WATER QUALITY MODELING OF RIVER YAMUNA USING MATLAB PROGRAMMING

A PROJECT REPORT SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF DEGREE

OF

MASTER OF TECHNOLOGY

IN

ENVIRONMENTAL ENGINEERING

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June, 2013

CERTIFICATE

It is to certify that the work presented in this report entitled **"WATER QUALITY MODELING OF RIVER YAMUNA USING MATLAB PROGRAMMING"** by **Sarah Khan, Roll No. 2K11/ENE/08** in partial fulfillment of the requirement for the award of the degree of Master of Technology in Environmental Engineering, Delhi Technological University (Formerly Delhi College of Engineering), Delhi, is an authentic record. The work is being carried out by her under our guidance and supervision in the academic year 2013. This is to our knowledge has reached requisite standards.

The work embodied in this major project has not been submitted for the award of any other degree to the best of our knowledge.

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ACKNOWLEDGEMENT

It is of extreme pleasure to express my deep sense of gratitude and indebtedness to my guide **Dr. S.K. SINGH**, Professor and head of the department, Environmental Engineering and co-guide **Dr. RAJEEV K. MISHRA**, Assistant Professor, Department of Environmental Engineering, Delhi Technological University (Formerly Delhi College of Engineering), for their invaluable guidance, encouragement and patient reviews. Without their help and guidance, this dissertation would have been impossible.

I am highly obliged and pay my gratitude to the Central Pollution Control Board, India for providing the required data regarding the water quality of river Yamuna and endow me with the information needed for my project.

I am grateful to my parents for their moral support, they have been always around to cheer me up, in the odd times of this work. I am also thankful to my classmates Sarbari Dutta and Charu Sharma & friends Bhavna Rathore and Heena Dhiman for their unconditional support and motivation during this work. Lastly I want to thank my friend Betsy Sebastian for helping me out with the coding part of my project.

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DECLARATION

I, hereby declare that the work being presented in this Project Report entitled **"Water Quality Modeling of River Yamuna using MATLAB Programming"** is an original piece of work and an authentic report of our own work carried out during the period of 4^{th} Semester as a part of our major project.

The data presented in this report was generated & collected from various sources during the above said period and is being utilized by us for the submission of our Major Project Report to complete the requirements of Master's Degree of Examination in Environmental Engineering, as per Delhi Technological University curriculum.

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ABSTRACT

Water Quality Modeling plays a significant role in predicting the health of streams, rivers, lakes and various other surface water sources. By means of modeling various parameters that effects quality of water can be estimated and proper measures can be applied based on the predicted results which help in safeguarding the detoriating condition of the resource. The work carried out in this project report deals with the study of water quality modeling emphasing river water quality modeling and thereby development of a mathematical model to predict DO and BOD concentration of the river. The area chosen for the simulation of model is the 22 km stretch of river Yamuna at Delhi. The river Yamuna occupies a unique position in the cultural ethos of India. Being the largest tributary of river Ganga it has been one of the most important river of northern India. But due to rapidly increasing urbanization along its stretch the river is now compromising with its quality. The entire stretch of Yamuna river from origin to its confluence with Ganga is used for various human activities, the results of these activities are the generation of wastewater. River Yamuna receives significantly high amount of organic matter, which is generally, originates from domestic as well as industrial sources. For biodegradation, this organic waste requires oxygen, causing significant depletion of dissolved oxygen in river water. The oxygen depletion not only affects biotic community of the river but also affects its self-purification capacity. In this project model is made to run for three different cases, firstly for each month of the year, secondly the variation on the basis of yearly average where the actual scenario of river has been compared with the case in which one of the solution to the problem is applied that shows the improving condition. And lastly the variation at minor points has been observed to identify the most problematic region. Thus an effort has been made in the direction of improving the quality of Yamuna by predicting its DO and BOD level form source till end so that suitable recommendations can be provided to the decision makers for future scope.

Keywords: Mathematical Modeling, Water Quality, River Yamuna, Biological Oxygen Demand, Dissolved Oxygen

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LIST OF ABBREVIATIONS

DO	Dissolved Oxygen
BOD	Biochemical Oxygen Demand
CPCB	Central Pollution Control Board
NCT	National Capital Territory
CBOD	Carbonaceous Biological Oxygen Demand
NBOD	Nitrogenous Biological Oxygen Demand
SIMCAT	SIMulation of CATchments
EA	Environment Agency
TOMCAT	Temporally Overall Model for CATchments
USEPA	United States Environmental Protection Agency
QUASAR	QUAlity Simulation Along River systems
QUESTOR	QUality Evaluation and Simulation TOol for River systems
DHI	Danish Hydraulic Institute
UPM	Urban Pollution Management
WJC	Western Yamuna Canal
EJC	Eastern Yamuna Canal
SOD	Sediment Oxygen Demand
u/s	Upstream
d/s	Downstream
ETP	Effluent Treatment Plant

CHAPTER – 1

INTRODUCTION

1.1 BACKGROUND

Water is life and thus the quality of water is an essential measure of the quality of life or rather the assurance of the existence of life. Water is one of the most important and basic natural resources and the development of this natural resource plays a crucial role in economic and social development processes. Water covers 71% of the Earth's surface and is vital for all known forms of life**.** Of which 96.5% is found in oceans, 1.7% as groundwater, 1.7% in glaciers and icecaps of Antartica and Greenland, a small fraction in other large water bodies, and 0.001% in the air as water vapour and clouds (formed of solid and liquid water particles suspended in air). Only 2.5% of the Earth's water is freshwater and less than 0.3% of all freshwater is in rivers, lakes, atmosphere and an even smaller amount of the Earth's freshwater (0.003%) is contained within biological bodies and manufactured products. While the total amount of water available in the world is constant and is generally said to be adequate to meet all the demands of mankind, its quality and distribution over different regions of the world is uneven and causes problems of scarcity and suitability. It is therefore imperative that man develops, uses and manages this scarce commodity as rationally and efficiently as possible. In order to execute this task, accurate and adequate information must be available about the quality of this natural resource under constantly changing human pressures and natural forces**.**

Water on Earth moves continually through the hydrological cycle of evaporation and transpiration together termed as evapotranspiration, condensation, precipitation and runoff, usually reaching the sea. Water has always been perceived as a gift from the gods as it rained from the heavens. The hydrological cycle is a major driving force which explains the interactions between the atmosphere, hydrosphere and lithosphere. The most fundamental human needs of water are for drinking, cooking and personal hygiene. To meet these needs, the quality of the water used must pose no risk to human health. Natural water bodies are able to serve many uses. One of them is the transport and assimilation of waterborne wastes. But as natural water bodies assimilate these wastes, their quality changes. The quality of the water in nature also affects the condition of ecosystems, that all living organisms depend on. At the same time, humans use water bodies as convenient sinks for the disposal of domestic, industrial and agricultural wastewaters. This of course degrades the quality of those water bodies. If the quality of water drops to the extent that other beneficial uses are adversely impacted, the assimilative capacities of those water bodies have been exceeded with respect to those impacted uses. Water resources management involves the monitoring and management of water quality as much as the monitoring and management of water quantity. It employ measures to insure that the total pollutant loads discharged into receiving water bodies do not exceed the ability of those water bodies to assimilate those loads while maintaining the levels of quality specified by quality standards set for those waters.

Freshwater is a finite resource, essential for agriculture, industry and even human existence. Without freshwater of adequate quantity and quality sustainable development will not be possible. Water pollution and wasteful use of freshwater threaten development projects and make water treatment essential in order to produce safe drinking water. Discharge of toxic chemicals, over-pumping of aquifers, long-range atmospheric transport of pollutants and contamination of water bodies with substances that promote algal growth (possibly leading to eutrophication) are some of today's major causes of water quality degradation. It has been unequivocally demonstrated that water of good quality is crucial to sustainable socio-economic development. Aquatic ecosystems are threatened on a world-wide scale by a variety of pollutants as well as destructive land-use or water-management practices. Some problems have been present for a long time but have only recently reached a critical level, while others are newly emerging. Gross organic pollution leads to disturbance of the oxygen balance and is often accompanied by severe pathogenic contamination. Accelerated eutrophication results from enrichment with nutrients from various origins, particularly domestic sewage, agricultural run-off and agro industrial effluents. Lakes and impounded rivers are especially affected.

Direct contamination of surface waters with metals in discharges from mining, smelting and industrial manufacturing is a long-standing phenomenon. However, the emission of airborne metallic pollutants has now reached such proportions that long-range atmospheric transport causes contamination, not only in the vicinity of industrialized regions, but also in more remote areas. Similarly, moisture in the atmosphere combines with some of the gases produced when fossil fuels are burned and, falling as acid rain, causes acidification of surface waters, especially lakes. Contamination of water by synthetic organic micropollutants results either from direct discharge into surface waters or after transport through the atmosphere. Today, there is trace contamination not only of surface waters but also of groundwater bodies, which are susceptible to leaching from waste dumps, mine tailings and industrial production sites.

The composition of surface and underground waters is dependent on natural factors (geological, topographical, meteorological, hydrological and biological) in the drainage basin and varies with seasonal differences in runoff volumes, weather conditions and water levels. Large natural variations in water quality may, therefore, be observed even where only a single watercourse is involved. Human intervention also has significant effects on water quality. Some of these effects are the result of hydrological changes, such as the building of dams, draining of wetlands and diversion of flow. More obvious are the polluting activities, such as the discharge of domestic, industrial, urban and other wastewaters into the watercourse (whether intentional or accidental) and the spreading of chemicals on agricultural land in the drainage basin.

Pollutant loadings degrade water quality. High domestic waste loads can result in high bacteria, viruses and other organisms that impact human health. High organic loadings can reduce dissolved oxygen to levels that can kill parts of the aquatic ecosystem and cause obnoxious odors. Nutrient loadings from both urban and agricultural land runoff can cause excessive algae growth, which in turn may degrade the water aesthetically, recreationally, and upon death result in low dissolved oxygen levels. Toxic heavy metals and other micropollutants can accumulate in the bodies of aquatic organisms, including fish, making them unfit for human consumption even if they themselves survive.

Pollutant discharges originate from point and non-point sources. A common approach to controlling point source discharges, such as from storm water outfalls, municipal wastewater treatment plants or industries, is to impose standards specifying maximum allowable pollutant loads or concentrations in their effluents. This is often done in ways that are not economically efficient or even environmentally effective. Effluent standards typically do not take into account the particular assimilative capacities of the receiving water body. Non-point sources are not as easily controlled and hence it is difficult to apply effluent standards to non-point source pollutants. Pollutant loadings from non-point sources can be much more significant than point source loadings. Management of non-point water quality impacts requires a more ambient-focused water quality management program.

Water quality monitoring is the foundation on which water quality modeling is based. Monitoring provides the information that permits rational decisions to be made on the following:

- Describing water resources and identifying actual and emerging problems of water pollution.
- Formulating plans and setting priorities for water quality modeling.
- Developing and implementing water quality modeling programs.
- Evaluating the effectiveness of modeling actions.

Ambient-based water quality prediction and management involves considerable uncertainty. No one can predict what pollutant loadings will occur in the future, especially from area-wide non-point sources. In addition to uncertainties inherent in measuring the attainment of water quality standards, there are uncertainties in models used to determine sources of pollution, to allocate pollutant loads, and to predict the effectiveness of implementation actions on meeting water quality standards. The models available to help managers predict water quality impacts relatively simple compared to the complexities of actual water systems. These limitations and uncertainties should be understood and addressed as water quality management decisions are made based on their outputs.

1.2 OBJECTIVES OF THIS STUDY

The DO concentration is a primary measure of a stream's health, but the DO concentration responds to the BOD load. Many streams and rivers in India as well as in the other parts of the world have suffered from DO deficit, which is very critical to aquatic life. Investigators have continuously studied the DO uptake characteristics in stream water in relation to different sinks and sources in order to develop mathematical models describing the DO consumption. The minimum value of the DO concentration has been of particular significance in wastewater treatment design calculations and to regulatory agencies.

In India CPCB is the nodal agency responsible for monitoring and publishing water quality data and reports. It has categorized surface water quality in the certain classes based on the DO and BOD concentration of rivers and streams. According to CPCB, the river water quality standard assigned to the river Yamuna in NCT stretch is class C (Table 1). This classification is done according to the best use designated to the surface water.

Table 1.1: The surface water quality classification given by CPCB, India

Characteristic	Class				
	A	B	C	D	E
DO (mg/l)	>6	>5	>4	>4	<4
BOD(mg/l)	<2	<3	<4	<6	>6

Source: (CPCB, 1980-81)

A:Drinking water sources without conventional treatment but after disinfection.
B:Bathing, Swimming and Recreation.
C:Drinking water source after conventional treatment.
D:Propagation of wild life, fisheries etc.
E:Irrigation, industrial cooling and controlled waste disposal.

Water quality modeling in a river has developed from the pioneering work of Streeter and Phelps (1925) who developed a balance between the dissolved oxygen supply rate from reaeration and the DO consumption rate from stabilization of an organic waste in which the BOD deoxygenation rate was expressed as an empirical first order reaction, producing the classic DO sag model. When the dispersion process is considered, the governing equation becomes a partial differential equation.

The primary objective of the study presented here is to predict the water quality of river Yamuna passing through the NCT of Delhi by assessing the surface water quality parameters.

Main Objectives of the study are:

1. To study the concept of Surface Water Quality Modeling emphasing river water quality modeling.
2. To study the softwares already in use for developing Water Quality Models.
3. To develop DO-BOD model using MATLAB as a programming tool.
4. Implementation of developed model on river Yamuna flowing through Delhi segment for assessing its quality for three different cases.

Case A The model is made to run for a time period of one year from janurary-2011 to December-2011 and the predicted values are compared with the observed values of data set collected from CPCB. The location under consideration is the 22 km stretch between Wazirabad barrage and Okhla. barrage. The DO-BOD profile is drawn for the complete stretch at each node points (the confluence point of drain with river).

Case B In this case the actual scenario of low water discharge d/s of Wazirabad barrage has been compared with the scene in which the flow d/s is maintained to meet out the environment flow concern of various stretches (this flow has been calculated by using mike11 model; Rai, 2011), using data for the year-2011.

Case C In the last case the DO-BOD profile between two subsequent nodes is determined to predict the change in quality of water in-between, using data for the year 2011.

CHAPTER – 2

LITERATURE REVIEW

2.1 HISTORICAL PERSPECTIVE OF SURFACE WATER QUALITY MODELING

During the last few years, research in numerical modeling of surface water bodies has led to some significant advances. More sophisticated computational frameworks which take advantage of rapidly increasing computer power have been developed. These include more complete fundamental equations describing the physical processes occurring, improved specification of the boundary conditions which drive the flow and refined numerical procedures which better describes the geometry of the simulation region and take advantage of the ever increasing power of computer. Additionally more attention has been paid to model verification than in the past. Significant efforts were made to compare the numerical behavior of various models as well as to compare the relative abilities of these models in matching measured data sets. Thus hydrodynamic modeling is now a little less art and a bit more science than few years ago.

River water quality modeling has a long history that dates back to the pioneering work of Streeter and Phelps in 1925. Streeter and Phelps described the bacterial decomposition of organic carbon characterized by BOD and its impact on dissolved oxygen conditions. In the course of the next half-century, this simple, first-order kinetics approach was further developed in three major steps. The first was the refinement of the two-state-variable model by introducing the settling rate (of particulate matter) in addition to the decay rate (of dissolved matter) and the so-called sediment oxygen demand. The model was also improved by using research results on the surface reaeration rate. Finally, an extension was made by distinguishing between CBOD and NBOD, which led to a third state variable. The second step was the incorporation of a simplified nitrogen cycle, ammonia, nitrate, and nitrite appeared as new components. This extension appears in QUAL1, the first model of the QUAL family. Ten years later the third step further extended the approach by incorporating phosphorus cycling and algae, which resulted in organic nitrogen, organic phosphorus, dissolved phosphorus, and algae biomass (in terms of chlorophyll a) as additional state variables. This model is known today as QUAL2E and is widely used. It has also been adopted in a practically unchanged form in various simulation software and decision support systems.

2.1.1 Advancement in River Water Quality Modeling at global level

The DO concentration is a primary measure of a stream’s health, it responds to the BOD load. DO concentration is a common indicator of the health of the aquatic ecosystem. DO was originally modeled in the Ohio River (US) by Streeter and Phelps (1925). who developed a balance between the dissolved oxygen supply rate from reaeration and the dissolved oxygen consumption rate from stabilization of an organic waste in which the BOD deoxygenation rate was expressed as an empirical first order reaction, producing the classic dissolved oxygen sag model. DO-BOD models are the extension of box model which is based on the concept of mass transfer phenomenon, two process govern this phenomenon, advective mass transfer and dispersive mass transfer. When the dispersion process is considered, the governing equation becomes a partial differential equation. However, the effect of dispersion on BOD and DO in small rivers is negligible as given by Li, 1972, Thomann, 1974, McCutcheon, 1989. Several investigators such as Thomas, 1957, Young and Clark, 1965, Clark and Viessman, 1965, Nemerow, 1974, Tebbutt and Berkun, 1976 presented data showing that second order rather than first order reactions frequently describe the stabilization of wastewaters, but none of these authors incorporated a second order BOD reaction into the DO sag equation. Butts and Kothandaraman, 1970 analyzed stream samples from the Illinois River and found that in the majority of these samples, BOD decay was described better by a first order reaction model. Adrian and Sanders 1998 developed an analytical solution for the DO sag equation which incorporated a second order BOD reaction, but their development involved integration of cumbersome equations. The literature on BOD reaction orders which are less than first order has been reviewed by Adrian and Sanders 1992-93 while Adrian 1999, Adrian and Sanders 1998, and Adrian 2004, reviewed three-halves order, second order, and multiorder BOD reactions, respectively. Apart from these advancements several other models have been developed and various reports have been published considering the basics taken from above literatures. A water quality modeling study was performed for water quality management of large river systems where autochthonous sources and denitrification play an important role in BOD and nitrogen dynamics. The model was based on the USEPA’s QUAL2E and several modifications were made in the computer code to overcome limitations of QUAL2E by Seok Soon Park and Yong Seok Lee, 2001 at Nakdong River, Korea. A stochastic model for the evolution of DO and BOD components along a river with independent BOD point inputs has been developed by Boano, Revelli and Ridolfi, 2005. The model examines the case in which the initial conditions and the concentrations of the inputs are affected by uncertainty. Another study was conducted taking in account application of automated QUAL2K for water quality modeling and management in the Bagmati River, Nepal by Kannel, S. Lee, Y.S. Lee, S.R. Kanel, G.J. Pelletier, 2007.

2.1.2 River Water Quality Simulations in India

In India, a large number of river water quality modeling efforts have been made during the recent past for BOD and DO simulations. Bhargava 1983, Choudhary 1992, Kazmi and Hansen 1997, Ghosh and McBean 1998, Jain 1996, Jain 1998, Abbasi 1999, Priyadarshini and Reddy 2000, Dikshit 2000, Sharma 2000, Hussain and Jha 2003, Gupta 2004, Kazmi and Agrawal 2005, Paliwal and Sharma, 2007, have made their contributions towards it. Refined models for BOD and DO simulations in river Kali by Jha, Ojha and Bhatia 2007, which is one of the most polluted rivers in India, use of STREAM II as a modeling package to determine the pollution load due to organic matter in the River Yamuna during its course through Delhi, India Sharma and Singh 2008 are some of the studies which were carried out few years back. Tyagi, Gakkhar, Bhargava, 1998 have made an effort to present a mathematical model accounting for dispersion effects, settling of the settleable part of BOD and the periodic variation of the BOD source. A water quality Beck modified Khanna Bhutiani model was developed to study limnological status of river Suswa (tributary of river Ganga, Dehradun) by Bhutiani and Khanna, 2006.

2.2 A review of available in-stream Models

The models currently used over the world for simulating water quality include RQP, SIMCAT, TOMCAT, ISIS, MIKE-11 and QUASAR. Most of the widely-used models are designed to simulate the traditional set of 'sanitary determinants' such as BOD, ammonium (NH_4^+) and DO. The use of a particular model depends on the systems to be modeled and on the legislation in place in that country. Regulatory bodies tend to use 'tried and tested' models that are generally simple, while other organizations such as academic institutions often use models to investigate more fundamental aspects of processes or transport mechanisms. In larger systems, water quality data are generally collected to provide qualitative analysis while intensive monitoring and data collection will only occur at the small scale where the objective is to quantify model parameters for specific processes. Thus, it will generally be the case that data will need to be collected from a number of sources when modeling large systems. The limiting factor of data availability explains the popularity of hybrid/stochastic models. These models provide the necessary statistical output for relating to the water quality standards, but they also require relatively little data because they generally do not attempt to represent hydrochemical processes other than by a simple first order decay rates. Because of this, they can be applied to almost any river catchment with no detailed knowledge of that catchment, but the assumptions made and the limitations of using a model with such simple processes must be acknowledged.

2.2.1 SIMCAT

In UK, several river water-quality modeling tools have been developed since the introduction of percentile based standards which utilize the Monte Carlo simulation approach. SIMCAT is an EA model that describes the water quality of rivers in a catchment. SIMCAT is a stochastic, 1D, steady state, deterministic model which represents inputs from point-source effluent discharges and the behavior of solutes in the river on the basis of three types of behavior:

- Conservative substances which are assumed not to be transformed in any way such as chloride;

- Non-conservative substances which decay, where a first-order (exponential) relationship is used to represent the transformation, for example BOD and nitrate;
- DO is represented by a relationship involving BOD decay, temperature and reaeration.

