8	996843.2	0	20	6.699996	2.1	49.2	0.4	9.9	1.6	1.9
469526.5	996836.1	20	40	7.099998	3.9	49.3	0.4	10.6	5.3	1.9
469530.8	996817.2	40	60	7.099998	4.0	49.3	0.4	10.6	5.6	1.9
469539.6	996799.4	60	80	7.700001	4.5	55.6	0.4	10.8	6.6	1.9
469548.4	996781.5	80	100	7.700001	4.5	55.6	0.4	10.8	6.5	1.9
469557.1	996763.7	100	120	8.000003	4.6	56.5	0.4	10.9	6.7	1.9
469570.9	996756.2	120	140	8.300004	4.6	57.3	0.4	10.9	6.8	1.9
469590.3	996760.6	140	160	7.800002	4.6	56.1	0.4	10.9	6.6	1.9
469609.7	996765	160	180	6.100006	3.5	42.6	0.4	10.4	4.6	1.9
469629.1	996769.4	180	200	6.100006	3.5	42.6	0.4	10.4	4.6	1.9
469648.5	996773.8	200	220	6.100006	3.5	42.6	0.4	10.4	4.6	1.9
469667.9	996778.3	220	240	5.600003	3.1	38.2	0.4	10.3	4.0	1.8
469684.5	996770.5	240	260	7.099998	4.0	49.3	0.4	10.6	5.7	1.9
469700	996758	260	280	5.800004	3.4	41.8	0.4	10.4	4.4	1.9
469715.5	996745.5	280	300	6.699996	3.9	48.0	0.4	10.6	5.5	1.9
469731	996733	300	320	6.699996	3.9	48.1	0.4	10.6	5.4	1.9
469735.1	996720.6	320	340	6.699996	3.9	48.1	0.4	10.6	5.3	1.9

A-4: Sub Reach 3B

Nodal Point Location		Spatial Location (m)		DL (m2/ sec)	K1	K2	K3	K4	Kn	Kr20
X	Y	From	To		(d^{-1})	(d^{-1})	(d^{-1})	(gm d^{-1} m^{-2})	(d^{-1})	(d^{-1})
469720.2	996708.1	0	20	6.5	2.1	44.4	0.4	9.9	1.6	1.8
469731.1	996691.5	20	40	7.2	1.9	50.5	0.4	9.9	1.5	1.9
469742	996674.8	40	60	7.2	1.8	50.5	0.4	9.9	1.4	1.9
469730.6	996660	60	80	15.6	5.4	120.7	0.4	10.1	3.2	2.2
469726.7	996644.4	80	100	6.6	1.5	44.8	0.4	9.9	1.3	1.9
469739.6	996637.1	100	120	8.8	2.3	60.1	0.4	9.9	1.7	1.9
469757	996646.8	120	140	8.0	2.1	57.5	0.4	9.9	1.6	1.9
469774.7	996654.4	140	160	8.0	2.1	57.5	0.4	9.9	1.6	1.9
469794.3	996650.6	160	180	8.0	2.1	57.5	0.4	9.9	1.6	1.9
469790	996636.4	180	200	8.0	2.1	57.5	0.4	9.9	1.6	1.9
469786.3	996619	200	220	7.2	1.8	50.5	0.4	9.9	1.4	1.9
469798	996611.3	220	240	8.6	2.2	59.2	0.4	9.9	1.6	1.9
469815.2	996621.2	240	260	7.6	1.8	51.7	0.4	9.9	1.5	1.9
469833.2	996617.5	260	280	7.8	2.1	57.1	0.4	9.9	1.6	1.9
469827.6	996599.8	280	300	8.2	2.1	58.0	0.4	9.9	1.6	1.9
469820.1	996581.4	300	320	6.3	1.4	44.0	0.4	9.9	1.3	1.9
469810.3	996565.4	320	340	10.9	3.3	80.6	0.4	9.9	2.2	2.0
469791.5	996558.7	340	360	10.6	3.3	80.6	0.4	9.9	2.2	2.0
469787.3	996540.2	360	380	6.5	1.7	49.3	0.4	9.9	1.4	1.9
469775.8	996528.1	380	400	8.4	2.2	59.7	0.4	9.9	1.6	1.9
469768.1	996519.5	400	420	8.7	2.6	67.1	0.4	9.9	1.8	2.0
469781.8	996505.5	420	440	6.0	1.4	43.6	0.4	9.9	1.2	1.9
469800.8	996499.5	440	460	5.8	1.4	43.2	0.4	9.8	1.2	1.9
469819.8	996493.5	460	480	5.8	1.4	43.2	0.4	9.8	1.2	1.9
469838.8	996487.6	480	500	11.2	3.4	82.4	0.4	9.9	2.2	2.0
469843.8	996470.8	500	520	14.0	5.1	115.7	0.3	10.1	3.1	2.2
469844.7	996451	520	540	11.1	3.3	82.0	0.4	9.9	2.2	2.0
469855.6	996438.2	540	560	14.4	5.2	117.2	0.3	10.1	3.1	2.2
469864.1	996425.4	560	580	7.7	2.1	57.5	0.4	9.9	1.6	1.9
469859.9	996406	580	600	7.0	1.7	50.5	0.4	9.9	1.4	1.9
469857	996386.6	600	620	6.8	1.7	50.1	0.4	9.9	1.4	1.9
469862.8	996367.5	620	640	5.8	1.3	43.2	0.4	9.8	1.2	1.9
469868.5	996348.5	640	660	8.7	2.5	66.6	0.4	9.9	1.8	2.0
469874.2	996329.4	660	680	8.7	2.5	66.6	0.4	9.9	1.8	2.0
469885.5	996313.3	680	700	8.7	2.5	66.6	0.4	9.9	1.8	2.0
469897.9	996297.7	700	720	7.9	2.1	58.0	0.4	9.9	1.6	1.9
469902.3	996278.8	720	740	7.3	1.7	51.3	0.4	9.9	1.4	1.9
469904.4	996259	740	760	7.2	1.7	50.9	0.4	9.9	1.4	1.9