SIMCAT can model up to 600 reaches and can include up to 1400 features such as rivers, discharges, abstractions, diffuse pollution, and weirs. Once the model skeleton has been assembled, the model can be run with up to 2400 shots possible. For each run, the model randomly selects values for flow and quality from the given distributions for all of the inputs and can take account of default or user-defined correlations between flow and quality at different sites. For example, the user can specify a percentage correlation between the flow rate at an effluent discharge and the flow in the receiving river. Starting at the top reach in the system, the process equations are solved for each determinant the output from this reach is then used as the inputs for the next reach in the network and so on down the system. This procedure is then repeated for the required number of shots and summary statistics for each reach are calculated from the results. It is clear that the model SIMCAT is capable of producing simulations of DO in freshwater systems. As a steady-state model, SIMCAT cannot represent temporal variability, which can be significant in lowland rivers, and although monthly distributions can be entered as an alternative to annual ones this can only provide limited improvements whilst increasing the data requirements significantly. A major concern regards the auto-calibration routines. Whilst they will certainly expedite model application, it will be too easy for an inexperienced user to accept parameter values or runoff rates for the systems that are unrealistic. If the preceding limitations are accepted and understood, SIMCAT will continue to be of use to regulatory bodies, but the lack of a dynamic mode and the overly simplistic processes suggest that this model is not particularly suitable for complex scenarios or in a predictive context.

2.2.2 TOMCAT

The model TOMCAT was developed by the UK water utility company Thames Water in the early 1980s (Bowden and Brown, 1984). The model was developed to assist in the process of reviewing effluent quality standards at all Thames Water sites in order to meet river-water quality objectives. With this in mind, the model was designed so that rapid applications to any catchment were possible, it could allow the estimation of diurnal and time of travel effects, and be able to correlate any effluent discharge to the river with the flow in the receiving water. The correlations enable TOMCAT to take account of seasonal and diurnal effects in the observed quality and flow data and then reproduce these effects in the simulated data. Since this model was developed by Thames Water, it is clear that TOMCAT has been used in modeling activities on the River Thames and its tributaries. The model was designed to be quick and easy to set up and to produce output suitable for comparison with UK legislation, and so in these respects it is well suited to modeling by both water utility companies and regulators. However, if the distributions of the determinants required have not already been calculated, this must be carried out using as large a data set as possible if the results are to be meaningful. Furthermore, even with excellent data, the model will be limited by the over simplistic descriptions of flow and water-quality processes, and despite the inclusion of some seasonality it is not a dynamic model and so cannot examine shorter-term variability such as diurnal effects. Therefore, like SIMCAT, TOMCAT will prove to be of use for modeling lowland rivers to organizations like water utility companies and the EA, but the lack of a dynamic mode and the overly simplistic processes (including DO) suggest that this model is not suitable for simulating anything other than the general condition of a river, nor can it be deemed suitable for predictive modeling.

2.2.3 QUAL2E

The QUAL2E model (Brown and Barnwell, 1987) is the latest version of the model QUAL-II which was itself developed by Tufts University and the USEPA from the model QUAL-I by F.D. Masch & Associates and the Texas Development Board in the 1960s. The QUAL2E model is a 1D, steady-state model of in-stream flow and water-quality. It simulates DO and (up to 15) associated water quality determinants along a river and its tributaries. As a steady-state model, it is limited to periods when the stream flows and any discharges are essentially constant. However, the model is able to account for the effects of meteorological diurnal variations on certain water-quality determinants such as DO and temperature. The literature review did not reveal any applications of QUAL2E to UK river systems, but it has been successfully applied in many situations around the world. The model is clearly useful for simulating water quality in freshwater systems. However, the use of single values rather than statistics as inputs may also lead to errors in representing the real system. Perhaps the greatest concern with regard to simulating DO is the fact that this is a steady-state model. The model documentation claims that some seasonality and diurnal effects are accounted for, but QUAL2E is not a dynamic model and so cannot account for shorter-term variability such as diurnal effects. Lowland rivers can show significant temporal variability over a range of scales, and it is known that that certain acceptable quality limits are exceeded from time to time. This indicates that stream quality should not be judged only in terms of say yearly average indices, but that transient, intermittent deterioration of quality is also important, and may be of growing concern for the future.

2.2.4 QUASAR, HERMES and QUESTOR

The three models QUASAR, HERMES and QUESTOR are actually all versions of the same model called QUASAR which was developed from a model of the Bedford Ouse QUASAR describes the time-varying (dynamic) transport and transformation of solutes in branched river systems using 1D ordinary, lumped parameter differential equations of mass conservation. PCQUASAR and QUESTOR also have the option of running the model stochastically using a Monte Carlo method like SIMCAT and TOMCAT. HERMES has been simplified as it is only used for teaching purposes, but PC-QUASAR and QUESTOR are capable of simulating large branched river systems with multiple influences such as effluent discharges, abstractions and weirs, etc. QUASAR satisfies many of the inadequacies of SIMCAT and TOMCAT in that the process descriptions are much more complete, and improves on QUAL2E as well, because it can run dynamically and stochastically, but the data requirements for running this model are considerable for dynamic simulations. Of more concern is the flow representation, which is rather simple for a dynamic model and will not cope with complex flow patterns such as backflows. However, in non-tidal rivers this should not be an issue other than during extreme flow conditions. As a stochastic model, QUASAR should be improved to include correlations and an increased number of distribution types as available in SIMCAT and TOMCAT, but as a dynamic model QUASAR seems to be well suited to modeling large freshwater river systems provided there are sufficient data.

2.2.5 MIKE-11

MIKE-11 has been developed by the DHI and forms part of a suite of software marketed by themselves and other consultants in the UK and Europe. The model has been developed from the DHI's system 11 originally released in 1972 and is marketed as a modular package based around a 1D full-hydrodynamic model that simulates the dynamic water movements in a river or stream. The modules that may be added include those that simulate advection–dispersion, water quality, sediment transport, eutrophication, and rainfall-runoff. MIKE-11 is widely used as a hydraulic model by flood defence workers in the EA, but it is also used as a water quality model as part of the UPM methodology where it is used to assess the impact of intermittent discharges on rivers and estuaries. Because it uses a full-hydrodynamic model it is capable of modeling tidal sections of rivers as well as in freshwater applications. From the literature search, the model MIKE-11 has been applied as a water-quality model to the River Derwent, near Derby in central England and the Yamuna River, near Delhi in northern India. The model is clearly well suited to complex systems and can cope with complex flow patterns such as backflows and loops in the system. The processes simulated are also comprehensive, although the level of complexity is perhaps too great at level six, because the data requirements will be too high and the calibration will be difficult. If instead the model is used at too low a level the ease of setting up the model may cause a user to erroneously assume that they have a calibrated model representing the most important processes in the river, while in fact given a scarce dataset the model may calibrate equally well using several combinations of parameters, any of which may most accurately reflect the in-stream processes. In this case, a simpler model could provide equally good results given the amount of data available and would not be so easily misinterpreted.

2.2.6 ISIS

The ISIS model has been developed by HR Wallingford from earlier models such as ONDA and SALMON-Q and the software has been developed and marketed by the consultancy Halcrow UK. ISIS is a dynamic model capable of simulating flow, but more as a flow model for the flood defence groups than for water-quality modeling. Like MIKE-11 it is modular comprising the following:

- Short term flood hydrology and long term hydrology including subsurface interaction.
- Flow routing and full hydrodynamic simulations.
- Simple water quality analysis for urban pollution management.
- Sediment transport modeling.

The model structure is therefore very similar to MIKE-11, although the actual water-quality process representations are different. The ISIS Quality module simulates a range of water quality determinants including: general conservative and decaying pollutants, coliforms, salt, temperature, pH, DO, BOD, organic and oxidised nitrogen, ammonium, phytoplankton (floating algae), macrophytes (fixed, rooted aquatic plants), benthic algae (algae on the river bed), adsorbed phosphorus, silicates, and cohesive sediments. It is also able to model some sediment–water column processes.

The literature review did not reveal any applications of ISIS as a water-quality model, although it is more widely used in flood simulation applications. The lack of presence in the literature is quite likely to be related to the high cost of the software. Expensive software is more often used in commercial than academic situations and so the results of applications do not often make it into the public literature. However, the hydrodynamic model allows ISIS to cope with the full range of flows seen in lowland rivers and it can even account for floods that leave the confines of the river bank. The water quality processes that can be simulated are numerous and the preceding sections have shown that the ISIS model is the most complex of all the water-quality models described in this review. Furthermore, ISIS would benefit from the ability to enter data in a more simple statistical format than the shape functions, such as means and standard deviations on a define distribution.

CHAPTER – 3

MODELING APPROACHES TO WATER QUALITY

3.1 GENERAL CONCEPT OF A MODEL

A model is a simplified representation of a system at some particular point in time or space intended to promote understanding of the real system. One of the most important aims for construction of models is to define the problem such that only important details becomes visible, while irrelevant features are neglected. We build models because they help us to:

(1) Define our problems,
(2) Organize our thoughts,
(3) Understand our data,
(4) Communicate and test that understanding, and
(5) Make predictions.

A model is therefore an intellectual tool. The ability to study and project multi-sectoral water uses in relation to social, economic and other considerations and their impacts on the water balance of a basin is an important aspect of water modeling. In terms of regulation modeling, the modeler can incorporate various user interests, as well as historical uses, to generate operating scenarios to verify the variations, alternatives of interest to the basin community, as well as the physical environment, that has been changed. Assessments of operating policy changes, impacts of floods, and changes in water quality are just a few examples where numerical models are used. Physically based models determine the flow and level changes that are currently being employed to determine the impact of man-made changes upon the river and its active biological community.

3.1.1 Stages of Modeling

It is helpful to divide up the process of modeling into four broad categories of activity, namely building, studying, testing and use. Although it might be nice to think that modeling projects progress smoothly from building through to use, this is hardly ever the case. In general, defects found at the studying and testing stages are corrected by returning to the building stage. Note that if any changes are made to the model, then the studying and testing stages must be repeated. A pictorial representation of potential routes through the stages of modeling is:

Figure 3.1 Flow chart showing stages of modeling

This process of repeated iteration is typical of modeling projects, and is one of the most useful aspects of modeling in terms of improving our understanding about how the system works.

3.1.2 Classification of Models

Mechanically, there are a many different ways to construct a model. There are two basic dimensions, however, and these define four classes of models with similar strengths and limitations. First, the underlying processes can be represented in either deterministic or stochastic forms. The difference is analogous to using the mean as a prediction summary versus using the full probability distribution of outcomes. Second, the dynamics over time can be explored either analytically or using computational methods. Analytic, or closed-form, solutions isolate the outcome on the left-hand side of an equation, with all of the determinants on the right-hand side, so it is clear how the outcome depends on the inputs. Not all processes can be represented this way. Computational, or numerical, solutions must be employed if there are non-trivial feedback loops in the process, so that the outcome ends up on both sides of the equation. Models of this sort are said to be analytically intractable. This happens very quickly as simplifying assumptions are relaxed, so most models that attempt to build in realistic heterogeneity need to be solved computationally. Deterministic models are usually built on group aggregates or macro-level states, while stochastic simulation models are usually built to reflect the micro-level states occupied by discrete individual persons. The primary difference between deterministic and stochastic models is how they define the movement between states. Deterministic models define the dynamics using the average rate of transition between states. Stochastic models define the dynamics using the probability that an individual makes the transition from one state to another. Analytic models of both sorts (deterministic and stochastic) are typically regarded as the ideal, since they reveal a process in terms of simple cause and effect. Many infectious processes are not simple in that way, however, and the assumptions made to gain tractability often come at the cost of ignoring important parts of the process, and thus failure to properly project the outcomes of interest. As computing power has become more widely available, the need for tractability has declined, and computational-deterministic models have become the workhorse of mathematical epidemiology.

Models can also be classified as:

- ***Conceptual model***
  The term conceptual model may be used to refer to models which are formed after a conceptualization process in the mind. Conceptual models represent human intentions or semantics. Conceptualization from observation of physical existence and conceptual modeling are the necessary means human employ to think and solve problems. Concepts are used to convey semantics during various natural languages based communication. Since that a concept might map to multiple semantics by itself, an explicit formalization is usually required for identifying and locating the intended semantic from several candidates to avoid misunderstandings and confusions in conceptual models.

- ***Mathematical model***
  A mathematical model is a description of a system using mathematical concepts and language. The process of developing a mathematical model is termed mathematical modeling. Mathematical models can take many forms, including but not limited to dynamical systems, statistical models, differential equations, or game theoretic models. These and other types of models can overlap, with a given model involving a variety of abstract structures. In general, mathematical models may include logical models, as far as logic is taken as a part of mathematics.

- ***Simple model***
  It is the type of Analytical model which provides a continuous solution over the model domain.

- ***Complex model***
  It is the type of Numerical model which provides a discrete solution i.e. values are calculated at only a few points.

- ***Analog model***
  This type of model deals with electrical current flow through a circuit board with resistors to represent hydraulic conductivity and capacitors to represent storage coefficient.

3.2 MATHEMATICAL MODELING

A mathematical model is a description of a system using mathematical concepts and language. The process of developing a mathematical model is termed mathematical modeling. Mathematical models are used not only in the natural sciences (such as physics, biology, earth science, meteorology) and engineering disciplines (e.g. computer science, artificial intelligence), but also in the social sciences (such as economics, psychology, sociology and political science); physicist. Statisticians, operation research analyst and economists use mathematical models most extensively. Mathematical models can take many forms, including but not limited to dynamical systems, statistical models, differential equations, or game theoretic models. These and other types of models can overlap, with a given model involving a variety of abstract structures. In general, mathematical models may include logical models, as far as logic is taken as a part of mathematics. In many cases, the quality of a scientific field depends on how well the mathematical models developed on the theoretical side agree with results of repeatable experiments. Lack of agreement between theoretical mathematical models and experimental measurements often leads to important advances as better theories are developed.

3.2.1 Black-box and White box Models

Mathematical modeling problems are used often classified into black box or white box models, according to how much a priori information is available of the system. A black-box model is a system of which there is no a priori information available. A white-box model (also called glass box or clear box) is a system where all necessary information is available. Practically all systems are somewhere between the black-box and white-box models, so this concept is useful only as an intuitive guide for deciding which approach to take. Usually it is preferable to use as much a priori information as possible to make the model more accurate. Therefore the white-box models are usually considered easier, because if you have used the information correctly, then the model will behave correctly. Often the a priori information comes in forms of knowing the type of functions relating different variables. In black-box models one tries to estimate both the functional form of relations between variables and the numerical parameters in those functions. Using a priori information we could end up. An often used approach for black-box models are neural networks which usually do not make assumptions about incoming data. The problem with using a large set of functions to describe a system is that estimating the parameters becomes increasingly difficult when the amount of parameters increases.

3.2.2 Classification of Mathematical Models

1. ***Linear vs. Nonlinear:***
   Mathematical models are usually composed by variables, which are abstractions of quantities of interest in the described systems, and operators that act on these variables, which can be algebraic operators, functions, differential operators, etc. If all the operators in a mathematical model exhibit linearity, the resulting mathematical model is defined as linear. The question of linearity and nonlinearity is dependent on context, and linear models may have nonlinear expressions in them. For example, in a statistical linear model, it is assumed that a relationship is linear in the parameters, but it may be nonlinear in the predictor variables. Similarly, a differential equation is said to be linear

if it can be written with linear differential operators, but it can still have nonlinear expressions in it. In a mathematical programming model, if the objective functions and constraints are represented entirely by linear equations**,** then the model is regarded as a linear model. If one or more of the objective functions or constraints are represented with a nonlinear equation, then the model is known as a nonlinear model. Nonlinearity, even in fairly simple systems, is often associated with phenomena such as chaos and irreversibility. Although there are exceptions, nonlinear systems and models tend to be more difficult to study than linear ones.

2. ***Deterministic vs. Probabilistic (Stochastic):***

   A deterministic model is one in which every set of variable states is uniquely determined by parameters in the model and by sets of previous states of these variables. Therefore, deterministic models perform the same way for a given set of initial conditions. A mathematically deterministic model is a representation y = f(x) that allows you to make predictions of y based on x.

   The model is used like this: when x=3, then we predict that y=f(3).

   This prediction does not necessarily occur in the past, future, or even the present. It is simply a hypothetical, "what-if" statement.

   For example, what would be the maximum stress (y) that a dam could bear, if we were to use x= (thickness of concrete).

   This type of model is deterministic because y is completely determined if you know x. In real life, it is extremely rare that we can completely determine a y using an x, and thus we must use probabilistic (stochastic) models. Conversely, in a stochastic model, randomness is present, and variable states are not described by unique values, but rather by probability distributions. A probability model is a representation Y ~ p(y), specifically means that y is generated at random from a probability distribution whose mathematical form is p(y).

3. ***Static vs. Dynamic:***

   A static model does not account for the element of time, while a dynamic model does. Dynamic models typically are represented with difference equations or differential equations.

4. ***Discrete vs. Continuous:***

   A discrete model does not take into account the function of time and usually uses time-advance methods, while Continuous models typically are represented with f(t) and the changes are reflected over continuous time intervals.

3.3 WATER QUALITY MODELING

Water quality models are tools for simulating the movement of precipitation and pollutants from the ground surface through pipe and channel networks, storage treatment units and finally to receiving waters. Both single-event and continuous simulation may be performed on catchments having storm sewers and natural drainage, for prediction of flows, stages and pollutant concentrations. Water quality models can be applied to many different types of water system, including streams, rivers, lakes, reservoirs, estuaries, coastal waters and oceans. The models describe the main water quality processes, and typically require the hydrological and constituent inputs (the water flows or volumes and the pollutant loadings). Mathematical models can be used to predict changes in ambient water quality due to changes in discharges of wastewater. Models are typically used to establish priorities for reduction of existing wastewater discharges or to predict the impacts of a proposed new discharge. Although a range of parameters may be of interest, a modeling exercise typically focuses on a few, such as dissolved oxygen, coliform bacteria, or nutrients. Predicting the water quality impacts of a single discharge can often be done quickly and sufficiently accurately with a simple model. Regional water quality planning usually requires a model with a broader geographic scale, more data, and a more complex model structure.

A simple but useful modeling approach that may be used in the absence of monitoring data is dilution calculations. In this approach the rate of pollutant loading from point sources in a water body is divided by the streamflow to give a set of estimated pollutant concentrations that may be compared to the standard. Simple dilution calculations assume conservative movement of pollutants. Thus, the use of dilution calculations will tend to be conservative and predict higher than actual concentrations for decaying pollutants. Combined runoff and water quality prediction models link stressors (sources of pollutants and pollution) to responses. Stressors include human activities likely to cause impairment, such as the presence of impervious surfaces in a watershed, cultivation of fields close to the stream, over-irrigation of crops with resulting polluted return flows, the discharge of domestic and industrial effluents into water bodies, installing dams and other channelization works, introduction of non-indigenous taxa and over-harvesting of fish. Indirect effects of humans include land cover changes that alter the rates of delivery of water, pollutants and sediment to water bodies. A review of direct and indirect effects of human activities suggests five major types of environmental stressors:

- Alterations in physical habitat.
- Modifications in the seasonal flow of water.
- Changes in the food base of the system.
- Changes in interactions within the stream biota.
- Release of contaminants.

Ideally, models designed to manage water quality should consider all five types of alternative management measures. A broad-based approach that considers these five features provides a more integrative approach to reduce the cause or causes of degradation (UNESCO, 2005).

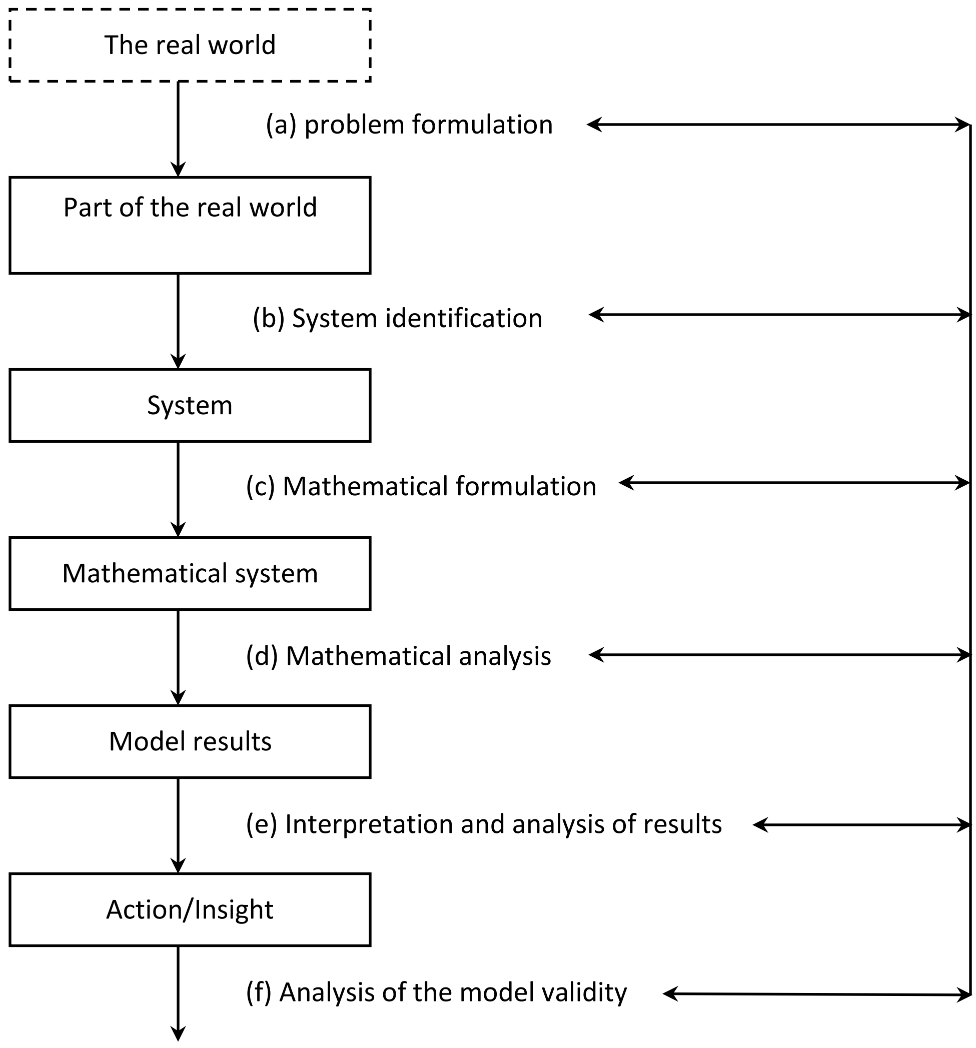


Figure 3.2 Flow chart showing Modeling Process

3.3.1 Classification of Water Quality Models

Water quality models are usually classified according to model complexity, type of receiving water, and the water quality parameters that the model can predict. The more complex the model is, the more difficult and expensive will be its application to a given situation. Model complexity is a function of four factors:

1. ***The number and type of water quality indicators-***
   In general, the more indicators that are included, the more complex the model will be. In addition, some indicators are more complicated to predict than others.
2. ***The level of spatial detail-***
   As the number of pollution sources and water quality monitoring points increase, so do the data required and the size of the model.
3. ***The level of temporal detail-***
   It is much easier to predict long-term static averages than short term dynamic changes in water quality. Point estimates of water quality parameters are usually simpler than stochastic predictions of the probability distributions of those parameters.
4. ***The complexity of the water body under analysis-***
   Small lakes that mix completely are less complex than moderate-size rivers, which are less complex than large rivers, which are less complex than large lakes, estuaries, and coastal zones.

For indicators of aerobic status, BOD, DO and temperature, simple, well-established models can be used to predict long-term average changes in rivers, streams, and moderate-size lakes. The behavior of these models is well understood and has been studied more intensively than have other parameters. Basic nutrient indicators such as ammonia, nitrate, and phosphate concentrations can also be predicted reasonably accurately, at least for simpler water bodies such as rivers and moderate-size lakes. Predicting algae concentrations accurately is somewhat more difficult but is commonly done in the United States and Europe, where eutrophication has become a concern in the past two decades. Toxic organic compounds and heavy metals are much more problematic. Although some of the models reviewed below do include these materials, their behavior in the environment is still an area of active research. Models can cover only a limited number of pollutants. In selecting parameters for the model, care should be taken to choose pollutants that are a concern in themselves and are also representative of the broader set of substances which cannot all be modeled in detail.

Table 3.1. Criteria for Classification of Water Quality Models

Sr. No.	Criterion	Comment
1	Single plant or regional focus	Simpler models can usually be used for single-plant marginal effects. More complex models are needed for regional analyses.
2	Static or Dynamic	Static (constant) or time-varying outputs
3	Stochastic or Deterministic	Stochastic models present outputs as probability distributions while deterministic models are point-estimates.
4	Type of receiving water (river, lake, or estuary)	Small lakes and rivers are usually easier to model. Large lakes, estuaries, and large river systems are more complex.
	Water Quality Parameters	
5	DO	Usually decreases as discharge increases. Used as a water quality indicator in most water quality models
6	BOD	A measure of oxygen-reducing potential for waterborne discharges. Used in most water quality models
7	Temperature	Often increased by discharges, especially from electric power plants. Relatively easy to model.
8	Ammonia nitrogen	Reduces dissolved oxygen concentrations and adds nitrate to water. Can be predicted by most water quality models.
9	Algal concentration	Increases with pollution, especially nitrates and phosphates. Predicted by moderately complex models.
10	Coliform bacteria	An indicator of contamination from sewage and animal waste
11	Nitrates	A nutrient for algal growth and a health hazard at very high concentrations in drinking water. Predicted by moderately complex models
12	Phosphates	Nutrient for algal growth. Predicted by moderately complex models
13	Toxic organic compounds	A wide variety of organic (carbon-based) compounds can affect aquatic life and may be directly hazardous to humans. Usually very difficult to model.
14	Heavy metals	Substances containing lead, mercury, cadmium, and other metals can cause both ecological and human health problems. Difficult to model in detail.

Source: Pollution Prevention and Abatement Handbook, WORLD BANK GROUP, Effective July 1998

3.3.2 Utility of Water Quality Models

Water Quality Models helps policy makers to make right decisions regarding mutilation of water quality for future scope. Monitoring data are the preferred form of information for identifying impaired waters. Model predictions might be used in addition to or instead of monitoring data for several reasons:

1. Modeling might be feasible in some situations where monitoring is not.
2. Integrated monitoring and modeling systems could provide better information than one or the other alone for the same total cost. For example, regression analyses that correlate pollutant concentration with some more easily measurable factor such as streamflow could be used to extend monitoring data for preliminary listing of impaired status purposes. Models can also be used in a Bayesian framework to determine preliminary probability distributions of impairment that can help direct monitoring efforts and reduce the quantity of monitoring data needed for making listing decisions at a given level of reliability.
3. Modeling can be used to assess future water quality situations resulting from different management strategies. For example, assessing the improvement in water quality after a new wastewater treatment plant is built, or the effect of increased industrial growth and effluent discharges.

3.4 GROUND WATER MODELING

Groundwater models are computer models of groundwater flow systems, and are used by hydrogeologists. Groundwater models are used to simulate and predict aquifer conditions. A model may be defined as a simplified version of a real-world system (here, a ground-water system) that approximately simulates the relevant excitation-response relations of the real-world system. Since real-world systems are very complex, there is a need for simplification in making planning and management decisions. The simplification is introduced as a set of assumptions which expresses the nature of the system and those features of its behavior that are relevant to the problem under investigation. These assumptions will relate, among other factors, to the geometry of the investigated domain, the way various heterogeneities will be smoothed out, the nature of the porous medium (homogeneity, isotropy), the properties of the fluid involved, and the type of flow regime under investigation.

3.4.1 Characteristics of Ground Water Model

A groundwater model may be a scale model or an electric model of a groundwater situation or aquifer. Groundwater models are used to represent the natural groundwater flow in environment. Some groundwater models include quality aspects of the groundwater. Such groundwater models try to predict the fate and movement of the chemical in natural, urban or hypothetical scenario. Groundwater models may be used to predict the effects of hydrological changes on the behavior of the aquifer and are often named groundwater simulation models. Also nowadays the groundwater models are used in various water management plans for urban areas.

As the computations in mathematical groundwater models are based on groundwater flow equations, which are differential equations that can often be solved only by approximate methods using a numerical analysis, these models are also called mathematical, numerical, or computational groundwater models. The mathematical or the numerical models are usually based on the real physics the groundwater flow follows. These mathematical equations are solved using numerical codes such as modflow, ParFlow, HydroGeoSphere etc. Various types of numerical solutions like the finite difference method and the finite element method are used.

3.4.2 Applicability of Ground Water Models

The applicability of a groundwater model to a real situation depends on the accuracy of the input data and the parameters. Determination of these requires considerable study, like collection of hydrological data (rainfall, evapotranspiration, irrigation, drainage) and determination of the parameters mentioned before including pumping tests. As many parameters are quite variable in space, expert judgment is needed to arrive at representative values. The models can also be used for the if-then analysis, if the value of a parameter is A, then what is the result, and if the value of the parameter is B instead, what is the influence. This analysis may be sufficient to obtain a rough impression of the groundwater behavior, but it can also serve to do a sensitivity analysis to answer the question, which factors have a great influence and which have less influence. With such information one may direct the efforts of investigation more to the influential factors.

When sufficient data have been assembled, it is possible to determine some of missing information by calibration. This implies that one assumes a range of values for the unknown or doubtful value of a certain parameter and one runs the model repeatedly while comparing results with known corresponding data. For example if salinity figures of the groundwater are available and the value of hydraulic conductivity is uncertain, one assumes a range of conductivities and the selects that value of conductivity as true that yields salinity results close to the observed values, meaning that the groundwater flow as governed by the hydraulic conductivity is in agreement with the salinity conditions. This procedure is similar to the measurement of the flow in a river or canal by letting very saline water of a known salt concentration drip into the channel and measuring the resulting salt concentration downstream.

3.5 SURFACE WATER MODELING

Surface water is generally defined as any water that is present at the surface of the Earth. This covers rivers, lakes, oceans and estuaries, as well as artificial bodies (reservoirs and canals). In general terms, water quality is assessed on the basis of a set of physical, chemical and biological variables, most of them concentrations of chemical entities or organisms, that are compared with criteria often a function of the type of water body and of its uses. Water quality models are tools that aim at representing the processes that govern the time evolution or the spatial variability of these variables. They cover physical characteristics, such as temperature, pH and conductivity, but also substances related with the organic loads to the water body and its trophic state, persistent chemicals and microbiological pollutants.

3.5.1 Basic theory of Surface Water Modeling

Water quality models can be applied to many different types of water system, including streams, rivers, lakes, reservoirs, estuaries, coastal waters and oceans. The models describe the main water quality processes, and typically require the hydrological and constituent inputs (the water flows or volumes and the pollutant loadings). These models include terms for dispersive and/or advective transport depending on the hydrological and hydrodynamic characteristics of the water body, and terms for the biological, chemical and physical reactions among constituents. Advective transport dominates in flowing rivers.

Let us consider an elementary water body, a cube of dx, dy and dz dimensions as shown in Figure 3.3. 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 V_{ex}, V_{ie}, and $V_{s.}$ components of the flow velocity vector. This process is termed the adjective mass transfer. The transfer of mass, that is the mass flux can be calculated in the direction x as $C \times V_x \times dy \times dz$, where C is the concentration of the substance in the water.
- The other means of mass transfer is termed the dispersion or dispersive transport. 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.

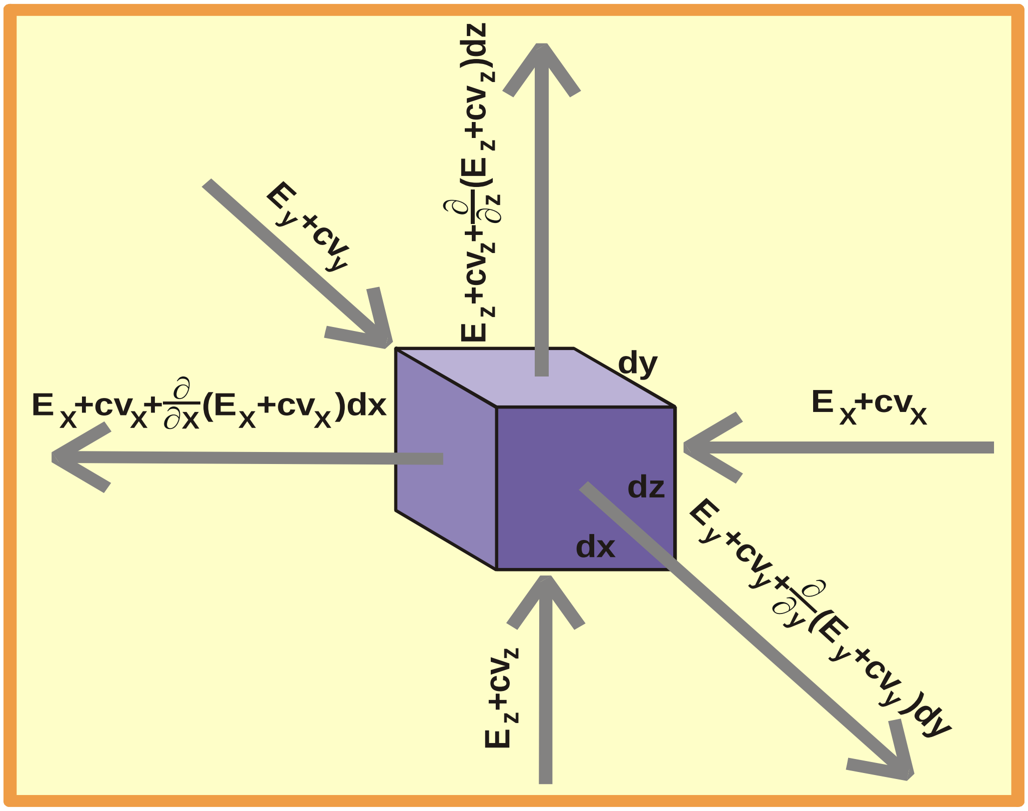


Figure 3.3 Diagram showing elementary water body representing mass flows

Advective transport dominates in flowing rivers. Dispersion is the predominant transport phenomenon in estuaries subject to tidal action. The basic principle of water quality models is that of mass balance. A water system can be divided into different segments or volume elements, also called computational cells. For each segment or cell, there must be a mass balance for each water quality constituent over time. Most water quality simulation models simulate quality over a consecutive series of discrete time periods, Δt. Time is divided into discrete intervals t and the flows are assumed constant within each of those time period intervals. For each segment and each time period, the mass balance of a substance in a segment can be defined. Components of the mass balance for a segment include, first, changes by transport (Tr) into and out of the segment; second, changes by physical or chemical processes (P) occurring within the segment, and third, changes by sources/discharges to or from the segment (S).

$$M_i^{t+\Delta t} = M_i^t + \Delta t \left(\frac{\Delta M_i}{\Delta t}\right)_{\mathrm{Tr}} + \Delta t \left(\frac{\Delta M_i}{\Delta t}\right)_{\mathrm{P}} + \Delta t \left(\frac{\Delta M_i}{\Delta t}\right)_{\mathrm{S}} \qquad \text{Eq (1)}$$

The mass balance has the following components:

- The mass in computational cell i at the beginning of a time step t: M_i^t
- The mass in computational cell i at the end of a time step t: $M_i^{t+\Delta t}$
- Changes in computational cell i by transport: $\left(\frac{\Delta M_i}{\Delta t}\right)_{\mathrm{Tr}}$
- Changes in computational cell i by physical, biochemical or biological processes: $\Delta t \left(\frac{\Delta M_i}{\Delta t}\right)_{\mathrm{P}}$
- Changes in computational cell *i* by sources (e.g. wasteloads, river discharges): $\Delta t \left(\frac{\Delta M_i}{\Delta t}\right)_{\mathrm{S}}$

Changes by transport include both advective and dispersive transport. Advective transport is transport by flowing water. Dispersive transport results from concentration differences. Dispersion in the vertical direction is important if the water column is stratified, and dispersion in the horizontal direction can be in one or two dimensions.

Changes by processes include physical processes such as re-aeration and settling, biochemical processes such as adsorption, transformation and denitrification, and biological processes such as primary production and predation on phytoplankton. Water quality processes convert one substance to another.

Changes by sources include the addition of mass by wasteloads and the extraction of mass by intakes. Mass entering over the model boundaries can be considered a source as well. The water flowing into or flowing out of the modeled segment or volume element is derived from a water quantity model.

- ***Advective Transport***

  The advective transport, $T_{x_0}^A$ (M/T), of a constituent at a site x_0 is the product of the average water velocity, V_{x_0}(L/ T), at that site, the surface or cross-sectional area, *A* (L^2), through which advection takes place at that site, and the average concentration, C_{x_0} (M/L^3), of the constituent:

$$T_{x_0}^A = V_{x_0} \times \mathrm{A} \times C_{x_0} \qquad \text{Eq (3.2)}$$

- ***Dispersive Transport***

  The dispersive transport, $T_{x_0}^{D}$ (M/T), across a surface area is assumed to be proportional to the concentration gradient $\frac{\partial C}{\partial x}|_{x=x_0}$ at site x_0 times the surface area A. Letting D_{x_0} (L^2/T), be the dispersion or diffusion coefficient at site x_0:

$$T_{x_0}^{D} = - D_{x_0} \times A \times \frac{\partial C}{\partial x}|_{x = xo} \qquad \text{Eq (3.3)}$$

Dispersion is done according to Fick's diffusion law. The minus sign originates from the fact that dispersion causes net transport from higher to lower concentrations, and so in the opposite direction of the concentration gradient. The concentration gradient is the difference of concentrations per unit length, over a very small distance across the cross section:

$$\frac{\partial C}{\partial x}|_{x} = \lim_{\Delta x \to 0} \left(\frac{C_{x+0.5\,\Delta x} - C_{x-0.5\Delta x}}{\Delta x}\right)^{1} \qquad \text{Eq (3.4)}$$

Dispersion coefficients should be calibrated or be obtained from calculations using turbulence models.

- ***Mass Transport by Advection and Dispersion***

  If the advective and dispersive terms are added and the terms at a second surface at site $x0 + \Delta x$ are included, a one dimensional equation results:

$$M_i^{t+\Delta t} = M_i^{t} + \Delta t \times \left(V_{x_0} C_{x_0} - V_{x_0+\Delta x} C_{x_0+\Delta x} - D_{x_0} \frac{\partial C}{\partial x}|_{xo} + D_{x_0+\Delta x} \frac{\partial C}{\partial x}|_{xo+\Delta x} \right) \times A \qquad \text{Eq (3.5)}$$

Or equivalently

$$M_i^{t+\Delta t} = M_i^{t} + \Delta t \times \left(Q_{x_0} C_{x_0} - Q_{x_0+\Delta x} C_{x_0+\Delta x} - D_{x_0} A_{x_0} \frac{\partial C}{\partial x}|_{x_0} + D_{x_0+\Delta x} A_{x_0} \frac{\partial C}{\partial x}|_{x_0+\Delta x} \right) \qquad \text{Eq (3.6)}$$

Where Q_{x0} (L^3/T) is the flow at site x_0.

If the previous equation is divided by the volume and the time interval Δt, then the following equation results in one dimension:

$$\frac{C_i^{t+\Delta t} - C_i^t}{\Delta t} = \frac{D_{x_0+\Delta x}\frac{\partial C}{\partial x}|_{x_0+\Delta x} - D_{x_0}\frac{\partial C}{\partial x}|_{xo}}{\Delta x} + \frac{V_{x_0}C_{x_0} - V_{x_0+\Delta x}C_{x_0+\Delta x}}{\Delta x}$$

Eq (3.7)

Taking the asymptotic limit $\Delta t \rightarrow 0$ and $\Delta x \rightarrow 0$, the advection–diffusion equation for one dimension results:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial C}{\partial x}\right) - \frac{\partial}{\partial x}(vC)$$ Eq (3.8)

The finite volume method for transport is a computational method of solving the advection–diffusion equation. The accuracy of the method will be related to the size of Δx, A ($A = \Delta y \Delta z$) and Δt.

By adding terms for transport in the y and z-direction, a three-dimensional model is obtained. Taking the asymptotic limit again will lead to a three-dimensional advection–diffusion equation.

$$\frac{\partial C}{\partial t} = D_x\frac{\partial^2 C}{\partial x^2} - V_x\frac{\partial C}{\partial x} + D_y\frac{\partial^2 C}{\partial y^2} - V_y\frac{\partial C}{\partial y} + D_z\frac{\partial^2 C}{\partial z^2} + V_z\frac{\partial C}{\partial z} + S + f_R(C,t)$$

Eq (3.9)

with dispersion coefficients *Dj* defined for each direction. If source terms '*S*' and 'f_R' are added as shown in the equation above, the so-called advection–diffusion reaction equation emerges. The additional terms represent:

- Discharges or wasteloads (*S*): these source terms are additional inflows of water or mass. As many source terms as required may be added to Equation 3.9. These could include small rivers, discharges of industries, sewage treatment plants, small wasteload outfalls and so on.
- Reaction terms or processes (f_R).

Processes can be split into physical and other processes. Examples of physical processes are:

- Settling of suspended particulate matter
- Water movement not affecting substances, like evaporation
- Volatilization of the substance itself at the water surface.

Examples of other processes are:

- Biochemical conversions like ammonia and oxygen forming nitrite
- Growth of algae (primary production)
- Predation by other animals
- Chemical reactions.

The relative importance of dispersion and advection depends on the degree of detail with which the velocity field is defined. A good spatial and temporal description of the velocity field within which the constituent is being distributed will reduce the importance of the dispersion term. Less precise descriptions of the velocity field, such as averaging across irregular cross sections or approximating transients by steady flows, may lead to a dominance of the dispersion term. Many of the reactions affecting the decrease or increase of constituent concentrations are often represented by first-order kinetics that assume the reaction rates are proportional to the constituent concentration. While higher-order kinetics may be more correct in certain situations, predictions of constituent concentrations based on first-order kinetics have often been found to be acceptable for natural aquatic systems.