469906.5	996239.2	760	780	6.1	1.4	44.1	0.4	9.8	1.2	1.9
469919.4	996238.9	780	800	6.7	1.7	49.7	0.4	9.9	1.4	1.9
469937.1	996244.9	800	820	7.0	1.7	50.5	0.4	9.9	1.4	1.9
469952.8	996233.1	820	840	8.8	2.5	67.1	0.4	9.9	1.8	2.0
469958.4	996214	840	860	10.0	2.7	71.0	0.4	9.9	1.9	2.0
469964.1	996194.9	860	880	11.0	3.3	82.0	0.4	9.9	2.2	2.0
469969.7	996175.8	880	900	12.6	4.1	97.5	0.3	10.0	2.6	2.1
469974.7	996156.9	900	920	9.9	2.7	70.6	0.4	9.9	1.9	2.0
469963.2	996140.6	920	940	5.4	1.1	38.8	0.4	9.8	1.1	1.8
469965.2	996121.1	940	960	6.7	1.6	49.7	0.4	9.9	1.4	1.9
469978.2	996108	960	980	6.2	1.4	44.1	0.4	9.8	1.2	1.9
469990.4	996096.1	980	1000	6.2	1.4	44.1	0.4	9.8	1.2	1.9
469981.9	996078.1	1000	1020	6.2	1.4	44.1	0.4	9.8	1.2	1.9
469973.3	996060.1	1020	1040	6.6	1.6	49.3	0.4	9.9	1.3	1.9
469964.8	996042.2	1040	1060	10.4	3.2	79.7	0.4	9.9	2.1	2.0
469956.2	996024.2	1060	1080	10.4	3.2	79.7	0.4	9.9	2.1	2.0
469952.1	996005.1	1080	1100	10.4	3.2	79.7	0.4	9.9	2.1	2.0
469950.8	995985.2	1100	1120	10.4	3.1	79.7	0.4	9.9	2.1	2.0
469957.5	995966.7	1120	1140	11.2	3.3	82.5	0.4	9.9	2.2	2.0
469967	995949.5	1140	1160	12.5	4.0	97.1	0.3	10.0	2.5	2.1
469980.2	995934.6	1160	1180	12.5	4.0	97.1	0.3	10.0	2.5	2.1
469993.5	995919.8	1180	1200	9.3	2.6	68.9	0.4	9.9	1.8	2.0
470012	995914.5	1200	1220	9.9	2.7	70.6	0.4	9.9	1.9	2.0
470031.6	995911.4	1220	1240	6.4	1.4	44.8	0.4	9.8	1.2	1.9
470048.5	995904.4	1240	1260	6.0	1.3	43.7	0.4	9.8	1.2	1.9
470051.6	995885.1	1260	1280	6.0	1.3	43.7	0.4	9.8	1.2	1.9
470052.3	995865.2	1280	1300	6.0	1.3	43.7	0.4	9.8	1.2	1.9
470066.7	995852	1300	1320	6.0	1.3	43.7	0.4	9.8	1.2	1.9
470082.7	995849.8	1320	1340	6.0	1.3	43.7	0.4	9.8	1.2	1.9
470099.4	995860.5	1340	1360	7.5	2.0	57.1	0.4	9.9	1.5	1.9
470118.1	995862.7	1360	1380	8.9	2.5	67.5	0.4	9.9	1.8	2.0
470137.9	995860.3	1380	1400	6.1	1.3	44.1	0.4	9.8	1.2	1.9
470157.6	995857.9	1400	1420	6.1	1.3	44.1	0.4	9.8	1.2	1.9
470169.5	995843.2	1420	1440	6.2	1.3	44.1	0.4	9.8	1.2	1.9
470185.5	995834.8	1440	1460	8.3	1.7	51.3	0.4	9.9	1.4	1.9
470203	995826.5	1460	1480	8.3	1.7	51.3	0.4	9.9	1.4	1.9
470219.3	995815	1480	1500	8.3	1.7	51.3	0.4	9.9	1.4	1.9
470235.6	995803.6	1500	1520	8.3	1.7	51.3	0.4	9.9	1.4	1.9
470254.9	995803.8	1520	1540	8.3	1.7	51.3	0.4	9.9	1.4	1.9
470274.8	995805.6	1540	1560	8.3	1.7	51.3	0.4	9.9	1.4	1.9
470294.6	995807.5	1560	1580	8.3	1.7	51.3	0.4	9.9	1.4	1.9

470310.7	995802.9	1580	1600	8.3	1.7	51.3	0.4	9.9	1.4	1.9
470314.8	995784.8	1600	1620	8.3	1.7	51.3	0.4	9.9	1.4	1.9
470307.1	995766.5	1620	1640	9.9	2.5	67.1	0.4	9.9	1.7	2.0
470299.5	995748.1	1640	1660	8.7	2.0	57.5	0.4	9.9	1.5	1.9
470286.2	995733.5	1660	1680	8.1	1.7	50.9	0.4	9.9	1.4	1.9
470271	995730.1	1680	1700	6.2	1.1	38.8	0.4	9.8	1.1	1.8
470254.2	995740.8	1700	1720	6.2	1.1	38.8	0.4	9.8	1.1	1.8
470237	995737	1720	1740	6.0	1.1	38.8	0.4	9.8	1.1	1.8
470235.5	995717.2	1740	1760	5.7	1.1	38.8	0.4	9.8	1.1	1.8
470234	995697.3	1760	1780	5.8	1.3	43.3	0.4	9.8	1.2	1.9
470236.2	995678.4	1780	1800	5.1	1.3	43.3	0.4	9.8	1.2	1.9
470247.1	995661.8	1800	1820	8.8	2.0	58.4	0.4	9.9	1.5	1.9
470247.5	995644.3	1820	1840	7.7	1.6	49.7	0.4	9.9	1.3	1.9
470239.3	995626.2	1840	1860	7.7	1.6	49.7	0.4	9.9	1.3	1.9
470231.1	995608.1	1860	1880	8.0	1.6	50.5	0.4	9.9	1.4	1.9
470222.9	995589.9	1880	1900	8.2	1.7	50.9	0.4	9.9	1.4	1.9
470224.4	995571.3	1900	1920	8.2	1.7	50.9	0.4	9.9	1.4	1.9
470230.8	995552.5	1920	1940	8.0	1.7	50.9	0.4	9.9	1.4	1.9
470237.2	995533.6	1940	1960	7.8	2.0	57.1	0.4	9.9	1.5	1.9
470243.5	995514.8	1960	1980	5.4	2.0	57.1	0.4	9.9	1.5	1.9
470249.9	995495.9	1980	2000	5.4	1.9	57.1	0.4	9.9	1.5	1.9
470256.3	995477.1	2000	2020	7.5	1.6	49.3	0.4	9.9	1.3	1.9
470269.7	995463	2020	2040	7.6	1.6	49.7	0.4	9.9	1.3	1.9
470284.9	995450.1	2040	2060	9.5	2.1	59.7	0.4	9.9	1.6	1.9
470298.9	995436.1	2060	2080	6.7	1.3	43.3	0.4	9.8	1.2	1.9
470311.9	995421	2080	2100	9.6	2.1	60.1	0.4	9.9	1.6	1.9
470326.8	995412.2	2100	2120	10.2	2.5	68.0	0.4	9.9	1.8	2.0
470346	995415.7	2120	2140	7.3	1.3	44.5	0.4	9.8	1.2	1.9
470364.7	995408.8	2140	2160	7.5	1.6	49.3	0.4	9.9	1.3	1.9
470383.4	995401.8	2160	2180	8.1	1.6	50.9	0.4	9.9	1.4	1.9
470402	995394.9	2180	2200	8.6	1.9	57.1	0.4	9.9	1.5	1.9
470420.7	995388	2200	2220	7.8	1.6	50.1	0.4	9.9	1.3	1.9
470431.2	995395.9	2220	2240	6.9	1.3	43.7	0.4	9.8	1.2	1.9
470435.3	995415.4	2240	2260	7.9	1.6	50.5	0.4	9.9	1.3	1.9
470449.3	995427.6	2260	2280	9.2	2.0	58.8	0.4	9.9	1.5	1.9
470466.7	995437.3	2280	2300	8.4	1.7	51.7	0.4	9.9	1.4	1.9
470484.1	995446.9	2300	2320	9.9	2.4	67.1	0.4	9.9	1.7	2.0
470500.9	995441.7	2320	2340	8.9	2.0	58.0	0.4	9.9	1.5	1.9
470517.6	995430.9	2340	2360	8.2	1.6	51.3	0.4	9.9	1.4	1.9
470534.3	995420	2360	2380	8.9	2.0	58.0	0.4	9.9	1.5	1.9
470551	995409.2	2380	2400	12.7	3.2	83.4	0.3	9.9	2.1	2.0

470567.7	995398.3	2400	2420	12.7	3.2	83.4	0.3	9.9	2.1	2.0
470584.3	995387.5	2420	2440	12.8	3.2	83.4	0.3	9.9	2.1	2.0
470601	995376.6	2440	2460	13.1	3.2	83.4	0.3	9.9	2.1	2.0
470617.7	995365.8	2460	2480	13.5	3.2	83.4	0.3	9.9	2.1	2.0
470634.4	995354.9	2480	2500	13.2	3.2	83.4	0.4	9.9	2.1	2.0

A-5: Sub Reach C

Nodal Point Location		Spatial Location (m)		DL (m2/sec)	K1 (d^{-1})	K2 (d^{-1})	K3 (d^{-1})	K4 (gm d^{-1} m^{-2})	Kn (d^{-1})	Kr20 (d^{-1})
X	Y	From	To							
470646.7	995340	0	20	11.3	1.9	35.5	0.2	9.9	1.6	1.8
470661.5	995327.8	20	40	9.1	2.1	35.5	0.2	9.9	1.9	1.8
470675.1	995316.7	40	60	10.6	2.8	46.4	0.4	9.9	2.7	2.3
470668.3	995298	60	80	11.9	3.7	58.4	0.4	10.0	4.0	3.0
470661.6	995279.2	80	100	11.8	4.3	58.3	0.4	10.1	4.9	3.6
470654.9	995260.5	100	120	10.4	4.2	46.2	0.4	10.0	5.0	3.7
470648.2	995241.8	120	140	8.4	3.7	34.8	0.2	10.0	4.5	3.5
470658.3	995227.5	140	160	3.4	3.4	34.8	0.2	10.0	4.2	3.5
470673.4	995214.6	160	180	8.2	4.0	45.7	0.4	10.0	5.0	4.4
470682.7	995198.1	180	200	6.4	3.4	35.5	0.2	10.0	4.2	3.8
470686.7	995178.7	200	220	6.5	3.2	35.5	0.2	9.9	4.0	3.7
470690.8	995159.2	220	240	8.2	3.6	45.0	0.4	10.0	4.5	4.1
470694.8	995139.7	240	260	6.2	3.1	34.5	0.2	9.9	3.8	3.5
470708	995125.7	260	280	6.2	3.1	34.5	0.2	9.9	3.8	3.4
470723.4	995113.1	280	300	6.2	3.1	34.5	0.2	9.9	3.7	3.3
470738.8	995100.5	300	320	7.0	3.3	39.2	0.2	10.0	4.0	3.4
470754.1	995087.8	320	340	10.3	4.3	58.4	0.4	10.0	5.2	4.3
470753.3	995073.3	340	360	10.3	4.3	58.4	0.4	10.0	5.2	4.3
470741.2	995057.5	360	380	8.4	4.1	52.9	0.4	10.0	4.9	4.1
470729.1	995041.7	380	400	8.2	4.1	52.3	0.4	10.0	4.9	4.1
470717.1	995025.8	400	420	8.2	4.1	52.3	0.4	10.0	5.0	4.1
470711.5	995006.8	420	440	8.2	4.1	52.3	0.4	10.0	5.0	4.1
470706.3	994987.6	440	460	7.3	3.9	46.3	0.4	10.0	4.7	3.9
470706.3	994967.7	460	480	5.9	3.6	39.8	0.2	10.0	4.3	3.5
470719.2	994953	480	500	8.6	4.5	58.0	0.4	10.1	5.5	4.4
470728.8	994936.1	500	520	8.6	4.5	58.0	0.4	10.1	5.5	4.4
470735.8	994917.5	520	540	8.6	4.5	58.0	0.4	10.1	5.5	4.4
470755.1	994916.6	540	560	9.5	4.7	60.5	0.4	10.1	5.8	4.5
470770.5	994913.3	560	580	7.4	4.0	46.3	0.4	10.0	4.8	3.9
470768	994894.8	580	600	7.1	3.9	45.7	0.4	10.0	4.8	3.9
470778.1	994877.6	600	620	4.9	3.2	32.2	0.2	10.0	3.9	3.2
470784.1	994859.6	620	640	5.4	3.4	35.5	0.2	10.0	4.1	3.3
470781.7	994839.9	640	660	6.2	3.6	40.1	0.2	10.0	4.4	3.5
470779.4	994820.1	660	680	6.5	3.9	44.3	0.4	10.0	4.6	3.8
470798.6	994820.9	680	700	9.0	4.7	59.1	0.4	10.1	5.7	4.5
470815.1	994813	700	720	5.3	3.3	35.2	0.2	10.0	4.0	3.3
470829.3	994799	720	740	5.3	3.3	35.2	0.2	10.0	4.0	3.3

470845.2	994803.3	740	760	9.3	4.7	60.1	0.4	10.1	5.9	4.5
470859.6	994804.5	760	780	10.7	5.3	69.5	0.4	10.1	6.6	4.9
470869.6	994787.3	780	800	5.8	3.5	39.2	0.2	10.0	4.2	3.5
470879.7	994770.2	800	820	5.6	4.3	38.7	0.2	10.1	5.2	3.5
470889.8	994753	820	840	7.4	4.8	46.2	0.4	10.1	5.8	3.9
470899.9	994735.8	840	860	7.4	4.8	46.2	0.4	10.1	5.8	3.9
470909.9	994718.7	860	880	15.8	8.0	100.4	0.3	10.5	10.2	6.3
470920	994701.5	880	900	7.0	4.7	45.5	0.4	10.1	5.7	3.9
470933.2	994688.4	900	920	7.0	4.7	45.5	0.4	10.1	5.7	3.9
470952.4	994683.2	920	940	6.3	4.4	40.3	0.2	10.1	5.3	3.5
470960.8	994671.6	940	960	6.1	4.4	40.0	0.2	10.1	5.3	3.5
470959.4	994652.9	960	980	9.4	5.6	60.0	0.3	10.2	6.8	4.5
470971.7	994637.3	980	1000	9.4	5.6	60.0	0.3	10.2	6.8	4.5
470984	994621.6	1000	1020	6.0	4.3	39.7	0.2	10.1	5.2	3.5
470996.3	994606	1020	1040	10.3	6.1	67.9	0.3	10.2	7.5	4.8
470980.7	994594.6	1040	1060	10.3	6.1	67.9	0.3	10.2	7.5	4.8
470969.1	994579.7	1060	1080	10.3	6.1	67.9	0.3	10.2	7.5	4.8
470965.1	994560.7	1080	1100	10.3	6.1	67.9	0.3	10.2	7.5	4.8
470969.2	994541.2	1100	1120	13.4	6.1	67.9	0.3	10.2	7.5	4.8
470973.2	994521.7	1120	1140	12.8	5.6	61.0	0.3	10.2	6.9	4.5
470977.3	994502.2	1140	1160	11.9	5.5	59.0	0.3	10.2	6.7	4.4
470981.4	994482.7	1160	1180	11.9	5.5	59.0	0.3	10.2	6.7	4.4
470985.5	994463.3	1180	1200	11.9	5.5	59.0	0.3	10.2	6.7	4.4
470990.7	994444.9	1200	1220	11.9	5.4	59.0	0.3	10.2	6.7	4.4
471009.9	994439.6	1220	1240	11.9	5.4	59.0	0.3	10.2	6.6	4.4
471029.1	994434.4	1240	1260	11.9	5.4	59.0	0.3	10.2	6.6	4.4
471048.3	994429.1	1260	1280	7.6	4.0	35.7	0.2	10.0	4.7	3.2
471067.5	994423.9	1280	1300	7.4	3.9	35.1	0.2	10.0	4.6	3.1
471086.7	994418.6	1300	1320	7.1	3.9	34.7	0.2	10.0	4.5	3.1
471104.4	994419.8	1320	1340	7.6	3.9	35.7	0.2	10.0	4.6	3.1
471119.4	994432.9	1340	1360	8.0	4.1	39.1	0.2	10.0	4.8	3.3
471134.4	994446	1360	1380	7.5	3.8	35.7	0.2	10.0	4.5	3.1
471149.4	994459.1	1380	1400	15.0	6.6	79.6	0.3	10.3	8.3	5.3
471164.4	994472.2	1400	1420	15.1	6.6	79.6	0.3	10.3	8.3	5.3
471179.3	994485.3	1420	1440	15.1	6.6	79.6	0.3	10.3	8.3	5.3
471194.3	994498.4	1440	1460	15.1	6.6	79.6	0.3	10.3	8.3	5.2
471209.3	994511.5	1460	1480	15.1	6.6	79.6	0.3	10.3	8.3	5.2
471224.3	994524.6	1480	1500	9.8	4.4	45.9	0.4	10.1	5.3	3.6
471239.8	994536.8	1500	1520	8.2	4.0	39.4	0.2	10.0	4.7	3.2
471258.5	994543.6	1520	1540	7.6	3.7	35.4	0.2	10.0	4.3	3.0
471277.2	994550.4	1540	1560	8.8	4.0	40.7	0.2	10.0	4.8	3.2