3.5.2 Derivation of practical Models from the basic model equation

The basic three-dimensional water quality model is seldom used in its original complex way (Eq (3.9)), mostly because three-dimensional problems occur rarely. For example river problems can be frequently reduced to one-dimensional (linear) or two-dimensional (longitudinal-transversal) problems. Another example is the fully mixed reactor type, or zero dimension, lake models, where no transport terms of the basic water quality models are included. Another reason of using simplified models is that transversal or vertical velocity measurement data are seldom available. The internal source-sink terms, that were only denoted in Eq (3.9) should be specified for each problem explicitly and they vary with the components considered. Here it will be briefly demonstrated how can one derive the simple (river and lake) model versions of Eq (3.9), which can be used in the practice. In order to arrive to some of the simple water quality models presented below, we have to make first series of assumptions and approximations:

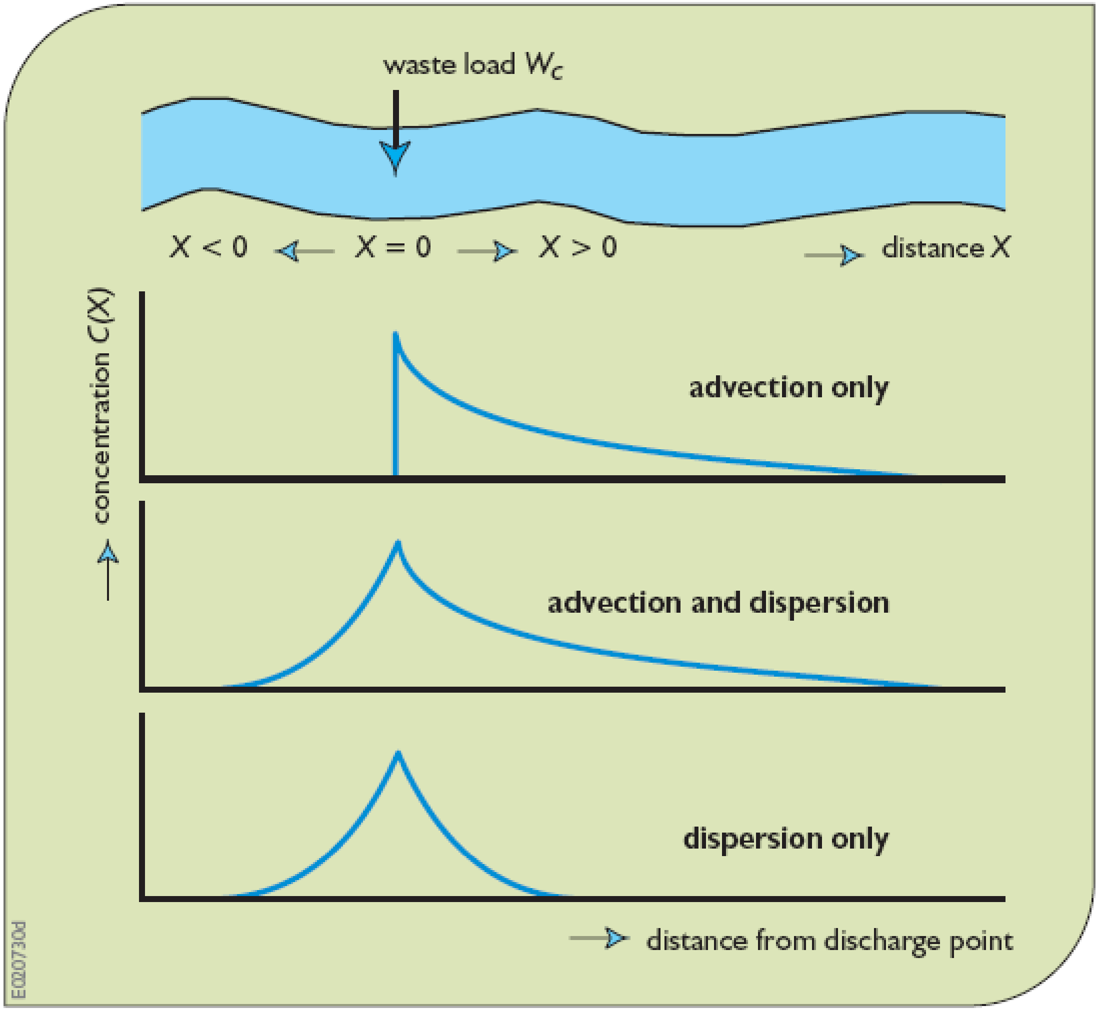


Figure 3.4 Constituent concentration distribution along a river resulting from a constant discharge of that constituent at a single point source in that river.

A. Neglect, for the time being, all terms accounting for dispersion. With this we assume that the system is fully mixed, which means that any external material input (load) to the river or lake will be instantaneously and fully mixed with the water. This is a very rough approximation. However, this approximation holds for long linear systems, e.g. in the case of smaller rivers with continuous steady input loads (waste water discharges). It also holds, or must be assumed, for most of the lakes, since neither measurement data of lake currents nor the spatial distribution of water quality monitoring points, will allow the consideration of dispersion effects.

B. In the case of a river average flow and concentrations over the cross section has to be taken. The only velocity component, which remains in the basic equation, is then v_x, the average longitudinal flow velocity.

C. In the case of a lake, a standing water body, neglect flow velocities and consider the water body fully mixed. In this case there remains only the internal source-sink term on the right hand side of the basic equation (Eq 3.9).

D. Consider one single water quality constituent with its concentration C and assume that it is subject to internal processes like decay, decomposition and settling. Assume that this process is proportional to the concentration of the constituent and the coefficient of proportionality is K, the decay (decomposition, settling, etc.) rate coefficient. (Assumption of first order reaction kinetics)

When considering a river of steady state conditions (with flow of the river and input material loads into the river not varying in time) then we have arrived at the practically identical river and lake models of the form given in equations Eq (3.10) and Eq (3.11).

<u>The most simple river model</u>

$$v_x \frac{dC}{dx} = -KC \qquad \text{Eq (3.10)}$$

<u>The most simple lake model</u>

$$\frac{dC}{dt} = -KC \qquad \text{Eq (3.11)}$$

Where,
C - is the concentration, the mass of the quality constituent in a unit volume of water ($M\ L^{-3}$)
v_x - is the mean flow velocity of a river reach investigated ($L\ T^{-1}$)
K - is the reaction rate coefficient for first order kinetics (T^{-1})
t - is the time of travel interpreted as $t=x/v$
x - the distance downstream (L)

Practically all water quality model equations, used in the everyday practice, can be derived in a similar way, by adding one or more dispersion and advection terms and by coupling the reaction processes, when more than one interacting water quality constituents are concerned.

Table 3.2 Basic river and lake Model forms

Description	General equation	Use
3-D models	$\frac{\partial C}{\partial t}+v_x\frac{\partial C}{\partial x}+v_y\frac{\partial C}{\partial y}+v_z\frac{\partial C}{\partial z}=$ $=\frac{\partial}{\partial x}\left(D_x\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_y\frac{\partial C}{\partial y}\right)+\frac{\partial}{\partial z}\left(D_z\frac{\partial C}{\partial z}\right)+S(x,y,z,t)\pm S_{internal}$	Oceans, seas, large lakes
2-D, horizontal river or lake models	$\frac{\partial C}{\partial t}+v_x\frac{\partial C}{\partial x}+\left(v_y\frac{\partial C}{\partial y}\right)=$ $=\frac{\partial}{\partial x}\left(D_x\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_y\frac{\partial C}{\partial y}\right)+S(x,y,t)\pm S_{internal}$	Wind induced circulation (in lakes), transversal mixing (in rivers)
2-D river model	$\frac{\partial C}{\partial t}+v_x\frac{\partial C}{\partial x}=\frac{\partial}{\partial y}\left(\varepsilon_y\frac{\partial C}{\partial y}\right)+S(x,y,t)\pm S_{internal}$	Mixing of pollutant plume
2-D vertical plane lake models	$\frac{\partial C}{\partial t}+v_y\frac{\partial C}{\partial y}+v_z\frac{\partial C}{\partial z}=$ $=\frac{\partial}{\partial y}\left(D_y\frac{\partial C}{\partial y}\right)+\frac{\partial}{\partial z}\left(D_z\frac{\partial C}{\partial z}\right)+S(y,z,t)\pm S_{internal}$	Wind induced currents in deep lakes (in a cross section)
1-D river models	$\frac{\partial C}{\partial t}+v_x\frac{\partial C}{\partial x}=\frac{\partial}{\partial x}\left(D_x\frac{\partial C}{\partial x}\right)+S(x,t)\pm S_{internal}$	Longitudinal dispersion (pollutant spill) model
Quasi 1-D river model	$v_x\frac{dC}{dx}=+S(x)\pm S_{internal}$	Steady state river models
0-D lake models	$\frac{dC}{dt}=S(t)\pm S_{internal}$	fully mixed reactor type lake models

Source: Description of the CAL programme on Water Quality Modelling, Dr. Géza Jolánkai and István Bíró (2000)

3.6 RIVER WATER MODELING

Rivers are the most important freshwater resource for man. Social, economic and political development has, in the past, been largely related to the availability and distribution of fresh waters contained in riverine systems. Major river water uses can be summarized as follows:

- Sources of drinking water supply,
- Irrigation of agricultural lands,
- Industrial and municipal water supplies,
- Industrial and municipal waste disposal,
- Navigation,
- Fishing, boating and body-contact recreation,
- Aesthetic value.

A simple evaluation of surface waters available for regional, national or trans-boundary use can be based on the total river water discharge. Rivers are complex systems of flowing waters draining specific land surfaces which are defined as river basins or watersheds. The characteristics of the river, or rivers, within the total basin system are related to a number of features. These features include the size, form and geological characteristics of the basin and the climatic conditions which determine the quantities of water to be drained by the river network.

Table 3.3 Classification of rivers based on discharge characteristics, the drainage area and river width

River size	Average discharge (m^3s^{-1})	Drainage area (km^2)	River width (m)	Stream Order [1]
Very large Rivers	> 10,000	> 10^6	> 1,500	> 10
Large rivers	1,000-10,000	100,000-10^6	800-1,500	7 to 11
Rivers	100-1,000	10,000-100,000	200-800	6 to 9
Small rivers	10-100	1,000-10,000	40-200	4 to 7
Streams	1-10	100-1,000	8-40	3 to 6
Small streams	0.1-1.0	10-100	1-8	2 to 5
Brooks	< 0.1	< 10	< 1	1 to 3

[1] Depending on local conditions

3.6.1 River zonation

Characteristic zones may be recognised in rivers and streams according to aspects of the habitats or biotic communities present, and the biological processes which occur along the length of the water course The aquatic zone of a river system is normally permanently submerged, and the associated communities are unable to withstand desiccation. The lentic zone and flood plain of a stream are the areas between the mean low water zone, e.g. the zone where reeds grow, and the mean high water limit. As a result, this area is subject to frequent, recurring fluctuations in water level. In large rivers the lentic zone may be very large and many meters wide, but in smaller rivers and streams it can be rather fragmented as the banks tend to be steep. As a result of increased erosion caused by human activity, particularly in deforested tropical areas, rivers and streams may become so deep that they cannot develop an active lentic zone. Above the lentic zone and flood plain, at the mean high water level is the terrestrial zone. The lower limit of this zone is often indicated by the visible growth of small trees and bushes. The terrestrial zone is usually considered as part of the alluvial valley, at least from the limit to which the valley floods (the recent alluvial plain). There is a close interrelationship between a stream and its valley, especially with old channels, backwaters, depressions and flood channels. In dry periods the water quality of these may be very different from the main river due to groundwater inputs, anoxic conditions, denitrification, etc. During floods, river water flows through these water bodies allowing the exchange of water, substrates and organisms. The soil water and nutrient budgets of the flood area are usually characterised by the river water, and the nature and shape of the soil surface is changed by erosion and siltation. This transitional zone (ecotone) between the river and the land is currently the subject of much scientific investigation. It is becoming increasingly appreciated that there is an ecological continuum from the aquatic zone to the flood plain and that this area provides the basis for self-purification within the ecosystem.

3.6.2 Self Purification of Natural Streams

The self purification of natural water systems is a complex process that often involves physical, chemical, and biological processes working simultaneously. The amount of DO in water is one of the most commonly used indicators of a river health. As DO drops below 4 or 5 mg/L the forms of life that can survive begin to be reduced. A number of factors affect the amount of DO available in a river. Oxygen demanding wastes remove DO, plants add DO during day but remove it at night, respiration of organisms removes oxygen. In summer, rising temperature reduces solubility of oxygen, while lower flows reduce the rate at which oxygen enters the water from atmosphere.

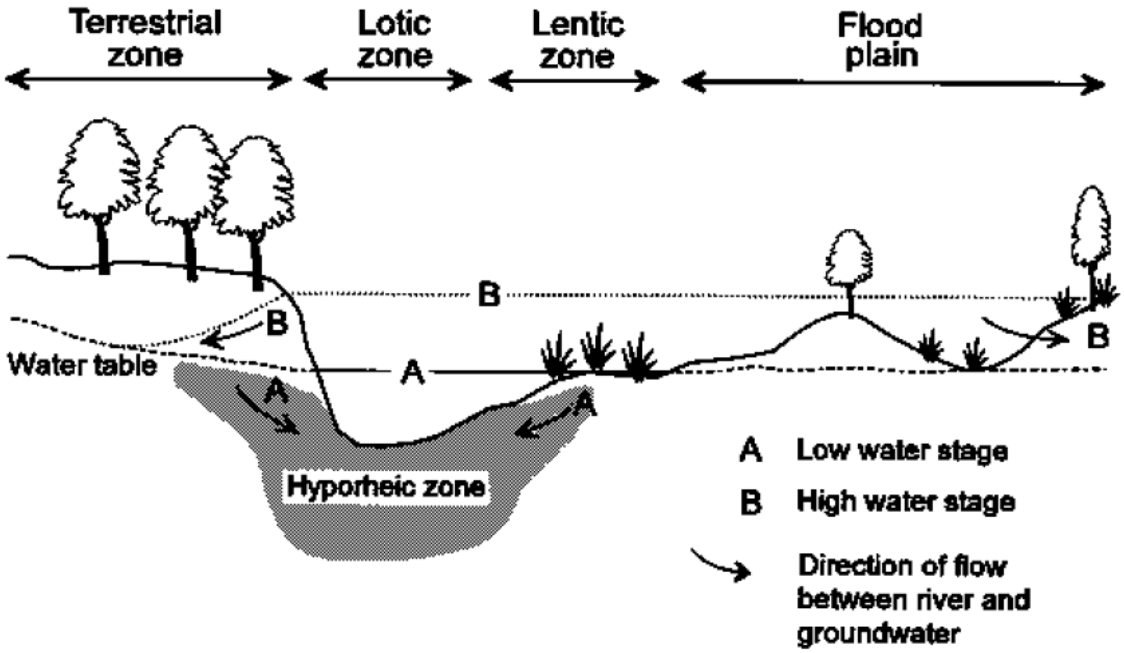


Figure 3.5 Generalized cross-section of a river showing the relationship between physical features and the low and high water stages

- ***Factors Affecting Self Purification***

1. **Dilution:** When sufficient dilution water is available in the receiving water body, where the wastewater is discharged, the DO level in the receiving stream may not reach to zero or critical DO due to availability of sufficient DO initially in the river water before receiving discharge of wastewater.

2. **Current:** When strong water current is available, the discharged wastewater will be thoroughly mixed with stream water preventing deposition of solids. In small current, the solid matter from the wastewater will get deposited at the bed following decomposition and reduction in DO.

3. **Temperature:** The quantity of DO available in stream water is more in cold temperature than in hot temperature. Also, as the activity of microorganisms is more at the higher temperature, hence, the self-purification will take less time at hot temperature than in winter.

4. **Sunlight:** Algae produces oxygen in presence of sunlight due to photosynthesis. Therefore, sunlight helps in purification of stream by adding oxygen through photosynthesis.

5. **Rate of Oxidation:** Due to oxidation of organic matter discharged in the river DO depletion occurs. This rate is faster at higher temperature and low at lower temperature. The rate of oxidation of organic matter depends on the chemical composition of organic matter.

- ***Stream Dissolved Oxygen***

The natural cycle of organic production and decomposition can be used to understand the environment in a stream below a wastewater discharge. If the river is unpolluted, dissolved oxygen concentrations above the discharge will be near saturation. The introduction of the sewage will elevate the levels of both dissolved and solid organic matter. This has three impacts:

1. The solid matter makes the water turbid and unsightly. Thus light cannot penetrate and plant growth is suppressed.

2. The solids settle downstream from the sewage outfall and create sludge beds that can emit noxious odours.

3. The organic matter provides food for heterotrophic organisms. Large populations of decomposer organisms break down the organic matter in the water and in the process deplete the dissolved oxygen. In addition, breakdown of organic matter takes place in the sludge bed, and a sediment oxygen demand supplements oxygen depletion in the water. Consequently, the right side of the cycle in Figure 3.6 begins to become overemphasized.

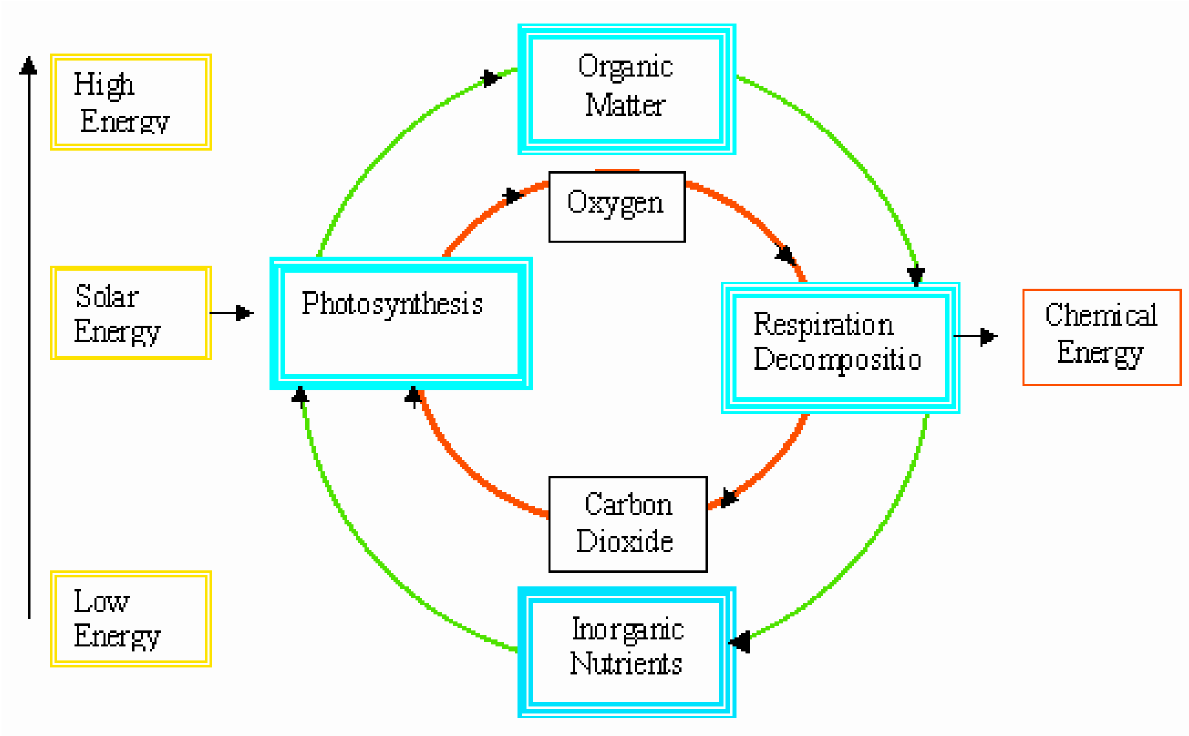


Figure 3.6 The natural cycle of organic production and decomposition

Aside from depletion, counteracting force acts to replenish oxygen in the stream. As dissolved oxygen levels drop, atmospheric oxygen enters the water across the air-water interface to compensate for the oxygen deficit. At first, oxygen depletion dwarfs this reaeration. However, as the organic matter is assimilated, the rate of depletion diminishes as the reaeration rate increases. Consequently, there comes a point at which the depletion and the reaeration will be in balance. At this point, a lowest or critical level of oxygen will be reached. Beyond this critical level, the reaeration process dominates and oxygen levels begin to rise again. Thus, a dissolved oxygen sag is created in the river below the sewage discharge.

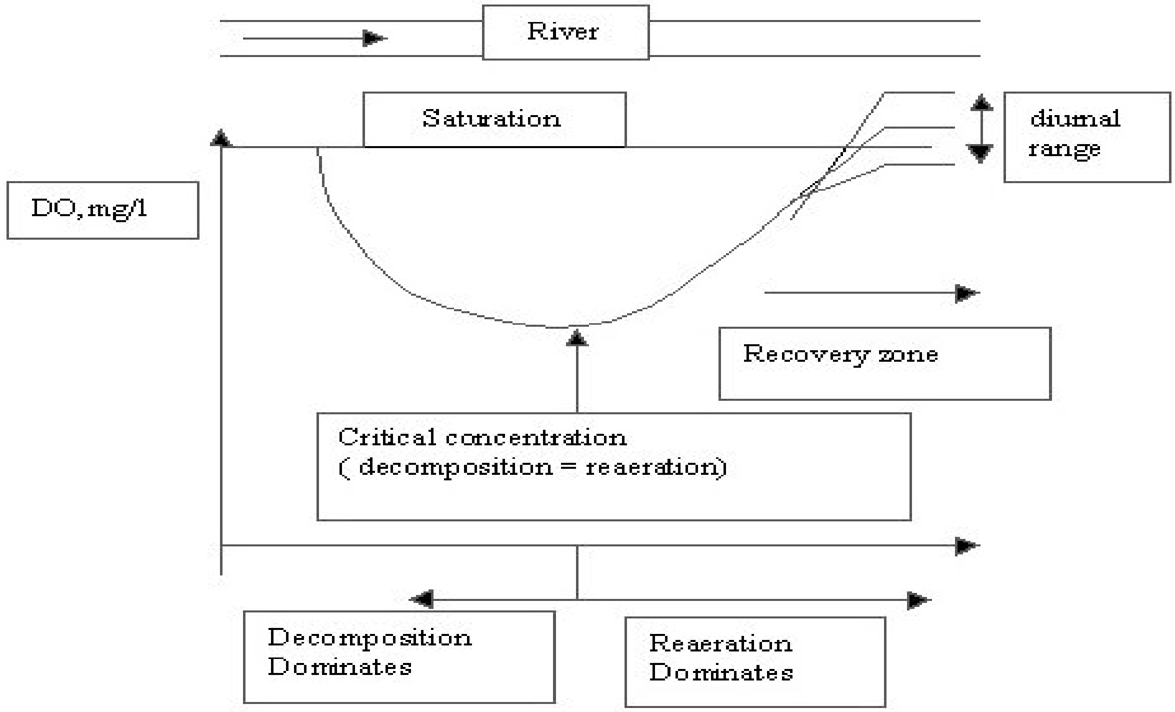


Figure 3.7 The DO sag that occurs below sewage discharges into streams

3.6.3 Oxygen Sag Analysis

The oxygen sag or oxygen deficit in the stream at any point of time during self purification process is the difference between the saturation DO content and actual DO content at that time.