471295.9	994557.2	1560	1580	8.4	4.0	40.0	0.2	10.0	4.7	3.2
471314.1	994556.7	1580	1600	11.4	4.8	53.2	0.4	10.1	5.8	3.9
471331.4	994547	1600	1620	10.6	4.7	51.5	0.4	10.1	5.6	3.8
471348.7	994537.2	1620	1640	11.0	4.7	52.2	0.4	10.1	5.7	3.9
471353.8	994518.3	1640	1660	11.0	4.7	52.2	0.4	10.1	5.7	3.8
471358.2	994498.9	1660	1680	11.0	4.7	52.2	0.4	10.1	5.6	3.8
471369	994497.2	1680	1700	11.0	4.7	52.2	0.4	10.1	5.6	3.8
471384.9	994509.2	1700	1720	10.7	4.6	51.5	0.4	10.1	5.5	3.8
471400.8	994521.2	1720	1740	10.6	4.6	51.5	0.4	10.1	5.5	3.8
471416	994515	1740	1760	10.6	4.6	51.5	0.4	10.1	5.5	3.8
471431	994501.9	1760	1780	7.1	3.5	34.5	0.2	10.0	4.0	2.8
471446	994488.8	1780	1800	10.2	4.5	50.5	0.4	10.1	5.4	3.7
471449.5	994470.5	1800	1820	7.8	3.6	36.1	0.2	10.0	4.1	2.9
471465.6	994464.5	1820	1840	7.9	3.8	39.1	0.2	10.0	4.4	3.0
471475.2	994456.8	1840	1860	7.7	3.5	35.8	0.2	10.0	4.1	2.9
471464.9	994439.8	1860	1880	7.7	3.5	35.8	0.2	10.0	4.0	2.8
471454.6	994422.7	1880	1900	11.3	4.6	52.9	0.4	10.1	5.5	3.8
471456.7	994410.3	1900	1920	10.0	4.4	50.2	0.4	10.1	5.2	3.6
471475.6	994404.1	1920	1940	10.0	4.4	50.2	0.4	10.1	5.2	3.6
471494.5	994398	1940	1960	11.2	4.6	52.9	0.4	10.1	5.5	3.8
471496.9	994383.5	1960	1980	17.2	7.5	94.0	0.2	10.5	9.5	5.8
471490.6	994364.6	1980	2000	15.1	6.4	79.7	0.3	10.3	8.0	5.1
471484.2	994345.7	2000	2020	15.4	6.5	80.4	0.3	10.3	8.1	5.1
471479.1	994326.9	2020	2040	7.9	3.7	39.2	0.2	10.0	4.2	3.0
471485.7	994308.1	2040	2060	9.1	4.0	44.7	0.4	10.0	4.7	3.3
471480.7	994289.7	2060	2080	9.1	4.0	44.7	0.4	10.0	4.7	3.3
471473	994271.3	2080	2100	9.1	4.0	44.7	0.4	10.0	4.7	3.3
471484.1	994262	2100	2120	8.5	3.7	40.1	0.2	10.0	4.3	3.0
471503.2	994256.4	2120	2140	10.4	4.1	46.3	0.4	10.0	4.8	3.4
471522.3	994250.8	2140	2160	8.4	3.4	34.9	0.3	10.0	3.8	2.8
471541.4	994245.3	2160	2180	3.4	3.3	34.9	0.3	10.0	3.7	2.8
471560.5	994239.7	2180	2200	8.2	4.1	45.8	0.5	10.0	4.7	3.5
471561.8	994223	2200	2220	6.4	3.4	35.6	0.4	10.0	3.8	2.9
471558.4	994203.4	2220	2240	6.5	3.4	35.6	0.4	10.0	3.8	2.9
471555	994183.8	2240	2260	8.2	4.0	45.1	0.6	10.0	4.6	3.5
471551.6	994164.2	2260	2280	6.2	3.3	34.7	0.4	10.0	3.7	2.8
471567.7	994152.6	2280	2300	6.2	3.3	34.7	0.4	10.0	3.6	2.8
471586.6	994151.2	2300	2320	6.2	3.3	34.7	0.4	10.0	3.6	2.8
471606.3	994153.3	2320	2340	7.0	3.6	39.3	0.4	10.0	4.0	3.0
471600.1	994136.1	2340	2360	10.3	4.9	58.5	0.5	10.1	5.8	4.1
471592.3	994117.8	2360	2380	10.3	4.9	58.5	0.5	10.1	5.8	4.1

471586.2	994100	2380	2400	8.4	4.5	53.0	0.5	10.1	5.3	3.8
471603	994089.4	2400	2420	8.2	4.5	52.4	0.5	10.0	5.2	3.8
471619.8	994078.7	2420	2440	8.2	4.5	52.4	0.5	10.0	5.2	3.8
471636.6	994068	2440	2460	8.2	4.5	52.4	0.5	10.0	5.2	3.8
471653.4	994057.4	2460	2480	7.3	4.0	46.4	0.5	10.0	4.7	3.5
471670.2	994046.7	2480	2500	5.9	3.6	39.9	0.4	10.0	4.0	3.0
471687	994036	2500	2520	8.6	4.9	58.1	0.5	10.1	5.7	4.1
471703.8	994025.4	2520	2540	8.6	4.8	58.1	0.5	10.1	5.7	4.1
471720.6	994014.7	2540	2560	8.6	4.8	58.1	0.5	10.1	5.7	4.1
471737.4	994004.1	2560	2580	9.5	5.0	60.5	0.5	10.1	6.0	4.2
471754.2	993993.4	2580	2600	7.4	4.0	46.4	0.5	10.0	4.6	3.4
471771	993982.7	2600	2620	7.1	3.9	45.8	0.5	10.0	4.5	3.4
471787.8	993972.1	2620	2640	4.9	3.0	32.4	0.4	9.9	3.3	2.5
471804.6	993961.4	2640	2660	5.4	3.2	35.6	0.4	9.9	3.5	2.7
471816.8	993947	2660	2680	6.2	3.5	40.2	0.4	10.0	4.0	2.9
471823.8	993928.3	2680	2700	6.5	3.8	44.4	0.5	10.0	4.3	3.3
471830.8	993909.7	2700	2720	9.0	4.9	59.1	0.5	10.1	5.8	4.1
471842.6	993895.4	2720	2740	5.3	3.2	35.3	0.3	9.9	3.5	2.7
471860.3	993886.3	2740	2760	5.3	3.1	35.3	0.3	9.9	3.5	2.6
471878	993877.3	2760	2780	9.3	4.9	60.2	0.5	10.1	5.9	4.1
471895.8	993868.2	2780	2800	10.7	5.6	69.5	0.5	10.2	6.8	4.6
471902.6	993849.6	2800	2820	5.8	3.4	39.2	0.3	10.0	3.8	2.8
471909.3	993830.8	2820	2840	5.6	3.4	38.9	0.3	10.0	3.8	2.8
471915.3	993811.9	2840	2860	7.4	3.9	46.4	0.5	10.0	4.5	3.3
471920.8	993792.7	2860	2880	7.4	3.9	46.4	0.5	10.0	4.5	3.3
471926.4	993773.6	2880	2900	15.8	8.2	100.4	0.4	10.5	10.5	6.5
471931.9	993754.5	2900	2920	7.0	3.9	45.7	0.5	10.0	4.4	3.3
471942.3	993738.8	2920	2940	7.0	3.9	45.7	0.5	10.0	4.4	3.3
471958.4	993727	2940	2960	6.3	3.5	40.5	0.3	10.0	3.9	2.9
471974.4	993715.2	2960	2980	6.1	3.4	40.2	0.3	10.0	3.8	2.8
471991.8	993712.2	2980	3000	9.4	4.9	60.1	0.4	10.1	5.8	4.1
472010.6	993718.6	3000	3020	9.4	4.9	60.1	0.4	10.1	5.8	4.1
472029.5	993725	3020	3040	6.0	3.4	39.8	0.3	10.0	3.8	2.8
472048.3	993731.3	3040	3060	10.3	5.5	68.1	0.4	10.2	6.7	4.5
472067.1	993734	3060	3080	10.3	5.5	68.1	0.4	10.2	6.7	4.5
472085.7	993727	3080	3100	10.3	5.5	68.1	0.4	10.2	6.7	4.5
472085.1	993707.6	3100	3120	10.3	5.5	68.1	0.4	10.2	6.7	4.5
472083.8	993687.8	3120	3140	13.4	5.5	68.1	0.4	10.2	6.7	4.5
472082.4	993667.9	3140	3160	12.8	5.0	61.1	0.4	10.1	5.9	4.1
472087.7	993650.8	3160	3180	11.9	4.8	59.1	0.4	10.1	5.7	4.0
472078.1	993633.7	3180	3200	11.9	4.8	59.1	0.4	10.1	5.7	4.0