Oxygen deficit, D = Saturation DO – Actual DO

The saturation DO value for fresh water depends upon the temperature and total dissolved salts present in it; and its value varies from 14.62 mg/L at 0 ^oC to 7.63 mg/L at 30 ^oC, and lower DO at higher temperatures.

The DO in the stream may not be at saturation level and there may be initial oxygen deficit 'Do'. At this stage, when the effluent with initial BOD load Lo, is discharged in to stream, the DO content of the stream starts depleting and the oxygen deficit (D) increases. The variation of oxygen deficit (D) with the distance along the stream, and hence with the time of flow from the point of pollution is depicted by the 'Oxygen Sag Curve' (Figure 3.8). The major point in sag analysis is point of minimum DO, i.e., maximum deficit. The maximum or critical deficit Dcrit occurs at the inflexion points of the oxygen sag curve.

- **Deoxygenation and Reoxygenation Curves**

When wastewater is discharged in to the stream, the DO level in the stream goes on depleting. This depletion of DO content is known as deoxygenation. The rate of deoxygenation depends upon the amount of organic matter remaining (Lt), to be oxidized at any time t, as well as temperature (T) at which reaction occurs. The variation of depletion of DO content of the stream with time is depicted by the deoxygenation curve in the absence of aeration. The ordinates below the deoxygenation curve (Figure 3.8) indicate the oxygen remaining in the natural stream after satisfying the bio-chemical demand of oxygen. When the DO content of the stream is gradually consumed due to BOD load, atmosphere supplies oxygen continuously to the water, through the process of re-aeration or reoxygenation,i.e. along with deoxygenation, re-aeration is continuous process.

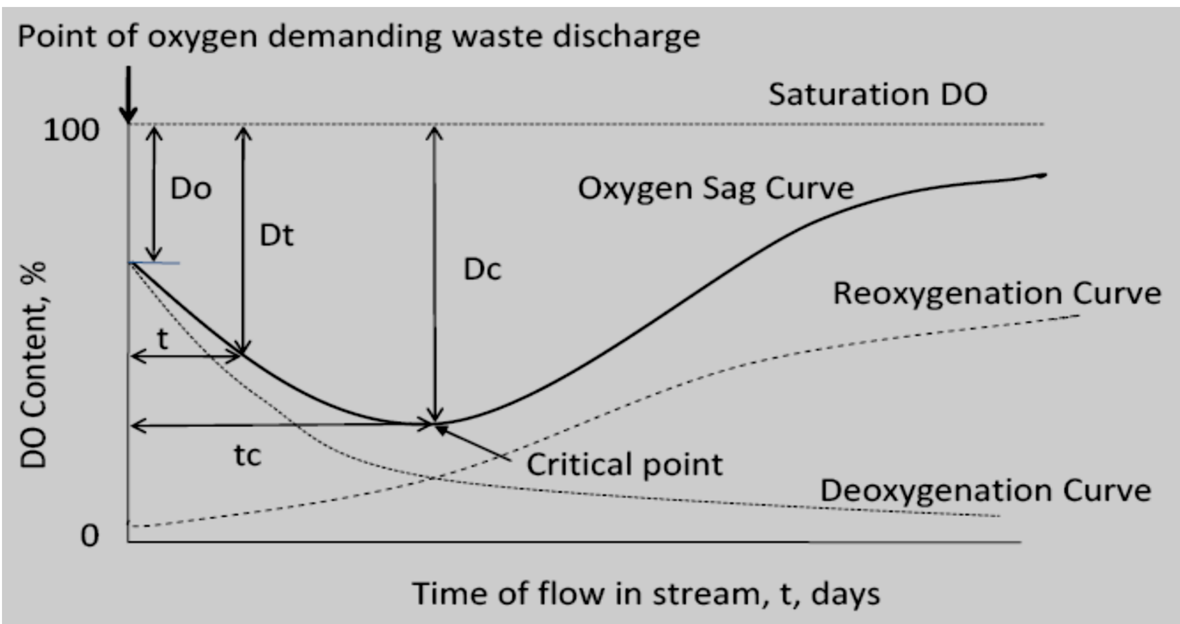


Figure 3.8 Deoxygenation, reoxygenation and oxygen sag curve

The rate of reoxygenation depends upon:

1. Depth of water in the stream: more for shallow depth.
2. Velocity of flow in the stream: less for stagnant water.
3. Oxygen deficit below saturation DO, since solubility rate depends on difference between saturation concentration and existing concentration of DO.
4. Temperature of water: solubility is lower at higher temperature and also saturation concentration is less at higher temperature.

CHAPTER – 4

MATERIALS AND METHODOLOGY

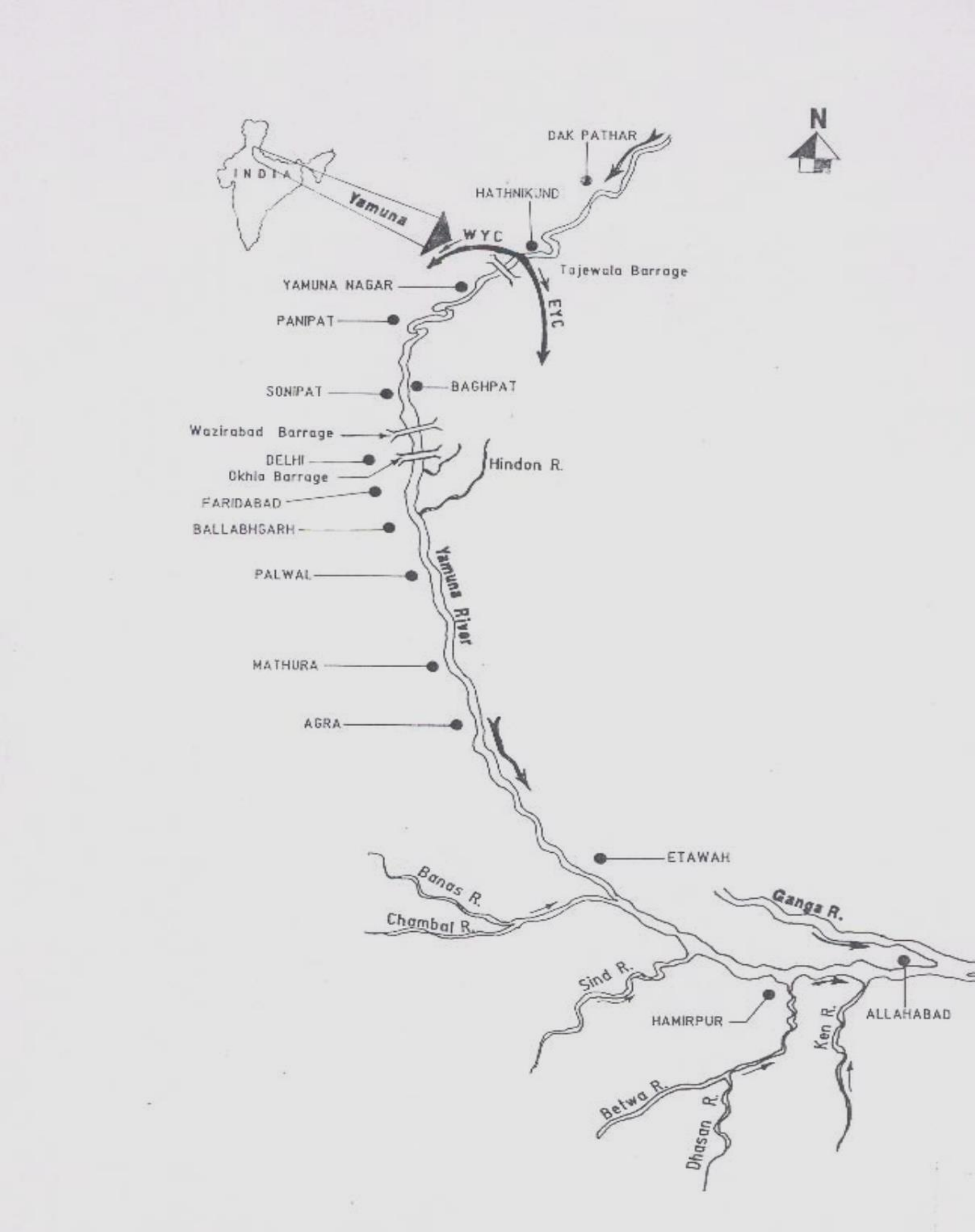
4.1 DESCRIPTION OF STUDY AREA

4.1.1 The Yamuna

The River Yamuna is as prominent and revered by millions as the great River Ganga and is its largest tributary. Various pilgrimage centers e.g. Yamunotri (Uttaranchal), Paonta Sahib (Himachal Pradesh), Mathura, Vrindavan, Bateshwar & Allahabad (all in Uttar Pradesh) are located at the banks of this holy river, as well as large urban centers like Yamuna Nagar, Sonepat, Delhi (the political nucleus of India), Gautam Budh Nagar, Faridabad, Mathura, Agra and Etawah are also established on its banks (Figure 4.1). The total length of Yamuna River from origin at Saptrishi Kund to its confluence with Ganga at Allahabad is 1376 km traversing through five states . The main stream of river originates from the Yamunotri glacier (Saptrishi Kund) near Bander punch peaks (380 59'N 78027'E) in the Mussoorie range of the lower Himalayas at an elevation of about 6320 meter above mean sea level in Uttarkashi district of Uttarakhand CPCB, 2005). In agriculture front also the Yamuna basin is one of the highly fertile and high food grain yielding basin, especially areas in Haryana and Western district in Uttar Pradesh. All this reflects that the River Yamuna not only flows in the hearts of Indian but also plays a significant role in the economy of the country. This river Yamuna is also influenced by the problems imparted by industrialization, urbanization and rapid agricultural developments similar to other riverine system.

The river flows through a series of curves and rapids for about 120 km after arising from the source, to emerge into Indo-Gangetic plains at Dak Patthar in Uttarankhand, where the river water discharge is regulated through a weir & diverted into a canal for irrigation and power generation. From Afterwards it flows down through famous Sikh religious center Paonta Sahib (Himachal Pradesh) and reaches Hathnikund in Haryana district where the major part of river water is diverted again into Eastern & Western Yamuna canals for irrigation. In dry season, no water is allowed to flow in the river, downstream to Hathnikund barrage the river regain water from ground water accumulation and through feeding canals and small tributaries. From Hathnikund the river indolently meanders and reaches Delhi at Palla after travelling a distance of about 224 km. At Wazirabad the river is trapped again through a barrage for drinking water supply to urban population at Delhi. From Wazirabad barrage no water is allowed to flow down particularly during summer, as the available water in the river is not adequate to fulfill the water supply demand of Delhi. The water flows in the Yamuna River down stream of Wazirabad is the treated, partially treated or untreated domestic & industrial wastewater contributed by various drains joining river Yamuna and canal water (CPCB, 2005). The stretch between Wazirabad to Okhla is of 22 km is our area of importance. The focus of this thesis is based on the modeling of this stretch. At Okhla barrage the water is again diverted into Agra Canal for irrigation. Similar to downstream of Wazirabad, at downstream Okhla barrage the water flows in the river is the drain water of domestic & industrial origin contributed mainly by Shahdara drain.

After travelling a distance of around 166 km, the river reaches at Mathura from where again a major part of water is diverted for drinking water supply through Gokul barrage. The Yamuna from Gokul barrage after receiving water through other important tributaries and city drains joins river Ganga at Allahabad after traversing about 790 km via cities of Agra, Bateshwar, Etawah, Hamirpur and Pratapgarh (CPCB, 2005).



Source: CPCB report, 2005

Figure 4.1 Location of Major Cities along Yamuna River

4.1.2 Segmentation of Yamuna River

The segmentation of the river is done by construction of barrages along its length. Thus the river becomes segmented in four distinguished independent segments.

- Segment I:
  This segments of length 157 km is starts from Yamunotri and terminate at Hathnikund/Tajewala barrage. The major source of water in this segment is the melting of glaciers. The water flow in this segment terminates into WJC and EJC for irrigation and drinking water purposes in command areas.

- Segment II:
  This segment of about 224 km lies between Hathnikund/Tajewala barrage and Wazirabad barrage. The main source of water in this segment is ground water accrual and contribution from few small tributaries. The water is diverted in this segment from WJC to fulfill the raw water demand for drinking water supply in Delhi. The water segment is terminated into Wazirabad barrage from where the water is pumped to the various water works as raw water for treatment to met drinking water demand of the capital city. No or very little water is allowed to flow downstream Wazirabad barrage during lean seasons.

- Segment III:
  This 22 km segment of Yamuna River is located in between Wazirabad barrage and Okhla barrage. This segment receives water from seventeen sewage drains of Delhi and also from WJC and Upper Ganga Canal via Najafgarh drain. This river segment terminates into Agra Canal.

- Segment IV:
  This Segment of Yamuna River is about 973 km long initiate immediately downstream to Okhla barrage and extends upto confluence to Ganga River at Allahabad. The source of water in this segment are ground water storage, its tributaries like Hindon, Chambal, Sindh, Ken, Betwa etc. and waste water carrying drains of Delhi, Mathura-Vrindavan, Agra and Etawah.

  At Mathura, recently Gokul barrage has been constructed to trap the Yamuna river water for drinking purposes. As the water demand will increase in future, It is likely that no water will be allowed to flow down stream like Wazirabad and Okhla barrage. This may create further segmentation of segment IV into two segments of 154 km & 804 km. With the construction of another barrage near Sikandara at Agra the river would be further segmented (CPCB, 2005).

Table 4.1 Segment details and trophic status of various stretches of river Yamuna

Sr. No.	**River Stretch**	**Segment details**	**Trophic status**
1	Himalayan Stretch	172 km from origin to Hathnikund barrage.	Oligotrophic
2	Upper Stretch	224 km from Hathnikund barrage to Wazirabad barrage.	Mesotrophic
3	Delhi Stretch	22 km from Wazirabad to Okhla barrage	Septic
4	Mixed Stretch	330 km from Okhla barrage to river Chambal confluence.	Mesotrophic/Eutrophic/Septic
5	Diluted Stretch	628 km from river Chambal confluence to river Ganga confluence.	Mesotrophic/Eutrophic

Source: CPCB, 2008

4.1.3 Utility of Yamuna River Water

The various uses of river water can be kept into two major groups. In one group the water is abstracted and transported away from the natural water bodies for beneficial uses and is called abstractive uses or uses involving collection and transportation. The other is, in which withdrawal and transportation of water is not required but the water is utilized. It is known as non-abstractive or in-situ water uses.

Table 4.2 Water Abstraction from Yamuna River

Sr. No.	Location	River Water Abstraction (approx MLD)	Abstraction Use
1	Hathnikund	20,000	Irrigation, Drinking water supply and others.
2	Wazirabad	1,100	Drinking water supply.
3	Wazirabad to Okhla	5,000	Irrigation and others.
4	Okhla to Etawah	400	Irrigation, Drinking water supply and others.
5	Etawah to Allahabad	475	Irrigation, Drinking water supply and others.

Source: CPCB, 2005

- **Non-Abstractive uses**

Hydropower- The total potential for hydropower development in the entire Yamuna basin is about 1300 MW.

Fisheries- The entire river stretch and tributaries is being utilized for fishing in unorganized manner. There is a large scope of farming for fish and other aquatic animals in stretches of River Yamuna.

River Bathing & Washing- On religious and cultural occasions millions of people take bath especially near religious towns in a congested stretch of the river within the span of a few hours. The river water is also used for washing clothes and utensils by nearby communities, particularly by the poor inhabitants.

Cattle bathing and Washing- The cattles at most of the towns & villages along the rivers are regularly taken toward the river for drinking and bathing. It is estimated that about 70% of the total cattle population in the Yamuna basin uses flowing water of river and canals for bathing and watering purposes directly. These cattle activities impart substantial impact on water quality.

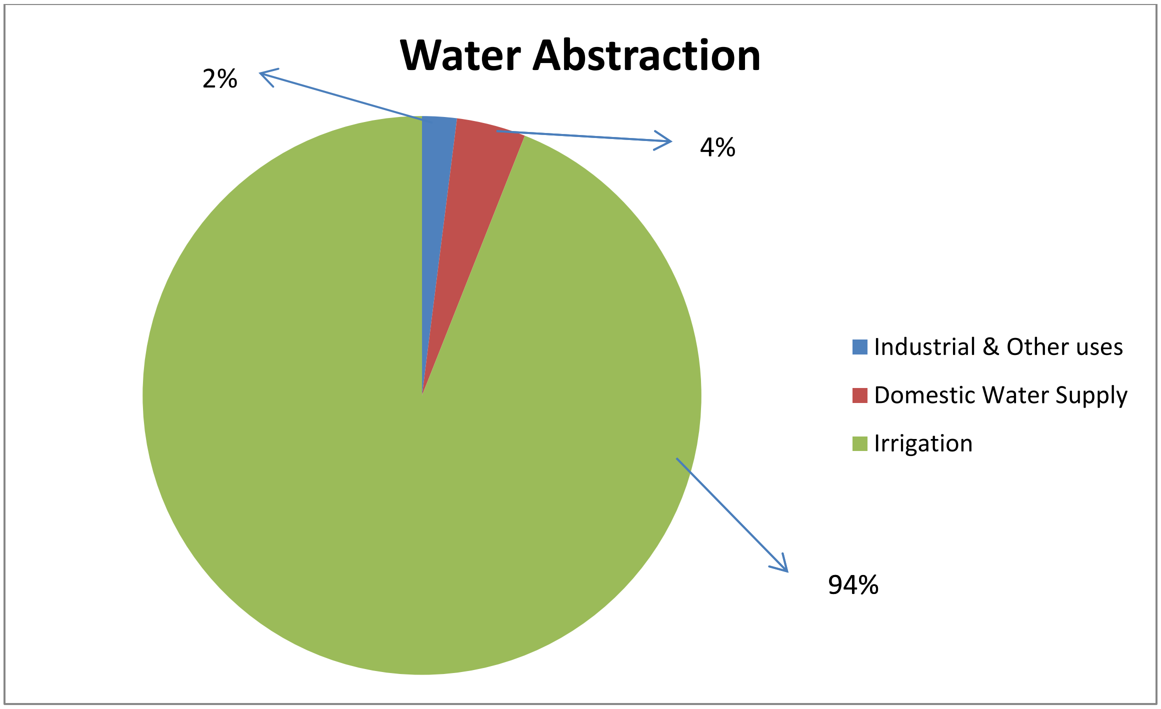
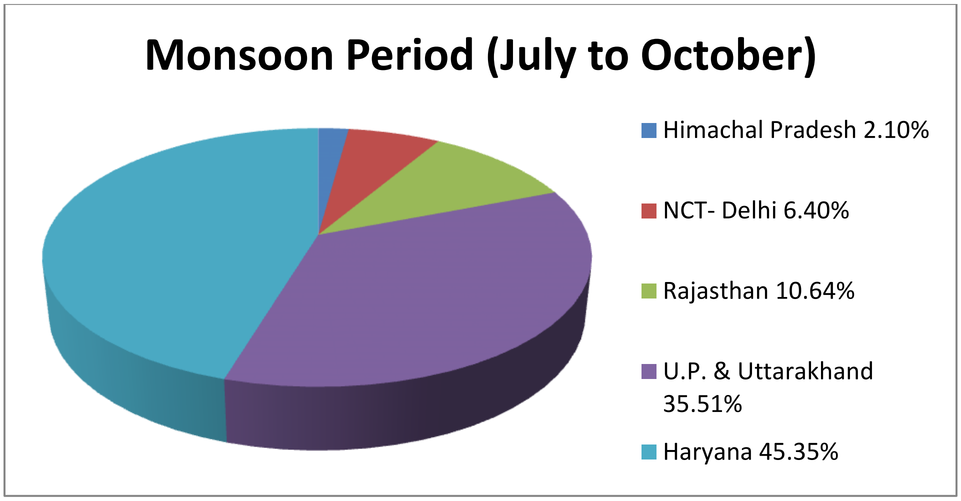
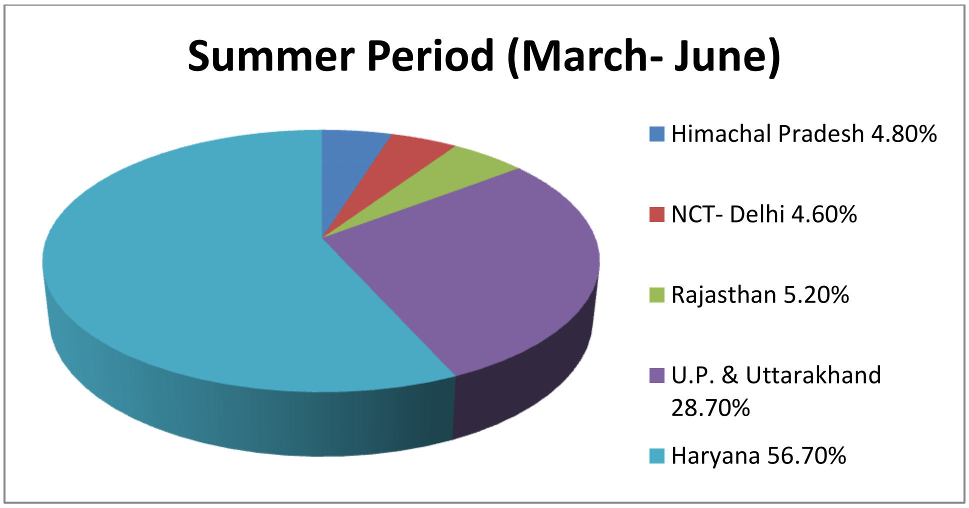