472066.6	993617.5	3200	3220	11.9	4.8	59.1	0.4	10.1	5.7	4.0
472059.6	993600.1	3220	3240	11.9	4.8	59.1	0.4	10.1	5.7	4.0
472054.9	993581.1	3240	3260	11.9	4.8	59.1	0.4	10.1	5.7	4.0
472045.9	993563.3	3260	3280	11.9	4.8	59.1	0.4	10.1	5.7	4.0
472034.2	993547.4	3280	3300	7.6	3.1	35.8	0.3	10.0	3.4	2.6
472025.7	993530.6	3300	3320	7.4	3.0	35.2	0.3	10.0	3.3	2.5
472026.6	993510.7	3320	3340	7.1	3.0	34.9	0.3	9.9	3.3	2.5
472027.4	993490.9	3340	3360	7.6	3.1	35.8	0.3	10.0	3.4	2.5
472031.5	993471.5	3360	3380	8.0	3.3	39.2	0.3	10.0	3.7	2.7
472037.1	993452.4	3380	3400	7.5	3.1	35.8	0.3	10.0	3.3	2.5
472044.2	993433.8	3400	3420	15.0	6.5	79.6	0.3	10.3	8.0	5.2
472050.6	993415.1	3420	3440	15.1	6.5	79.6	0.3	10.3	8.0	5.2
472051.5	993395.3	3440	3460	15.1	6.5	79.6	0.3	10.3	8.0	5.2
472052.4	993375.4	3460	3480	15.1	6.5	79.6	0.3	10.3	8.1	5.2
472048.2	993356.8	3480	3500	15.1	6.5	79.6	0.3	10.3	8.1	5.2
472052.3	993337.3	3500	3520	9.8	3.8	46.0	0.4	10.0	4.3	3.2
472056.5	993317.8	3520	3540	8.2	3.3	39.5	0.3	10.0	3.7	2.7
472046.5	993301.7	3540	3560	7.6	3.0	35.5	0.3	10.0	3.3	2.5
472031	993292.6	3560	3580	8.8	3.4	40.8	0.3	10.0	3.8	2.8
472011.1	993292.6	3580	3600	8.4	3.4	40.2	0.3	10.0	3.7	2.7
471993.4	993285.2	3600	3620	11.4	4.3	53.3	0.4	10.1	5.1	3.6
471976.8	993274.2	3620	3640	10.6	4.2	51.6	0.4	10.1	4.9	3.5
471960.2	993263.3	3640	3660	11.0	4.3	52.3	0.4	10.1	5.0	3.5
471943.6	993252.3	3660	3680	11.0	4.3	52.3	0.4	10.1	5.0	3.5
471926.9	993241.4	3680	3700	11.0	4.3	52.3	0.4	10.1	5.0	3.5
471910.3	993230.4	3700	3720	11.0	4.3	52.3	0.4	10.1	5.0	3.5
471901.6	993215.6	3720	3740	10.7	4.2	51.6	0.4	10.0	4.9	3.5
471903.3	993195.8	3740	3760	10.6	4.2	51.6	0.4	10.0	4.9	3.5
471904.9	993175.9	3760	3780	10.6	4.2	51.6	0.4	10.0	4.9	3.5
471906.5	993156.1	3780	3800	7.1	2.9	34.6	0.3	9.9	3.2	2.4
471908.2	993136.3	3800	3820	10.2	4.1	50.6	0.4	10.0	4.8	3.4

A-6: Sub Reach 2D

Nodal Point Location		Spatial Location (m)		DL	K1	K2	K3	K4 (gm d^{-1} m^{-2})	Kn	Kr20
X	Y	From	To	(m2/sec)	(d^{-1})	(d^{-1})	(d^{-1})		(d^{-1})	(d^{-1})
471909.8	993116.4	0	20	8.4	2.0	40.2	0.2	9.9	1.6	1.7
471911.5	993096.6	20	40	8.4	2.0	40.2	0.2	9.9	1.6	1.7
471924.9	993082.1	40	60	10.2	2.1	50.7	0.4	9.9	1.6	1.9
471925.1	993065.1	60	80	10.2	2.1	50.7	0.4	9.9	1.6	1.9
471912	993051.8	80	100	10.2	2.1	50.7	0.4	9.9	1.6	1.9
471894.5	993042.1	100	120	11.0	2.1	50.7	0.4	9.9	1.6	1.9
471877.7	993031.7	120	140	7.5	2.1	50.7	0.4	9.9	1.6	1.9
471862	993022.1	140	160	9.9	2.1	50.7	0.4	9.9	1.6	1.9
471842.8	993027.4	160	180	8.8	2.1	59.6	0.4	9.9	1.6	1.9
471823.6	993032.6	180	200	6.2	2.1	47.6	0.4	9.9	1.6	1.9
471804.4	993037.9	200	220	6.2	2.1	47.6	0.4	9.9	1.6	1.9
471785.2	993043.1	220	240	8.6	2.1	58.8	0.4	9.9	1.6	1.9
471766	993048.4	240	260	6.5	2.1	48.4	0.4	9.9	1.6	1.9
471747.2	993043.8	260	280	6.5	2.1	48.4	0.4	9.9	1.6	1.9
471728.4	993037.2	280	300	8.2	2.1	57.9	0.4	9.9	1.6	1.9
471714.8	993023.9	300	320	6.2	2.1	47.1	0.4	9.9	1.6	1.9
471699.5	993012.1	320	340	6.2	2.1	47.1	0.4	9.9	1.6	1.9
471681.6	993003.5	340	360	6.2	2.1	47.1	0.4	9.9	1.6	1.9
471663.2	992998	360	380	7.0	2.1	49.7	0.4	9.9	1.6	1.9
471646.6	992992.5	380	400	10.3	2.1	70.1	0.4	9.9	1.6	1.9
471632.8	992978.2	400	420	10.3	2.1	70.1	0.4	9.9	1.6	1.9
471619	992963.8	420	440	8.4	2.1	41.8	0.4	9.9	1.6	1.9
471605.2	992949.5	440	460	8.2	2.1	41.3	0.4	9.9	1.6	1.9
471591.4	992935.2	460	480	8.2	2.1	41.3	0.4	9.9	1.6	1.9
471586.8	992916	480	500	8.2	2.1	41.3	0.4	9.9	1.6	1.9
471582.7	992896.5	500	520	7.3	2.1	39.6	0.4	9.9	1.6	1.9
471578.6	992877	520	540	5.9	2.1	34.3	0.4	9.9	1.6	1.9
471588.9	992861.6	540	560	8.6	2.1	42.1	0.4	9.9	1.6	1.9
471602	992846.8	560	580	8.6	2.1	42.1	0.4	9.9	1.6	1.9
471608.4	992828	580	600	8.6	2.1	42.1	0.4	9.9	1.6	1.9
471613.8	992809.1	600	620	9.5	2.1	47.2	0.4	9.9	1.6	1.9
471608.5	992789.9	620	640	7.4	2.1	39.6	0.4	9.9	1.6	1.9
471603.2	992770.7	640	660	7.1	2.1	39.1	0.4	9.9	1.6	1.9
471602.4	992751	660	680	4.9	2.1	30.0	0.4	9.9	1.6	1.9
471602.4	992731.1	680	700	5.4	2.1	30.8	0.4	9.9	1.6	1.9
471602.4	992711.2	700	720	6.2	2.1	34.6	0.4	9.9	1.6	1.9

471599.1	992692	720	740	6.5	2.1	35.4	0.4	9.9	1.6	1.9
471590.2	992674.2	740	760	9.0	2.1	46.1	0.4	9.9	1.6	1.9
471581.3	992656.4	760	780	5.3	2.1	30.5	0.4	9.9	1.6	1.9
471572	992638.9	780	800	5.3	2.1	30.5	0.4	9.9	1.6	1.9
471558.4	992624.9	800	820	9.3	2.1	46.9	0.4	9.9	1.6	1.9
471539.9	992617.7	820	840	10.7	2.1	49.5	0.4	9.9	1.6	1.9
471521.4	992610.4	840	860	5.8	2.1	33.8	0.4	9.9	1.6	1.9
471502.8	992603.4	860	880	5.6	2.1	33.5	0.4	9.9	1.6	1.9
471483.1	992600.3	880	900	7.4	2.1	39.6	0.4	9.9	1.6	1.9
471463.7	992596.2	900	920	7.4	2.1	39.6	0.4	9.9	1.6	1.9
471445	992589.4	920	940	15.8	2.1	68.7	0.4	9.9	1.6	1.9
471426.3	992582.5	940	960	7.0	2.1	39.1	0.4	9.9	1.6	1.9
471407.6	992575.7	960	980	7.0	2.1	39.1	0.4	9.9	1.6	1.9
471389.1	992568.5	980	1000	6.3	2.1	34.9	0.4	9.9	1.6	1.9
471370.5	992561.3	1000	1020	6.1	2.1	34.6	0.4	9.9	1.6	1.9
471352	992554.1	1020	1040	9.4	2.1	46.9	0.4	9.9	1.6	1.9
471340.7	992568.9	1040	1060	9.4	2.1	46.9	0.4	9.9	1.6	1.9
471330.2	992585.7	1060	1080	6.0	2.1	34.3	0.4	9.9	1.6	1.9
471319.7	992602.6	1080	1100	10.3	2.1	48.5	0.4	9.9	1.6	1.9
471309.2	992619.5	1100	1120	10.3	2.1	48.5	0.4	9.9	1.6	1.9
471294.8	992614.7	1120	1140	10.3	2.1	48.5	0.4	9.9	1.6	1.9
471279.1	992602.5	1140	1160	10.3	2.1	48.5	0.4	9.9	1.6	1.9
471263.5	992590.3	1160	1180	13.4	2.1	104.3	0.4	9.9	1.6	1.9
471247.8	992578	1180	1200	12.8	2.1	102.6	0.4	9.9	1.6	1.9
471232.1	992565.8	1200	1220	11.9	2.1	99.1	0.4	9.9	1.6	1.9
471216.4	992553.5	1220	1240	11.9	2.1	99.1	0.4	9.9	1.6	1.9
471200.7	992541.3	1240	1260	11.9	2.1	99.1	0.4	9.9	1.6	1.9
471185	992529	1260	1280	11.9	2.1	99.1	0.4	9.9	1.6	1.9
471175.3	992512.9	1280	1300	11.9	2.1	99.1	0.4	9.9	1.6	1.9
471172.1	992493.7	1300	1320	11.9	2.1	99.1	0.4	9.9	1.6	1.9
471179.4	992475.2	1320	1340	7.6	2.1	65.4	0.4	9.9	1.6	1.9
471168.1	992459.6	1340	1360	7.4	2.1	64.2	0.4	9.9	1.6	1.9
471152.5	992449.4	1360	1380	7.1	2.1	63.7	0.4	9.9	1.6	1.9
471132.9	992446.1	1380	1400	7.6	2.1	65.4	0.4	9.9	1.6	1.9
471113.2	992442.8	1400	1420	8.1	2.1	74.3	0.4	9.9	1.6	1.9
471093.6	992439.5	1420	1440	7.6	2.1	65.4	0.4	9.9	1.6	1.9
471075.1	992433.3	1440	1460	15.1	2.1	110.8	0.4	9.9	1.6	1.9
471058.3	992422.6	1460	1480	15.1	2.1	110.8	0.4	9.9	1.6	1.9
471068.8	992407.6	1480	1500	15.1	2.1	110.8	0.4	9.9	1.6	1.9
471086.4	992398.4	1500	1520	15.1	2.1	110.8	0.4	9.9	1.6	1.9
471104.1	992389.3	1520	1540	15.1	2.1	110.8	0.4	9.9	1.6	1.9