Figure 4.2 Percentage of water abstracted from River Yamuna for various uses





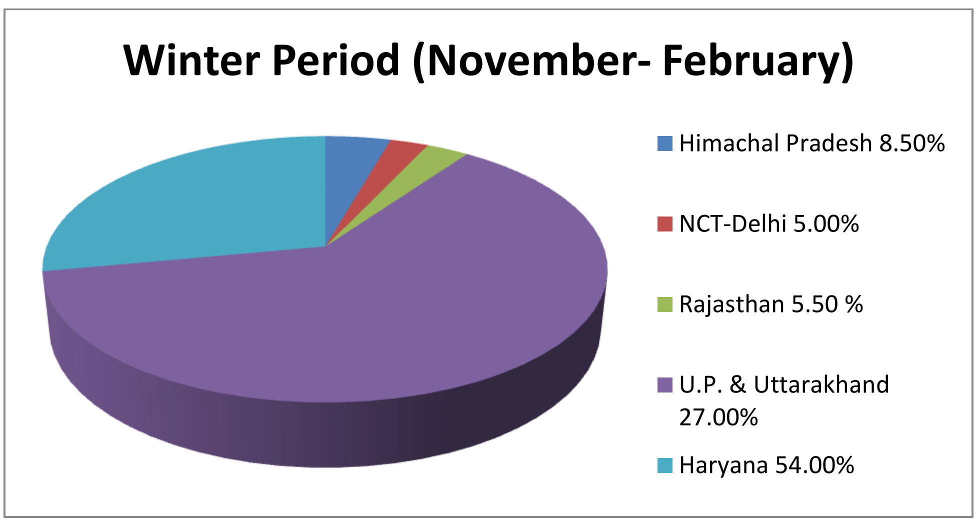


Figure 4.3 Sharing of Yamuna River Water among various States

4.1.4 Pollution Sources of River Yamuna

The entire stretch of Yamuna River from origin to confluence with Ganga is used for various human activities. The results of these activities are the generation of wastewater. The various sources of pollution are categorized in two groups:

- **Point Source of Pollution**

  Urban centers located along or near the bank of Yamuna River are the major pollution sources of River Yamuna. When the source of pollution is single, well specified and generate significant amount of pollutants such source is known as point source. The point source of pollution are further categories as:

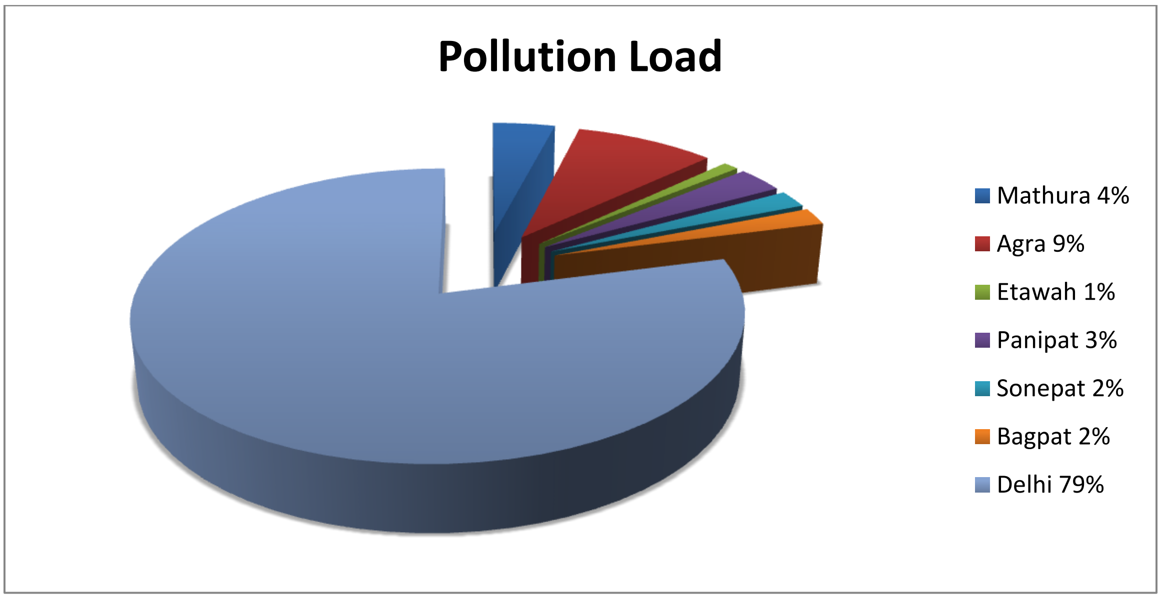


Figure 4.4 City-wise Contribution of Pollution Load in Yamuna River

A. Domestic Pollution

The major source of pollution in Yamuna river is domestic pollution. About 85% of the total pollution in the river is caused by the domestic sources mainly by the urban centers. The major of them are Panipat, Sonepat, Delhi, Ghaziabad, Mathura-Vrindavan, Agra, Etawah and Allahabad. The intensity of impact of domestic pollution on river depends on the efficiency of the wastewater collection system, type and length of the waste transportation system. If wastewater gets more retention time within urban premises before reaching to receiving water bodies, in such case the pollution load will reduce due to biodegradation and settling. The main constituents of the domestic waste are organic matters, micro-organisms, total salts, chlorides, nutrients, detergents, oil & grease etc.

B. *Industrial Pollution*

The categories of industries discharging wastewater into Yamuna river includes Pulp & paper, Sugar, Distilleries, Textiles, Leather, Chemical, Pharmaceuticals, Oil Refineries, Thermal Power Plants, food etc. In order to compliance to the environment laws, it is compulsory for these industries to treat the effluent to achieve prescribed standards before discharging effluent into the environment.

- **Non Point or Diffused Sources of Pollution**

Diffused sources are unspecified, numerous in numbers and contribution of each is of less significance. The pollutants originated from non-point sources are topsoil, organic matter, plant residues, nutrients, organic chemicals, toxicants, microorganisms etc. The important diffused pollution sources contributing to river Yamuna are:

A. Agricultural pollution sources.
B. Dumping of garbage and dead bodies.
C. Immersion of idols.
D. Pollution due to in-stream uses of water- The various sources of pollution in this category are Bathing and clothes washing, Cattle wading, Open defecation.

4.1.5 Area under Consideration

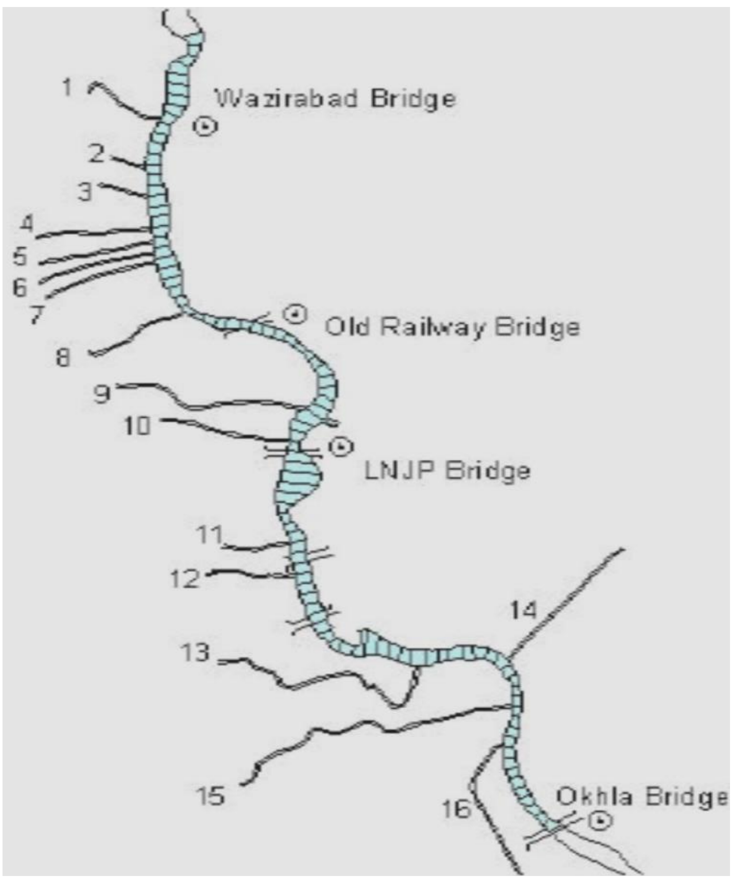
The study area chosen for the simulation of model for predicting the river water quality is the 22 km stretch of Yamuna between Wazirabad and Okhla barrage, i.e. segment III of the river. The river enters Delhi 1.5 km above village Palla and leaves Delhi at Jaitpur, downstream of the Okhla Bridge after traversing around 22 km (CPCB, 1999–2000). This stretch through its journey is joined by various drains contributing pollution load to the river. The major drains are:

1. Najafgarh Drain- This drain is 0.3 km downstream from Wazirabad Barrage and is the main pollutants contributing drain.
2. Magazine Road Drain- This is 1.3 km from Wazirabad Barrage.
3. Sweeper Colony Drain- This is 1.4 km from Wazirabad Barrage.
4. Khyber Pass Drain- About 2.4 km from Wazirabad Barrage on outer Ring Road.
5. Metcalf House Drain- About 3.4 km from Wazirabad Barrage.
6. ISBT Drain- About 4.4 km from Wazirabad barrage near ISBT Kashmere Gate, close to the Metro Rail Power feeder station.
7. Tonga Stand Drain- About 5.4 km from Wazirabad Barrage.
8. Civil Mill Drain- This is 7.4 km d/s from Wazirabad barrage.
9. Drain No. 14- About 8.1 km d/s of Wazirabad Barrage.

10. Power House Drain- 9.2 km d/s from Wazirabad Barrage.
11. Sen Nursing Home drain- 10.6 km d/s from Wazirabad barrage.
12. Barapulla Drain- 14.2 km d/s from Wazirabad barrage, near Sarai Kale Khan Bus Stand, Delhi.
13. Maharani Bagh Drain- About 17.7 km from Wazirabad Barrage.

River Sampling Locations:

1. Palla- About 15 km u/s from Wazirabad barrage. Sampling at this location reflects the water quality before receiving the wastewater discharges from Delhi and raw water quality for Delhi's water supply.
2. Nizamuddin Bridge- 14 km d/s from Wazirabad barrage. The water quality at this location reflects the impact of wastewater discharge.
3. Agra Canal- 24 km d/s from Wazirabad barrage. The water quality at this location reflects the impact of discharge of treated, partially treated effluents from Okhla Sewage treatment Plant, other drains joining the river/canal and Hindon-cut.



Legends

1. Najafgarh drain.
2. Magzine road drain.
3. Sweeper colony drain.
4. Khyber pass drain.
5. Metcalf house drain.
7. ISBT + Mori gate drain.
8. Tonga stand drain.
9. Civil mill drain.
10. Power house drain.
11. Sen nursing home drain.
12. Drain no. 14
13. Barapulla drain.
15.Maharani bagh drain.

Figure 4.5 : Simplified diagram showing location across the study area

Table 4.3 Details of Stream Reach Configration

Sr. No.	Start and End nodes of Reach	Reach chainage		Reach name
		Begin (km)	End (km)	
1	Wazirabad to Najafgarh dr.	0.0	0.3	Najafgarh
2	Najafgarh dr. to Magzine road dr.	0.3	1.3	Magzine road
3	Magzine road dr. to Sweeper colony dr.	1.3	1.4	Sweeper colony
4	Sweeper colony dr. to Khyber pass dr.	1.4	2.4	Khyber pass
5	Khyber pass dr. to Metcalf house dr.	2.4	3.4	Metcalf house
6	Metcalf house dr. to Morigate dr.	3.4	4.4	Morigate
7	Morigate dr. to Tonga stand dr.	4.4	5.4	Tonga stand
8	Tonga stand dr. to Civil mill dr.	5.4	7.4	Civil mill
9	Civil mill dr. to Drain no. 14	7.4	8.1	Drain no. 14
10	Drain no. 14 to Power house dr.	8.1	9.2	Power house no.
11	Power house dr. to Sen nursing home dr.	9.2	10.5	Sen nursing home
12	Sen nursing home dr. to Barapulla dr.	10.5	14.2	Barapulla
13	Barapulla dr. to Maharani bagh dr.	14.2	17.7	Maharani bagh

4.2 MODEL DESCRIPTION

4.2.1 Programming Tool

MATLAB(matrix laboratory) is a numerical computing environment and fourth-generation programming language. Developed by Math Works, MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces and interfacing with programs written in other languages, including C, C++, Java and Fortran. Matlab is an interactive software system for numerical computations and graphics, it has a variety of graphical capabilities, and can be extended through programs written in its own programming language. Many such programs come with the system; a number of these extend Matlab's capabilities to nonlinear problems, such as the solution of initial value problems for ordinary differential equations. Matlab is designed to solve problems numerically, that is, in finite-precision arithmetic. Therefore it produces approximate rather than exact solutions.

4.2.2 Input Variables

Input variables required by the model is divided into different classes as (a) hydraulic constants to simulate the transport of pollutants and (b) reactions rate constants to simulate kinetics of decay of pollutants

(a) Hydraulic Constants

The power equations, written below, were used to calculate depth and velocity utilizing coefficient and exponent of depth, velocity and flow rate.

$V = a Q^b$; $H = c Q^d$ Eq (4.1)

Where,
V = average cross-sectional velocity
H = average cross-sectional depth
Q = flow rate
a, c = coefficients for flow on velocity and depth respectively.
b, d = exponents for flow on velocity and depth respectively.

Table 4.4 Ranges of discharge coefficients and exponents

Input Variables	Value (ranges)
Coefficient on flow for velocity	0.032-0.08
Exponent on flow for velocity	0.300-0.425
Coefficient on flow for depth	0.126-0.33
Exponent on flow for depth	0.245-0.475

Source: CPCB, 1982-83, Ghosh, 1996, Chapra, 1997

(b) Reaction rate Constants

The value of the reaeration coefficient K_2 depends, eventually, on the hydraulic parameters of the stream and a large number of experimental formulae have been presented in various literatures (Gromiec, 1983, Jolánkai 1979, 1992). These expressions deviate from each other, sometimes substantially. For the purpose of this study the value of K_2 as a function of flow velocity v and stream depth H, has been adopted The rate coefficient of biochemical decomposition of organic matter, K_1 has been adopted from table 4.5.

Table 4.5 Ratio $f=K_2/K_1$ in function of the verbally described hydraulic condition of the stream

Description of the water body	Range of $f=K_2/K_1$
Small reservoir or lake	0.5 - 1.0
Slow sluggish stream, large lake	1.0 - 2.0
Large slow river	1.5 - 2.0
Large river of medium flow velocity	2.0 - 3.0
Fast-flowing stream	3.0 - 5.0
Rapids and water falls	5.0 - and above

Source: Description of the CAL programme on Water Quality Modelling, Dr. Géza Jolánkai and István Bíró (2000)

Both the reaeration coefficient K_2 and especially the decomposition rate coefficient K_1 depend on the ambient (water) temperature.

The settling rate and SOD were assumed to be zero for the entire course of the river. CPCB (1982 – 83) reported that only 25 % of the total BOD reaching Yamuna was settleable for the considered stretch and a part of this settled material decomposes anaerobically because the river generally has low DO levels (CPCB, 1982 - 83 and Kazmi, 2000). Thus the settling process removes only a small part of the total BOD without disturbing the DO profile of the river. Whatever BOD was removed through settling was assumed to get balanced by the loads contributed by non-quantified non-point sources such as bathing, washing, cattle wading and religious offerings of flowers, sweets and milk (CPCB, 1999-2000). The high turbidity in the stretch diminishes the penetration of light to deeper layers, preventing the growth of phytoplankton (Kazmi,2000).Therefore, photosynthetic oxygenation was also taken as zero.

4.2.3 Assumptions

Following assumptions can be made for proper functioning of model and in case of inadequacy of data. A large number of assumption will lead to miscrepancy of results which deviate more from the actual value. But some assumptions is seems to be necessary to predict the actual results.

1. The terms accounting for dispersion has been neglected.

2. With this we assume that the system is fully mixed, which means that any external material input (load) to the river or lake will be instantaneously and fully mixed with the water.

3. In this case of a river average flow and concentrations over the cross section has been taken.

4. The only velocity component, which remains in the basic equation, is then v_x, the average longitudinal flow velocity.

5. The model is considered to be Steady-state model i.e., $\partial S/\partial t = 0$

6. Within the each reach, all model parameters like K_1, K_2, velocity, depth, etc., remains the same.

7. SOD is assumed to be zero for the entire course of river. Sedimentation is a mechanism with an important bearing on both BOD and DO levels in a stream (Chapra 1997, CPCB (1982–1983).

4.2.4 Calibration

Calibration is one of the most important step of modeling wherein the exact value of parameters to be used in a model is estimated using trial and error method so as to have accurate prediction by the model. Model calibration is actually the process by which one obtains estimates for the model parameters through the comparison of field observations and model predictions. Even if the steady state condition is assumed, the environmental parameters can still vary due to random changes of temp, stream discharge, time of day, and general weather conditions. Due to this inherent dynamic nature of the environment, discrepancies between the predicted and observed results are bound to occur. Calibration is done so as to obtain optimum goodness of fit between predicted and observed data.

4.2.5 Initial and Boundary conditions

The initial and the boundary conditions are the data used to define the initial water quality condition at the beginning of the simulation. This include the initial DO, BOD and flow i.e., point load, background flow and concentration (Table 4.6 and 4.7).

Table 4.6 Characteristics of various pollution (point) loads from drains

Drains	NAJAFGARH DRAIN			MAGZINE ROAD DRAIN (DELHI)			SWEEPER COLONY DRAIN (DELHI)		
Months	Flow (m^3/s)	DO (mg/l)	BOD (mg/l)	Flow (m^3/s)	DO (mg/l)	BOD (mg/l)	Flow (m^3/s)	DO (mg/l)	BOD (mg/l)
Jan-11	23.52	0	80	0.17	0	212	0.07	0	56
Feb-11	22.62	0	70	0.11	0	314	0.03	0	139
Mar-11	26.09	0	91	0.03	0	321	0.07	0	60
Apr-11	22.63	0	48	0.13	0	213	0.08	0	94
May-11	25.84	0	61	0.20	0	397	0.07	0	60
Jun-11	21.21	0	33	0.12	0	201	0.06	0	22
Jul-11	24.68	0	28	0.09	0	197	0.08	0	40
Aug-11	26.86	0	46	0.11	0	235	0.07	0	27
Sept-11	27.70	0	36	0.16	0	132	0.09	0	45
Oct-11	25.28	0	33	0.07	0	227	0.05	0	80
Nov-11	24.37	0	41	0.11	0	148	0.04	0	20
Dec-11	25.69	0	76	0.17	0	259	0.06	0	48

Drains	KHYBER PASS DRAIN (DELHI)			METCALF HOUSE DRAIN (DELHI)			ISBT + MORI GATE DRAIN (DELHI)		
Months	Flow (m^3/s)	DO (mg/l)	BOD (mg/l)	Flow (m^3/s)	DO (mg/l)	BOD (mg/l)	Flow (m^3/s)	DO (mg/l)	BOD (mg/l)
Jan-11	0.03	0	13	0.11	0	56	0.55	0	75
Feb-11	0.13	0	33	0.05	0	132	0.49	0	101
Mar-11	0.03	0	7	0.09	0	21	0.54	0	190
Apr-11	0.03	0	3	0.05	0	31	0.51	0	60
May-11	0.02	0	12	0.09	0	31	0.63	0	152
Jun-11	0.04	0	2	0.08	0	17	0.61	0	68
Jul-11	0.06	0	8	0.05	0	16	0.45	0	45
Aug-11	0.04	0	3	0.06	0	7	0.64	0	30
Sept-11	0.05	0	7	0.13	0	10	0.54	0	27
Oct-11	0.04	0	4	0.06	0	8	0.39	0	61
Nov-11	0.03	0	4	0.07	0	20	0.35	0	67
Dec-11	0.02	0	7	0.06	0	15	0.24	0	41

Table 4.6 cont...

Drains	TONGA STAND DRAIN (DELHI)			CIVIL MILL DRAIN (DELHI)			POWER HOUSE DRAIN (DELHI)		
Months	**Flow (m^3/s)**	**DO (mg/l)**	**BOD (mg/l)**	**Flow (m^3/s)**	**DO (mg/l)**	**BOD (mg/l)**	**Flow (m^3/s)**	**DO (mg/l)**	**BOD (mg/l)**
Jan-11	0.05	0	23	0.39	0	73	0.65	0	79
Feb-11	0.08	0	302	0.30	0	140	-	0	139
Mar-11	0.07	0	179	0.23	0	156	0.75	0	92
Apr-11	0.09	0	269	0.18	0	84	0.76	0	93
May-11	0.10	0	185	-	0	-	0.67	0	72
Jun-11	0.13	0	228	0.19	0	118	1.3	0	114
Jul-11	0.07	0	136	NF	0	NF	2.08	0	85
Aug-11	0.09	0	134	0.01	0	26	2.38	0	107
Sept-11	0.07	0	73	0.14	0	12	4.25	0	36
Oct-11	0.03	0	100	0.05	0	18	4.43	0	67
Nov-11	0.05	0	135	0.29	0	69	3.75	0	72
Dec-11	0.05	0	139	0.80	0	81	2.95	0	77

[1]NF=No flow condition

Drains	SEN NURSING HOME DRAIN (DELHI)			DRAIN NO.14 (DELHI)			BARAPULLA DRAIN (DELHI)		
Months	**Flow (m^3/s)**	**DO (mg/l)**	**BOD (mg/l)**	**Flow (m^3/s)**	**DO (mg/l)**	**BOD (mg/l)**	**Flow (m^3/s)**	**DO (mg/l)**	**BOD (mg/l)**
Jan-11	0.65	0	98	0.19	0	7	1.20	0	83
Feb-11	0.54	0	162	0.19	0	88	1.39	0	84
Mar-11	0.65	0	108	0.22	0	21	1.47	0	87
Apr-11	0.98	0	91	0.08	0	2	1.56	0	61
May-11	0.45	0	166	0.04	0	7	1.67	0	39
Jun-11	1.01	0	30	0.04	0	24	1.54	0	42
Jul-11	0.53	0	61	0.21	0	14	1.49	0	51
Aug-11	0.97	0	52	0.06	0	12	1.24	0	58
Sept-11	0.94	0	35	0.22	0	4	4.69	0	47
Oct-11	0.89	0	150	0.14	0	6	1.29	0	86
Nov-11	0.67	0	73	0.17	0	11	1.20	0	39
Dec-11	0.88	0	166	0.09	0	28	1.23	0	71

Table 4.6 Cont....