471105.7	992374.4	1540	1560	9.8	2.1	80.8	0.4	9.9	1.6	1.9
471093.6	992359	1560	1580	8.2	2.1	74.9	0.4	9.9	1.6	1.9
471080.2	992344.6	1580	1600	7.6	2.1	64.8	0.4	9.9	1.6	1.9
471084.1	992325.1	1600	1620	8.8	2.1	77.3	0.4	9.9	1.6	1.9
471088.1	992305.5	1620	1640	8.4	2.1	76.1	0.4	9.9	1.6	1.9
471087.2	992287.5	1640	1660	11.4	2.1	97.3	0.4	9.9	1.6	1.9
471073.2	992273.4	1660	1680	10.6	2.1	83.6	0.4	9.9	1.6	1.9
471059.1	992259.4	1680	1700	11.0	2.1	84.7	0.4	9.9	1.6	1.9
471045	992245.3	1700	1720	11.0	2.1	84.7	0.4	9.9	1.6	1.9
471030.9	992231.3	1720	1740	11.0	2.1	84.7	0.4	9.9	1.6	1.9
471019.6	992214.9	1740	1760	11.0	2.1	84.7	0.4	9.9	1.6	1.9
471008.7	992198.3	1760	1780	10.7	2.1	83.6	0.4	9.9	1.6	1.9
470997.7	992181.7	1780	1800	10.6	2.1	83.6	0.4	9.9	1.6	1.9
470986.7	992165.1	1800	1820	10.6	2.1	83.6	0.4	9.9	1.6	1.9
470975.8	992148.5	1820	1840	7.1	2.1	63.1	0.4	9.9	1.6	1.9
470964.8	992131.9	1840	1860	10.2	2.1	82.0	0.4	9.9	1.6	1.9
470953.8	992115.3	1860	1880	7.8	2.1	73.7	0.4	9.9	1.6	1.9
470942.9	992098.6	1880	1900	7.9	2.1	74.3	0.4	9.9	1.6	1.9
470929	992084.6	1900	1920	7.7	2.1	65.4	0.4	9.9	1.6	1.9
470913.9	992071.6	1920	1940	7.7	2.1	65.4	0.4	9.9	1.6	1.9
470897.2	992060.9	1940	1960	11.3	2.1	96.7	0.4	9.9	1.6	1.9
470880.2	992050.6	1960	1980	10.0	2.1	81.4	0.4	9.9	1.6	1.9
470863.1	992040.2	1980	2000	10.0	2.1	81.4	0.4	9.9	1.6	1.9
470846.1	992029.9	2000	2020	11.2	2.1	96.7	0.4	9.9	1.6	1.9
470829.6	992018.9	2020	2040	17.2	2.1	134.4	0.4	9.9	1.6	1.9
470814.5	992007.7	2040	2060	15.1	2.1	110.8	0.4	9.9	1.6	1.9
470794.8	992010.5	2060	2080	15.4	2.1	111.9	0.4	9.9	1.6	1.9
470775.1	992013.3	2080	2100	7.9	2.1	74.3	0.4	9.9	1.6	1.9
470755.4	992016.2	2100	2120	9.1	2.1	78.5	0.4	9.9	1.6	1.9
470737.6	992009	2120	2140	9.1	2.1	78.5	0.4	9.9	1.6	1.9
470720	992007.2	2140	2160	9.1	2.1	78.5	0.4	9.9	1.6	1.9
470702.3	992016.3	2160	2180	8.5	2.1	76.1	0.4	9.9	1.6	1.9
470685.3	992008.4	2180	2200	8.4	2.1	76.1	0.4	9.9	1.6	1.9
470672.4	991994	2200	2220	10.2	2.1	82.0	0.4	9.9	1.6	1.9
470662.6	991976.7	2220	2240	10.2	2.1	82.0	0.4	9.9	1.6	1.9
470652.8	991959.3	2240	2260	10.2	2.1	82.0	0.4	9.9	1.6	1.9
470643	991942	2260	2280	10.2	2.1	82.0	0.4	9.9	1.6	1.9
470633.2	991924.7	2280	2300	18.4	2.1	80.7	0.4	9.9	1.6	1.9
470623.4	991907.4	2300	2320	18.4	2.1	80.7	0.4	9.9	1.6	1.9

Appendix-B: Model Input Data

B-1 Field Measured Data

Month	River Reach	Location		Q (Estimated)	Measured Field Data	
		X	Y		W	H
October	1	468884.8	1000515	0.366	4	0.27
		468897.7	999239.3		4.2	0.21
		468952.8	998050		3.8	0.19
		468949.4	997616.9		3.9	0.16
	2	469857	996386.6	0.464	4.0	0.24
		469981.9	996078.1		3.8	0.31
		470157.6	995857.9		3.9	0.28
		470899.9	994735.8		3.6	0.36
	3	471431	994501.9	0.577	5.1	0.29
		471480.7	994289.7		4.7	0.37
		471558.4	994203.4		4.9	0.33
		470942.9	992098.6		4.6	0.41
	4	470588.2	991225.4	1.08	4.8	0.35
		470683.3	991024.2		5.3	0.41
		471222.9	990147		5.4	0.31
		471409	990173.2		5.6	0.36
	5	471995.9	990177.3	1.41	5.2	0.32
		472163.9	990177.3		5.7	0.29
		472393.3	989845.5		6.3	0.28

		473454.2	988815.8			
November	1	468884.8	1000515	0.126	3.5	0.15
		468897.7	999239.3		3.8	0.13
		468952.8	998050		3.5	0.10
		468949.4	997616.9		3.5	0.09
	2	469857	996386.6	0.16	3.6	0.15
		469981.9	996078.1		3.4	0.19
		470157.6	995857.9		3.5	0.17
		470899.9	994735.8		3.3	0.22
	3	471431	994501.9	0.199	4.3	0.20
		471480.7	994289.7		4.0	0.25
		471558.4	994203.4		4.2	0.23
		470942.9	992098.6		3.9	0.28
	4	470588.2	991225.4	0.374	3.9	0.26
		470683.3	991024.2		4.3	0.31
		471222.9	990147		4.4	0.23
		471409	990173.2		4.6	0.27
	5	471995.9	990177.3	0.486	4.0	0.27
		472163.9	990177.3		4.4	0.25
		472393.3	989845.5		4.8	0.24
		473454.2	988815.8		5.2	0.26
January	1	468884.8	1000515	0.088	3.4	0.11

		468897.7	999239.3		3.7	0.09
		468952.8	998050		3.3	0.08
		468949.4	997616.9		3.4	0.08
	2	469857	996386.6	0.123	3.5	0.13
		469981.9	996078.1		3.3	0.17
		470157.6	995857.9		3.4	0.15
		470899.9	994735.8		3.3	0.20
	3	471431	994501.9	0.14	4.1	0.18
		471480.7	994289.7		3.8	0.23
		471558.4	994203.4		4.0	0.20
		470942.9	992098.6		3.7	0.25
	4	470588.2	991225.4	0.263	3.6	0.24
		470683.3	991024.2		4.0	0.28
		471222.9	990147		4.1	0.21
		471409	990173.2		4.2	0.25
	5	471995.9	990177.3	0.342	3.7	0.26
		472163.9	990177.3		4.0	0.23
		472393.3	989845.5		4.4	0.23
		473454.2	988815.8		4.7	0.24
February	1	468884.8	1000515	0.102	3.5	0.12
		468897.7	999239.3		3.7	0.10
		468952.8	998050		3.4	0.09

		468949.4	997616.9		3.5	0.09
	2	469857	996386.6	0.129	3.5	0.13
		469981.9	996078.1		3.4	0.13
		470157.6	995857.9		3.5	0.17
		470899.9	994735.8		3.3	0.16
	3	471431	994501.9	0.16	4.2	0.19
		471480.7	994289.7		3.9	0.24
		471558.4	994203.4		4.0	0.21
		470942.9	992098.6		3.8	0.26
	4	470588.2	991225.4	0.301	3.7	0.25
		470683.3	991024.2		4.1	0.29
		471222.9	990147		4.2	0.22
		471409	990173.2		4.4	0.25
	5	471995.9	990177.3	0.391	3.8	0.26
		472163.9	990177.3		4.1	0.24
		472393.3	989845.5		4.6	0.23
		473454.2	988815.8		4.9	0.25
March	1	468884.8	1000515	0.124	3.5	0.14
		468897.7	999239.3		3.8	0.13
		468952.8	998050		3.4	0.09
		468949.4	997616.9		3.5	0.09
	2	469857	996386.6	0.157	3.6	0.15

		469981.9	996078.1		3.4	0.19
		470157.6	995857.9		3.5	0.17
		470899.9	994735.8		3.4	0.22
	3	471431	994501.9	0.195	4.3	0.20
		471480.7	994289.7		4.0	0.25
		471558.4	994203.4		4.2	0.23
		470942.9	992098.6		3.9	0.28
	4	470588.2	991225.4	0.366	3.9	0.26
		470683.3	991024.2		4.3	0.31
		471222.9	990147		4.3	0.23
		471409	990173.2		4.5	0.27
	5	471995.9	990177.3	0.476	4.0	0.27
		472163.9	990177.3		4.3	0.25
		472393.3	989845.5		4.8	0.24
		473454.2	988815.8		5.1	0.25

B-2: Hydrological and Metrological Data

Mean Monthly rainfall in three stations (mm).