Drains	MAHARANI BAGH DRAIN (DELHI)		
Months	**Flow (m^3/s)**	**DO (mg/l)**	**BOD (mg/l)**
Jan-11	0.41	0	179
Feb-11	0.43	0	253
Mar-11	0.36	0	193
Apr-11	0.35	0	156
May-11	0.35	0	116
Jun-11	0.41	0	78
Jul-11	0.40	0	64
Aug-11	0.41	0	113
Sept-11	0.53	0	57
Oct-11	0.45	0	115
Nov-11	0.43	0	95
Dec-11	0.38	0	47

Source: CPCB 2003-12, unpublished

Table 4.7 Observed Data at Sampling locations

Drains	PALLA				NIZAMUDDIN BRIDGE - MID STREAM				AGRA CANAL (KALINDI KUNJ)			
Months	**WT °C**	**BOD (mg/l)**	**DO (mg/l)**	**Flow (m^3/s)**	**WT °C**	**BOD (mg/l)**	**DO (mg/l)**	**Flow (m^3/s)**	**WT °C**	**BOD (mg/l)**	**DO (mg/l)**	**Flow (m^3/s)**
Jan-11	11.6	2	9.6	14.5	12.5	15	0.0	-	13.5	23	0.0	-
Feb-11	15.0	2	10.3	14.7	14.5	26	0.0	-	15.0	25	0.0	-
Mar-11	17.0	2	7.6	12.3	17.5	24	0.0	-	17.5	16	0.0	-
Apr-11	24.5	1	6.6	17.6	24.5	19	0.0	-	25.0	18	0.0	-
May-11	31.0	3	10.0	11.0	28.5	25	0.0	-	29.0	19	0.0	-
Jun-11	25.0	1	9.3	15.99	28.0	17	0.0	-	28.5	9	0.0	-
Jul-11	31.0	2	5.0	83.3	29.5	4	2.2	-	30.0	4	0.8	-
Aug-11	31.5	4	6.6	189.0	30.0	4	2.3	-	30.0	3	1.0	-
Sept-11	28.0	2	7.1	162.4	27.5	5	4.5	-	27.5	6	3.6	-
Oct-11	28.0	3	6.5	36.4	27.0	11	0.0	-	-	-	-	-
Nov-11	21.0	2	6.9	22.4	21.5	20	0.0	-	22.5	25	0.0	-
Dec-11	17.0	3	8.9	15.0	17.0	20	0.0	-	18.0	13	0.0	-

Source: CPCB 2003-12, unpublished

* The background flow of the river is considered keeping in view the Environmental flow concern for various stretches (Rai, 2011).

* The initial concentration for the simulation purpose is taken from the data obtained at Palla.

Table 4.8 Yearly Average characteristics of various pollution (point) loads from drains

Drains	**DO (mg/l)**	**BOD (mg/l)**	**Flow (m^3/s)**
Najafgarh drain	0	53.58	22.469
Magzine road drain	0	238	0.137
Sweeper colony drain	0	57.583	0.064
Khyber pass drain	0	8.583	0.043
Metcalfhouse drain	0	30.33	0.075
ISBT + mori gate	0	76.417	0.495
Tonga stand	0	58.583	0.073
Civil mill	0	64.75	0.215
Drain no. 14	0	86.083	0.558
Power house drain	0	32.417	0.763
Sen nursinghome drain	0	18.667	0.138
Barapulla drain	0	54.5	1.664
Maharani bagh drain	0	122.18	0.438

Source: CPCB 2003-12, unpublished

* The time period taken for simulation purpose is 2011

Table 4.9 Yearly Average of Observed data at Sampling locations

Sampling Points	**WT (°C)**	DO **(mg/l)**	BOD **(mg/l)**	Flow **(m^3/s)**
Palla	23.38	7.87	2.25	3.9
Nizamuddin bridge-mid stream	23.17	0.75	15.83	-
Agra canal (kalindi kunj)	21.375	0.45	13.42	-

Source: CPCB 2003-12, unpublished

* The time period taken for simulation purpose is 2011

* The initial concentration for the simulation purpose is taken from the data obtained at Palla.

4.2.6 Simulation Methods

Most of those who will be using water quality models will be using simulation models that are commonly available from governmental agencies (e.g. USEPA), universities, or private consulting and research institutions such as the Danish Hydraulics Institute, Wallingford software or WL | Delft Hydraulics (Ambrose et al., 1996; Brown and Barnwell, 1987; Cerco and Cole, 1995; DeMarchi et al., 1999; Ivanov et al., 1996; Reichert, 1994; USEPA, 2001; WL | Delft Hydraulics, 2003).

These simulation models are typically based on numerical methods that incorporate a combination of plug flow and continuously stirred reactor approaches to pollutant transport. Users must divide streams, rivers, and lakes and reservoirs into a series of well-mixed segments or volume elements. A hydrological or hydrodynamic model calculates the flow of water between all of these. In each simulation time step, plug flow enters these segments or volume elements from upstream segments or elements. Flow also exits from them to downstream segments or elements. During this time the constituents can decay or grow, as appropriate, depending on the conditions in those segments or volume elements. At the end of each time-step, the volumes and their constituents within each segment or element are fully mixed. The length of each segment or the volume in each element reflects the extent of dispersion in the system.

- ***Numerical Accuracy***

Water quality simulation models based on physical, biological and chemical processes typically include time rate of change terms such as dC/dt. While it is possible to solve some of these differential equations analytically, most water quality simulation models use numerical methods.

- ***Traditional Approach***

Most water quality simulation models simulate quality over a consecutive series of discrete time periods. Time is divided into discrete intervals and the flows are assumed constant within each of those time period intervals. Each water body is divided into segments or volume elements, and these are considered to be in steady-state conditions within each simulation time period. Advection or plug flow (i.e. no mixing or dispersion) is assumed during each time period. At the end of each period mixing occurs within each segment or volume element to obtain the concentrations in the segment or volume element at the beginning of the next time step.

- ***Backtracking Approach***

The backtracking approach permits any simulation timestep duration to be used along with any segmenting scheme. Unlike the traditional approach, water can travel through any number of successive segments or volume elements in each simulation time step.

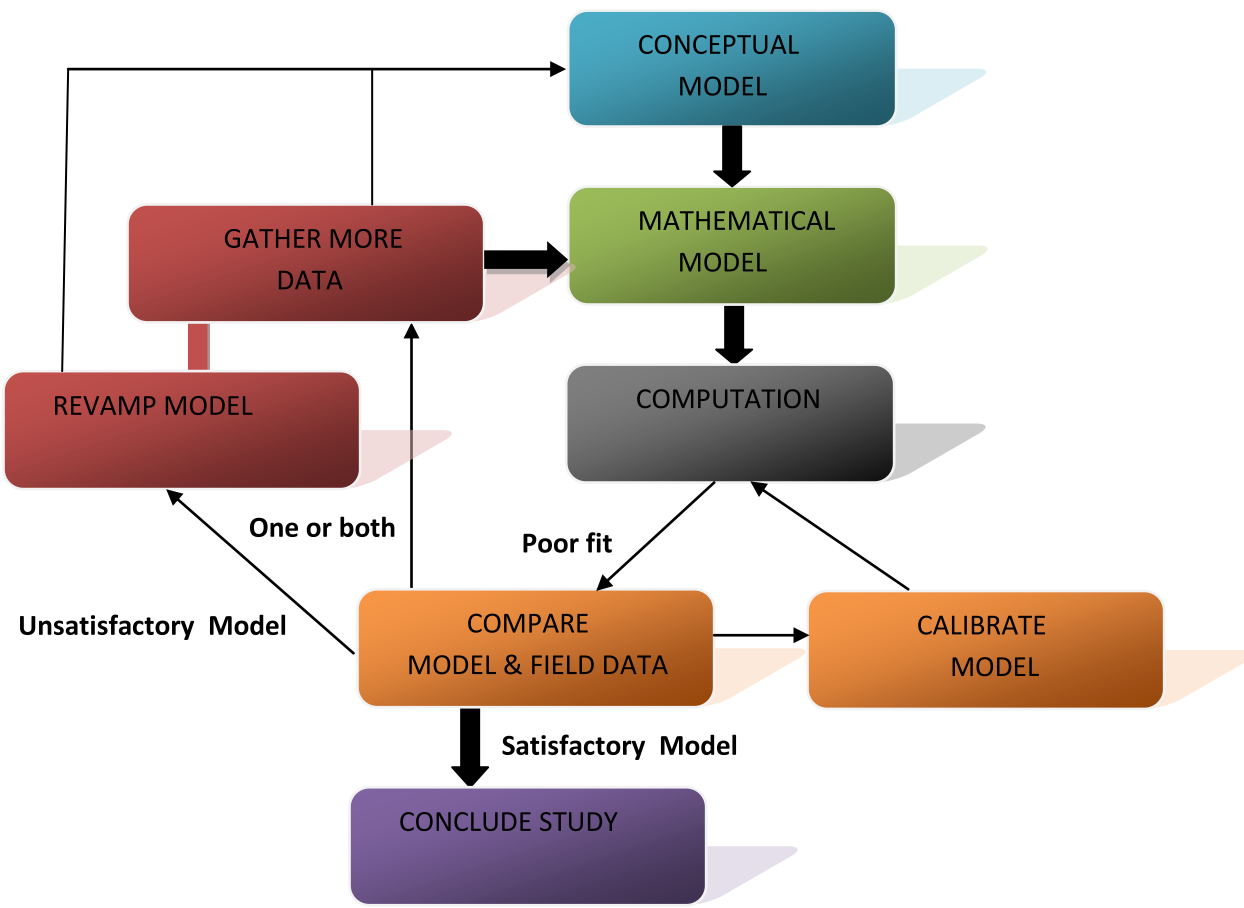
CHAPTER – 5

DEVELPOMENT OF MATHEMATICAL MODEL FOR DO-BOD PREDICTION

5.1 STEPWISE DESCRIPTION OF DEVELOPMENT OF MODEL

A mathematical model is nothing but the interpretation of a real scenario by means of formulation of equations describing that scenario. A model can be developed in the following ways:

Start by defining the problem



Make Recommendations/Decisions

Figure 5.1 Steps to be followed while developing a Model

Step 1:

The first and the foremost step in the development of a model prior to mathematical formulation is the concept theory on the basis of which whole modeling process depends. The concept comes with the purpose and situation. Whether the model that will going to be developed is a river model or a lake model or some other surface water source model, the area is to be chosen keeping in mind the general characteristics of the site, the parameters should be chosen whose prediction is required to be obtained from the model, reference from the previous studies conducted on that site. After forming the conceptual model and deciding the parameter for the purpose of studying, the modeling tool has to be chosen which is compatible with the scenario, the next step is the formulation of mathematical equations.

Step 2:

The mathematical equations governing the concentration of parameters and related equations under study are identified as in the case of present study the equations used for calculating the DO-BOD parameters are in the form of partial equations. These partial equations are solved using MATLAB. The solution of the partial equations and the other empirical equations are formulated in the sequence to obtain desired results. The formulation of the equations are coded in the MATLAB's own programming language.

Step 3:

This step includes the computation of results. After successfully formulating the model, the input variables which are to be provided are arranged in the form of matrix. The following elements are to be provided as input:
a,c = coefficients for flow on velocity and depth respectively.
b,d = exponents for flow on velocity and depth respectively.
y = Range of 'f' from table 3.4, for the purpose of this study it has chosen for the large river with slow flow velocity, i.e. '1.5-2'.
DO_s = DO concentration of the effluent from drain.
DO_b = DO concentration of the river.
L_s = BOD concentration of the effluent from drain.
L_b = BOD concentration of the river.
T = Water temperature.
q_s = Discharge from the drain.
Q_b = Flow rate of the river.
X = Distance between two nodes or distance of a reach.

For each month as in case A separate matrix of (13 × 5) is formed and given as input.

Step 4:

In this step the results obtained are compared with the observed set of data, If there is large discrepancies occur then there are others option either the model should be calibrated to obtain best fit values of input parameters but this require large value of observed data set which can be correlated with the model output to give best fit results. As in our case there is inadequacy of observed data so correlation between the two set of values is not possible. In such situation one has to reconstruct the model and if possible gather as much data so best fit equation of correlation can be obtained which minimizes the error.

If the model provide satisfactory results then a plot of DO v/s distance and BOD v/s distance is plotted which give us predicted water quality condition of river over the distance. Based on which certain decision can be made as well as recommendations can be given which are beneficial for the policy makers working in this direction.

5.2 DERIVATION OF MATHEMATICAL EXPRESSION FOR BOD-DO MODEL

The BOD decay model describes the decomposition of biodegradable organic matter (termed here L) in function of the time (which is the time of travel along the stream, t=x/v). In Equation 5.2 the initial conditions, e.g. $L=L_0$ at x = 0 ($t=t_0$) are calculated by the Dilution equation.

$$\frac{dL}{dt} = - K_1 L \qquad \text{Eq (5.1)}$$

$$L = L_0 e^{-K_1 t} \qquad \text{Eq (5.2)}$$

Where,

L - BOD in the water (mg/l^3)

L_0 - Initial BOD in the stream (below waste water discharge),

K_1 - is the rate coefficient of biochemical decomposition of organic matter (day^{-1})

t - is the time, that is the time of travel in the river interpreted as t=x/v, where x is the distance downstream of the point of effluent discharge (t, given usually in days).

The traditional dissolved oxygen model describes the fate, the sag, of the dissolved oxygen in the river as influenced by the decay of biodegradable organic matter and the reaeration process across the water surface.

$$\frac{dD}{dt} = K_1 L - K_2 D \qquad \text{Eq (5.3)}$$

$$D = \frac{K_1 L_0}{K_2 - K_1}\left(e^{-K_1 t} - e^{-K_2 t}\right) + D_0 e^{-K_2 t} \qquad \text{Eq (5.4)}$$

Where,

D - is the oxygen deficit of water (mg/l^3),

D_0 - is the initial oxygen deficit in the water (d/s of effluent outfall),

K_2 - is the reaeration rate coefficient (day^{-1})

The dilution equation

$$L_0 = \frac{L_S q_S + L_b Q_b}{q_S + Q_b} \qquad \text{Eq (5.5)}$$

$$DO_0 = \frac{DO_S q_S + DO_b Q_b}{q_S + Q_b} \qquad \text{Eq (5.6)}$$

Where

L_b - is the background concentration of BOD in the river (mg/l),

L_s - is the BOD content of the waste water (mg/l),

DO_0 - is the initial concentration of DO in the river, D/s of the effluent discharge point (mg/l),

DO_b - is the background concentration of DO in the river (mg/l),

DO_s - is the DO content of the waste water (mg/l),

Q_b - discharge (rate of flow) of the river u/s of the effluent outfall (m^3/sec),

q_s - the effluent discharge (m^3/sec).

The initial oxygen deficit equation

This set of equations is used to calculate the initial oxygen deficit of the water d/s of a point source sewage discharge as compared to the saturation dissolved oxygen concentration, which latter is temperature dependent.

$$D_0 = DO_{sat} - DO_0 \qquad \text{Eq (5.7)}$$

$$DO_{sat} = 14.61996 - 0.04042T + 0.00842\,T^2 - 0.00009T^3 \qquad \text{Eq (5.8)}$$

Where,

DO_{sat} - is the saturation oxygen concentration of water,

T - is the water temperature (^oC)

Critical values of the oxygen sag curve

This set of four equations is used to compute the lowest DO concentration (highest oxygen deficit) in the river water d/s of a single source of sewage water along with the corresponding time of travel and d/s distance.

$$t_{crit} = \frac{1}{K_2 - K_1} \ln \frac{K_2}{K_1}\left(1 - \frac{D_0 (K_2 - K_1)}{L_0 K_1}\right)$$ Eq (5.9)

$$x_{crit} = v \times t_{crit}$$ Eq (5.10)

$$D_{crit} = \frac{K_1}{K_2} L_0 e^{-K_1 t_{crit}}$$ Eq (5.11)

$$DO_{crit} = DO_{sat} - D_{crit}$$ Eq (5.12)

Where,

t_{crit} - the critical time of travel (time during which the water particle arrives to the point of lowest DO concentration in the stream),

x_{crit} - the critical distance d/s of the point of effluent discharge (the point of lowest DO concentration),

D_{crit} - is the critical (highest) oxygen deficit in the water, along the river,

DO_{crit} - is the critical (lowest) DO concentration of the water.

Equation for estimating K_2

$$K_2 = 2.148 \times v^{0.878} \times H^{-1.48}$$ Eq (5.13)

Where,

v - is the average flow velocity in the river reach, (m/sec), given by Eq (4.1)

H- is the average depth of flow over the river reach, (m), given by Eq (4.1)

For the estimation of the value of K_1 the Table of Fair (ref. Jolánkai, 1979) can be used, where known value of K_2, from the Eq (5.13) can be applied. This Table expresses the ratio $f = K_2/K_1$ in function of the verbally described hydraulic condition of the stream as shown in Table 4.5**.**

5.3 IMPLEMENTATION OF DEVELOPED MODEL

As a part of this research Traditional Approach has been applied. MATLAB is used as a programming tool in which mathematical formulation of the required partial equation are encoded to obtained desired results with input data are given in the form of matrices. In this, the Wazirabad barrage is taken as first node point and further node points are considered where confluence of drains with River takes place, the numbering of the node is done as its distance from Wazirabad barrage in increasing order. The distance between two consecutive nodes is called as a reach. Thus, there are in total 13 nodes excluding the end nodes (Wazirabad and Okhla) and 12 reaches in between. In this study, the modeling of 22 km stretch of Yamuna segment between Wazirabad and Okhla barrage has been done taking in account the following three different cases:

Case A

In this case model is made to run for a period of 12 months from January-2011 to December-2011. The background flow of the river in this case is considered in such a way so that sufficient water discharge should be maintained d/s of Wazirabad barrage inorder to meet out the Environmental Flow concern of the subsequent reaches (Rai, 2011). The output obtained at the end of each monthly run will give the concentration of DO and BOD just u/s of each node point. Thus a DO and BOD profile of the stretch can be obtained for all the months. This will help us in predicting the quality of river at that stretch if sufficient water supply is allowed to be maintained downstream.

Case B

In case B model is made to run one time taking yearly average data for the year-2011 in which two scenarios has been compared, one in which actual case of low water supply d/s of Wazirabad is taken while in the other the flow is maintained as in case A taking in account the average of monthly input data.

Case C

In the last case the DO and BOD profile of the river is predicted in between the two nodes for all the reaches. This case will help us to predict the water quality characteristics of the river between two drains, thus the major load contributing drain will be determined. The input data used for the purpose is the average of monthly data for the year-2011.

5.4 MATLAB CODING

```
clc
load pre.txt
%a = input('enter the value of a')
%b = input('enter the value of b')
%c = input('enter the value of c')
%d = input('enter the value of d')
%y = input('enter the value of y')
%DOs = input('enter the value of DOs')
%DObo = input('enter the value of DOb')
%intr = input ('enter the no of interval in x');
y=p;
DOs=q;
DObo=r;
intr=4;
Lb=s;
Ls = pre(:,1);
qs = pre(:,2);
Qb= pre(:,3);
T = pre(:,4);
X = pre(:,5);
a = pre(:,6);
b = pre(:,7);
c = pre(:,8);
d = pre(:,9);
[mx,nx]=size(X);
%Lb = input('enter the value of Lb to start the program')
%Lo = ((Ls.*qs)+(Lb.*Qb))./(Qb+qs)

DOb = DObo
%DOo = ((DOs*qs)+(DOb*Qb))./(Qb+qs)
xmatrix =zeros(mx,intr+1);
Xn=zeros(mx,intr+2);
DOM = ones(1,intr+2);
DOMN =zeros(mx,intr+2);
TT=zeros(mx,intr+2);
do=zeros(mx,intr+2);
Ln=zeros(mx,intr+1);

for
    Lo(i) = ((Ls(i)*qs(i))+(Lb*Qb(i)))/(Qb(i)+qs(i))
    v(i) = (a(i))*(Qb(i)^b(i))
H(i)= (c(i))*(Qb(i)^d(i))
K2(i) = 2.148*(v(i)^0.878).*(H(i)^-1.48)
K1(i) = (K2(i)/y)
    DOo(i) = ((DOs*qs(i))+(DOb*Qb(i)))/(Qb(i)+qs(i))
    hh = X(i)/intr;
    x=0:hh:X(i);
    xmatrix(i,:)=x;
   [sx,n]=size(x);
    t = ((x./v(i))/86.4)
    %t(i,:)=tp;
    L = Lo(i)*exp(-t.*K1(i))
    Ln(i,:)=L;
   DOsat(i) = 14.61996-0.4042*T(i)+0.00842*(T(i)^2)-0.00009*(T(i)^3)
```

```
Do(i) = DOsat(i)- DOo(i)
D = (((K1(i)*Lo(i))*(exp(-t.*K1(i))-exp(-t.*K2(i)))./(K2(i)-
K1(i)))+Do(i)*exp(-t.*K2(i))
DO = DOsat(i)-D
tcrit(i) = 1/(K2(i)-K1(i))*log((K2(i)/K1(i))*(1-((Do(i)*(K2(i)-
K1(i)))/(Lo(i)*K1(i)))))
Xcrit(i) = v(i)*(tcrit(i)*86.4)
Dcrit(i) = ((K1(i)/K2(i))*(Lo(i)*exp(-K1(i)*tcrit(i))))
DOcrit(i) = DOsat(i)-Dcrit(i)
Xp = [x Xcrit(i)];
Xn(i,:)=Xp;
Tn =[ t tcrit(i)];
TT(i,:)= Tn;
dop = [DO DOcrit(i)];
do(i,:)=dop;
Lb=L(n);
DOb=DO(n);
DOMN(i,:) = DOM.*DOsat(i);

%pltL(i)=L(1,n)
%pltdo(i)=do(1,n)
end
figure(1);
plot(xmatrix',Ln');
figure(2);
plot(Xn',do');
hold on;
 plot(Xn',DOMN');
 hold off;
xlabel('distance in km');
ylabel('DO concentration in mgO2/l');
```

The input data is provided in the form of matrices. For each case same coding is applied with different set of input matrix which are developed for a particular case. Thus any user find it easily manageable as just he has to press run command to obtain the output. The coding in the MATLAB is done in command window whereas the results after running the programme can be obtained in the prompt window.