Station	J	F	M	A	M	J	J	A	S	O	N	D	Ann.total
Akaki	13.7	43.1	60.0	95.1	66.5	128.8	271.1	303.8	140.9	23.9	4.3	3.4	1154.7
AA Obs	17.2	43.6	65.0	93.7	86.4	128.9	257.9	279.7	176.5	38.9	8.4	8.8	1205.2
Bole	15.4	40.1	68.7	92.8	79.5	116.6	234.8	244.1	150.3	34.3	10.1	4.5	1091.3

Mean Monthly rainfall depth at Addis Ababa

	J	F	M	A	M	J	J	A	S	O	N	D	Ann.total
P(mm)	15.43	42.28	64.59	93.84	77.47	124.79	254.6	275.8	155.95	32.39	7.61	5.58	1150.4

Rainfall Coefficients

Station	J	F	M	A	M	J	J	A	S	O	N	D
Akaki	0.14	0.45	0.62	0.98	0.69	1.34	2.82	3.16	1.46	0.25	0.14	0.04
AA Obs	0.17	0.43	0.65	0.93	0.86	1.28	2.57	2.78	1.76	0.39	0.1	0.1
Bole	0.17	0.44	0.75	1.02	0.87	1.28	2.58	2.69	1.65	0.38	0.11	0.05

Mean Monthly Temperature at Addis Ababa (oC)

Temp.	J	F	M	A	M	J	J	A	S	O	N	D	Ann. Mean
Max.	23.3	24.1	24.6	23.9	24.6	22.9	20.3	20.1	21.1	22.4	22.6	22.8	22.7
Min.	8.2	9.5	10.9	11.5	11.7	10.8	10.8	10.8	10.5	9.2	7.9	7.5	9.9

B-3: Literature Parametric Values for Rate Constants and Kinetic Formulations

B-3 (a): DOs Values at Different Temperature Conditions

Temperature, °C	**DOs (mg/l)**
0	14.621
1	14.217
2	13.830
3	13.461
4	13.108
5	12.771
6	12.448
7	12.139
8	11.843
9	11.560
10	11.288
11	11.027
12	10.777
13	10.537
14	10.306
15	10.084
16	9.87
17	9.665
18	9.467
19	9.276
20	9.093
21	8.915
22	8.744
23	8.578
24	8.418
25	8.264
26	8.114
27	7.969

B-3 (b): Ranges of Kinetic Rate Constant Coefficients

Typical Ranges for Qual2E Reaction Coefficients					
Variable	Description	Unit	Range of values	Variable by Reach	Temperature Correction
K_1	Carbonaceous de-oxygenation rate constant	day^{-1}	0.02 - 3.4	Yes	Yes
K_2	Reaeration rate constant	day^{-1}	0.0 - 100	Yes	Yes
K_3	Rate of loss of CBOD due to settling	day^{-1}	-0.36 - 0.36	Yes	Yes
K_4	Benthic oxygen uptake (Sedment Oxygen Demand)	day^{-1}	Variable	Yes	Yes
α_5	O_2 uptake per unit of NH_3 oxidation	mg-O/mg N	3.0 - 4.0	No	No

B-3 (c): Literature Value for Temperature Correction Factor

Default Temperatyre Correction, Θ, Values For Qual2E		
Rate Coefficient	Symbol	**Θ**
BOD Decay	K1	1.047
BOD Settling	K2	1.024
Reaeration	K3	1.024
SOD Uptake	K4	1.060
Organic N Decay	β3 (Kn)	1.047

Appendix-C: Data for Model Calibration

C-1: Wastewater Quality and Quantity of Industrial Pollutants

Industry	Discharge, l/s	Observed Concentration, mg/l			Sub reach in which the industry discharges (see Figure 5.3)
		DO	BOD_5	NH_3-N	
Two oil industries in Woreda 07, Kebeles 17 & 1*	1.8	0	4951	70^+	2A
Addis Soft Drinks Factory	2.9	3.4	247	1.9	2B
Awash Winery	1.6	0	35122	474	3B
Abattoir	8.7	0	2371	101^+	2D

Adopted from Agzew (1998)

* Observed concentrations of the chemical parameters of Teramaj oil factory were adapted and the discharge is obtained by adding the industrial wastewater flow rate of each industry

$^+$ Total Kelajial Nitrogen (TKN) concentration was taken.

C-2: River Water Quality Data for Model Calibration

Sampling date	Sampling point	Distant from A1 (m)	Physical parameter				Chemical parameter					Bacteriological parameter	
			T (^{O}C)	TDS (mg/l)	TSS (mg/l)	TVS (mg/l)	P^{H}	BOD5 (mg/l)	COD (mg/l)	NH_3-N (mg/l)	DO (mg/l)	E.coli (MPN/100ml)	Total coliform (MPN/100ml)
19/09/98	A1	0	13	140	48	26	8.15	2	2.4	0.75	6.8	348000	348000
	A2	1692	13	184	53	45	7.94	11	24	1.46	6.9		
	A3	2983	14	238	124	120	7.69	31	86	4.84	6		
	A4	3614	14	246	37	30	8.05	5.4	7.2	5.24	6.1		
	A5	4947	14	251	38	37	8.04	17	29	5.10	6.1	240000	240000
	A0	5550	14	255	34	31	8.15	13	30	5.08	6.7		
26/09/98	B0	5550	13	275	33	16	8.01	8.2	24	12.14	4.5		
	B1	5550	13	716	136	132	8.15	91	204	47.25	0.5		
	B2	6110	14	369	56	35	7.89	37.7	90	19.08	0.7		
	B3	6465	14	353	113	97	7.61	102.2	200	16.18	0.4	918000	918000
	B4	8000	14	365	35	16	7.99	34.7	136	21.70	3.5		
	B5	8755	14	367	32	22	8.10	35.5	48	14.50	6.5	542000	542000
03/10/98	C1	8755	15	641	180	123	8.69	167	360	45.00	Nil		
	C2	8855	15	507	58	111	8.01	49	80	35.60	0.5	>16090000	>16090000
	C3	9325	15	453	503	259	8.02	180	449	33.55	2.2		
	C4	9775	15	461	259	134	8.22	120	300	17.55	1.2		

	C5	10375	15	477	223	162	8.19	119	440	95.00	0.8	16090000	16090000
	D1	10375	15	466	2284	1169	7.70	3540	8400	45.35	Nil		
17/10/98	D2	10455	15	427	20	19	7.84	45	39	17.78	2.7		
	D3	11805	16	422	80	79	7.78	22	78	19.00	Nil		
	D4	12645	18	422	75	65	7.94	187	234	19.72	1.0		
	E1	12645	18	234	18	2	8.33	3	5.8	11.62	5.5		
	E2	13295	18	406	80	53	8.05	180	234	18.67	1.8	3480000	3480000
	E3	13750	18	405	79	39	8.04	120	175	19.42	2.4		
21/10/98	F1	13750	19	175	48	19	7.95	6.6	16	10.27	5.7		
	F2	14450	19	303	86	24	7.48	13	72	11.50	0.5		
	F3	16150	19	140	91	46	8.09	3.5	20	5.15	6.3		
	F4	21750	19	428	63	33	7.88	26	88	11.60	2.5		
	F5	25950	19	393	281	65	8.21	33	168	16.92	5.3		
	F6	-	19	234	124	88	7.84	39	48	6.30	5.3	2300	2300

Adopted from Agzew (1998)