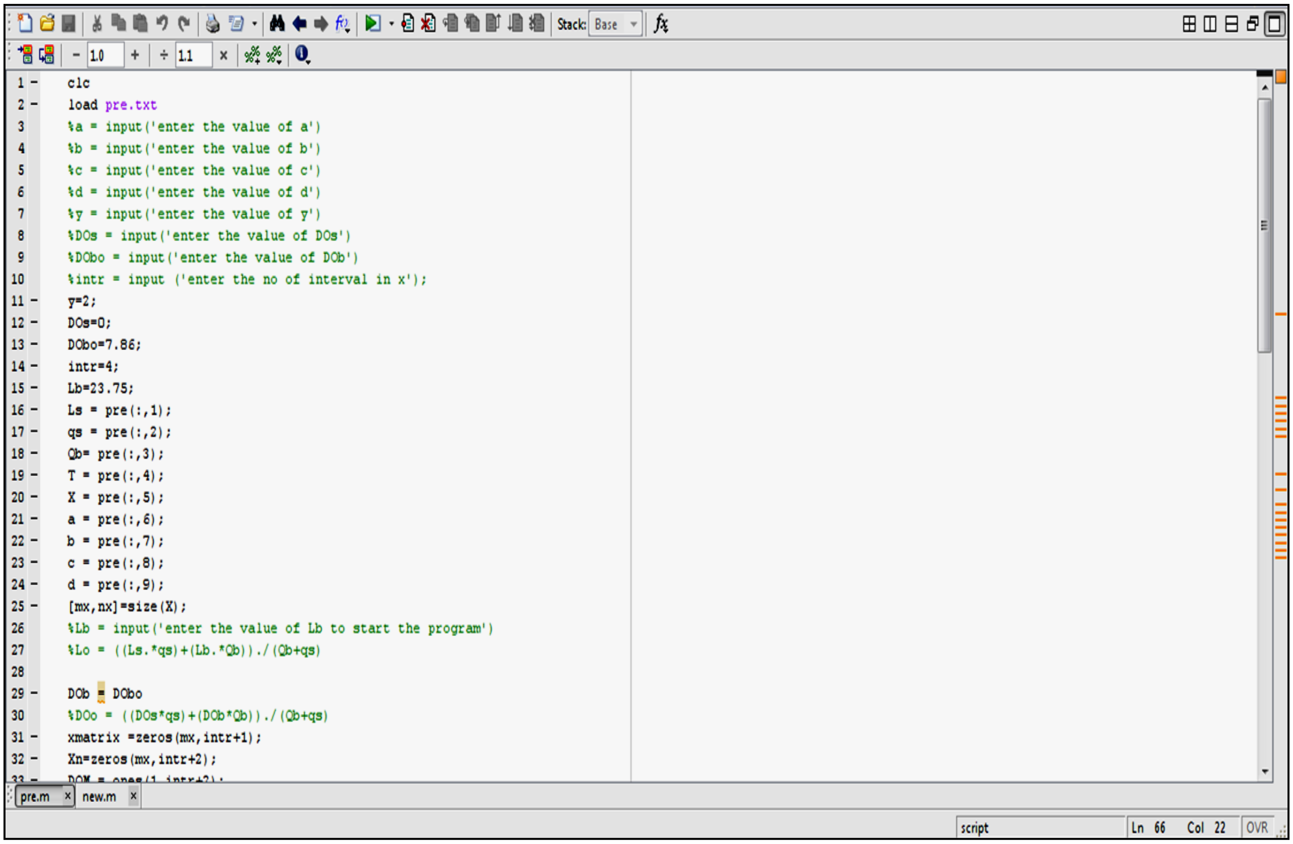


Figure 5.2 Picture of Command Screen

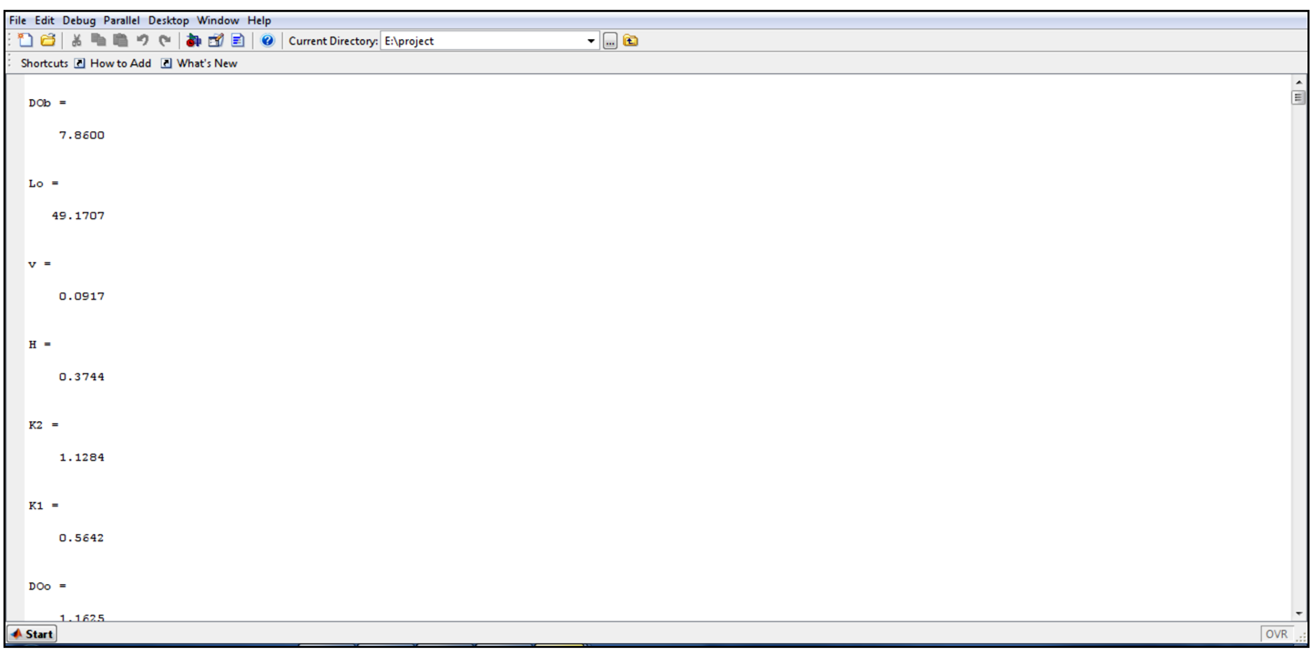


Figure 5.3 Picture of Prompt Screen

CHAPTER – 6

RESULTS AND DISCUSSION

6.1 ANALYSIS OF THE DEVELOPED MODEL

The Mathematical Model has been developed using MATLAB as described in the previous chapter. The model has been simulated monthly as well as yearly for each separate case, like for monthly simulation the same coding been saved in 12 different files one for each month implying the different monthly input conditions. The input data set is converted into a matrix form, each monthly input data has also been saved in the same folder along with its mother coded file with the same name. At any time whenever the user want to obtain results for a particular month the file naming that month should be opened in the command window of MATLAB and run command is given, as soon as the cursor clicked run, it will automatically take the input data from its source file and give the output at the prompt screen along with it two other screen also get opened which shows the variation of DO and BOD over distance as predicted by the model. The same is applied for the yearly data. Here just one mother file which contain coding and the other source file which contain its yearly input data matrix is needed. In MATLAB the model once developed can be applied for years with changing required input data set.

The input data as obtained from CPCB has been given in Table 4.6 and Table 4.7 for Case A where monthly observations are required whereas Table 4.8 and Table 4.9 gives the yearly data which has been obtained by averaging the monthly sets to be applied for Case B and Case C.

For the purpose of Case A, the model is made to run for a period of 12 months from January-2011 to December-2011. The background flow of the river in this case is considered in such a way so that sufficient water discharge should be maintained d/s of Wazirabad barrage inorder to meet out the Environmental Flow concern of the subsequent reaches (Rai, 2011). The output obtained at the end of each monthly run will give the concentration of DO and BOD just d/s of each node point. Thus a DO and BOD profile of the stretch can be obtained for all the months. This will help us in predicting the quality of river at that stretch if sufficient water supply is allowed to be maintained downstream. Table 6.1 to table 6.12 will gives the concentration of DO and BOD just u/s of the node points for each month, i.e. from Jan-2011 to Dec-2011.

Table 6.13 and Table 6.14 will give the predicted results regarding the actual scenario of low water discharged and condition of sufficient water discharge for the yearly data for the year-2011, respectively. The Concentration is obtained just u/s and just d/s of node taking yearly data for the year 2011. The hypothetical case has been taken from the paper by Rai, 2011 in which he had predicted the monthly discharge using mike-11 model. In our case average of his monthly predictions has been considered.

Case C represents the concentration of DO and BOD calculated between two nodes at five point where just d/s of previous node has been given the designation '$_0$' as L_0 or DO_0, whereas successive points as 1,2,3 and 4. '4' being the designation of point just u/s of the next node. In this also the average of monthly data as obtained from CPCB is taken for predicting yearly variations.

6.1.1 Model

The equations which has been used by the model for calculating the concentration of DO and BOD at predetermined points are sequentially formulated as follows:

BOD Calculation

- $L = L_0 e^{-K_1 t}$
- $L_0 = \frac{L_S q_S + L_b Q_b}{q_S + Q_b}$
- $t = (x/v) / 86.4$
- $K_1 = K_2 / y$

DO Calculation

- $D = \frac{K_1 L_0}{K_2 - K_1}(e^{-K_1 t} - e^{-K_2 t}) + D_0 e^{-K_2 t}$
- $DO_0 = \frac{DO_S q_S + DO_b Q_b}{q_S + Q_b}$
- $D_0 = DO_{sat} - DO_0$
- $DO_{sat} = 14.61996 - 0.04042T + 0.00842\, T^2 - 0.00009T^3$
- $K_2 = 2.148 \times v^{0.878} \times H^{-1.48}$
- $v = a\, Q^b$; $H = c\, Q^d$

The meaning of the above terms has been described in the previous chapters

6.2 MONTHLY VARIATION OF DO AND BOD OVER 22 Km STRETCH OF YAMUNA AT DELHI

Theoretically, maximum BOD concentration is found just d/s of the discharge point and as we move away from the source BOD starts decreasing as the self purification capacity of the river begins to play its part. In our case the variation of BOD has been observed single handedly over the complete stretch of 22 km which is joined by several drains in between, carrying with it tonnes of pollutant load. Therefore we observes some deviation from the general trend at few points.

6.2.1 Variation of DO and BOD in the month of January-2011

The winter period marks its beginning from November and ends till February. Thus January being the winter month faces low water discharge d/s in plains. The percentage share of water for NCT-Delhi for the winter period as shown in Figure 4.3 is 5%. But in our case the flow rate of the river is taken as 14.5 m^3/s (Table 4.7) to meet out the Environmental concern of all the reaches. The following Table shows the varying profile of DO and BOD for the month of Jan-11.

Table 6.1 Predicted concentration of DO and BOD just d/s of node points for each drains for Jan-2011

Months	Drains	BOD (mg/l)	DO (mg/l)	X (km)
Jan-11	**Najafgarh drain**	49.476	3.1932	0.3
	Magzine road drain	48.604	2.119	1
	Sweeper colony drain	48.461	2.0158	0.1
	Khyber pass drain	46.899	1.0839	1
	Metcalfhouse drain	45.439	0.2552	1
	ISBT + mori gate	44.406	0	1
	Tonga stand	42.985	0	1
	Civil mill	40.607	0	2
	Drain no. 14	39.576	0	0.7
	Power house drain	38.837	0	1.1
	Sen nursinghome drain	38.067	0	1.4
	Barapulla drain	35.173	0	3.6
	Maharani bagh drain	32.834	0	3.5

The predicted result has been compared with the observed values obtained at two sampling stations (Table 4.7) as shown in the following Figures.

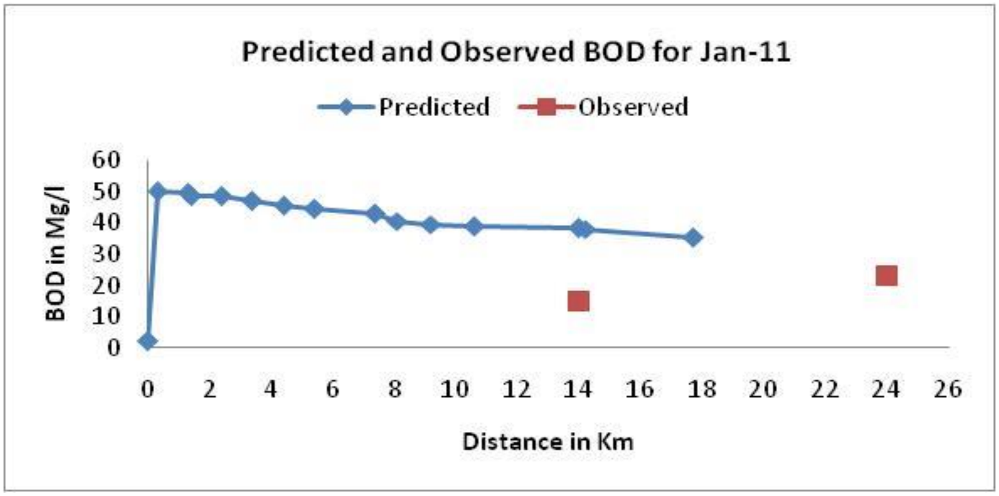


Figure 6.1 Predicted and Observed BOD profile of the river between Wazirabad and Okhla for the month of Jan-11

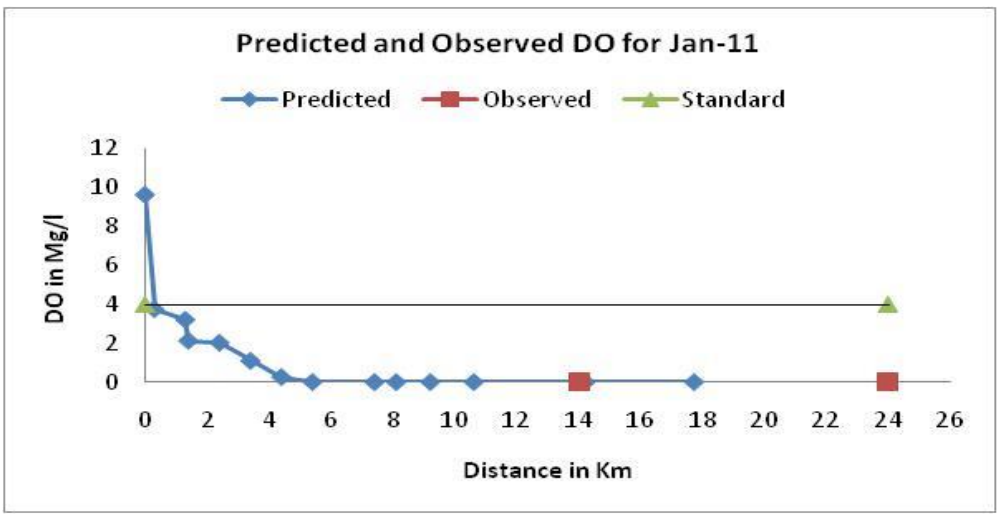


Figure 6.2 Predicted and Observed DO profile of the river between Wazirabad and Okhla for the month of Jan-11

Following points are taken into consideration from the above prediction:

1. The BOD continuously decreases as we move down from Najafgarh to Maharani bagh drain. The reason for this is that Najafgarh drain is the first drain in the series after the Wazirabad barrage the only discharge of water it receives is the flow itself carried by it along with the little from background flow of the river thus river's dilution capacity

become less for this reach as a result of which it shows maximum BOD concentration as compared to other reaches.

2. Also Jan is the winter month, the only water reaching the barrage is from the previous route of the river. The discharge from the Wazirabad barrage as predicted by Rai's model (Table 4.7) is sufficient for Environmental concern but not enough to completely dilute the BOD load.
3. DO concentration also decreases and after Metcalfhouse drain it become nil for rest of the stretch. Also none of the reach is capable of touching the standard level of 4 mg/l. This is because of the low water discharge, high pollutant load concentration and nil self purification capacity of the river.

6.2.2 Variation of DO and BOD in the month of February-2011

February is the last month of winter period which also faces the same situation but the condition improves little from the previous month. For the month of February the flow rate of the river is taken as 14.7 m^3/s (Table 4.7) to meet out the Environmental concern of all the reaches. The following Table shows the varying profile of DO and BOD for the month of Feb-11.

Table 6.2 Predicted concentration of DO and BOD just d/s of node points for each drains for Feb-2011

Months	Drains	BOD (mg/l)	DO (mg/l)	X (km)
Feb-11	**Najafgarh drain**	42.552	3.3984	0.3
	Magzine road drain	41.96	2.4696	1
	Sweeper colony drain	41.901	2.3813	0.1
	Khyber pass drain	40.53	1.5657	1
	Metcalfhouse drain	39.353	0.846	1
	ISBT + mori gate	38.863	0.1795	1
	Tonga stand	38.164	0	1
	Civil mill	36.527	0	2
	Drain no. 14	37.378	0	0.7
	Power house drain	37.729	0	1.1
	Sen nursinghome drain	36.325	0	1.4
	Barapulla drain	33.86	0	3.6
	Maharani bagh drain	32.404	0	3.5

The predicted result has been compared with the observed data set as shown in the following Figures.

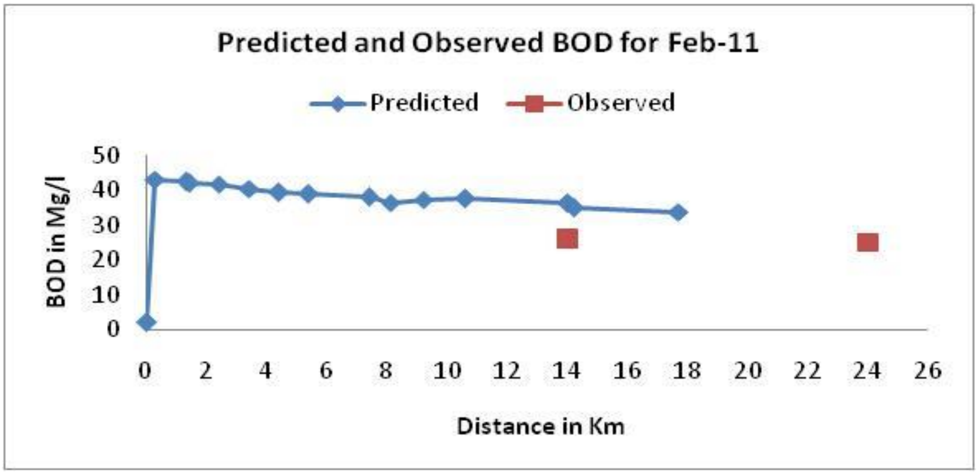


Figure 6.3 Predicted and Observed BOD profile of the river between Wazirabad and Okhla for the month of Feb-11

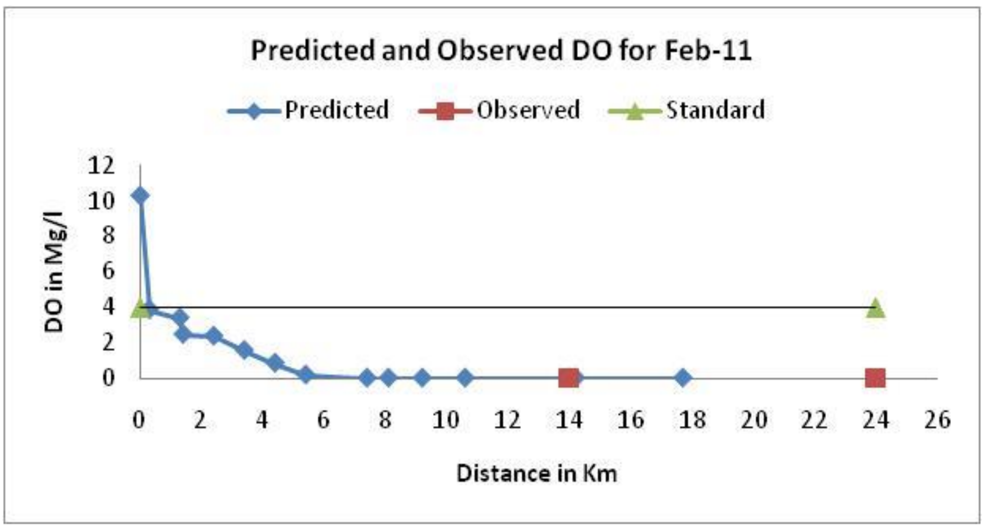


Figure 6.4 Predicted and Observed DO profile of the river between Wazirabad and Okhla for the month of Feb-11

The noticeable points from the above Table and figures are:

1. BOD concentration still high for Najafgarh drain become less than as obtained for the previous month for the same drain because of the increase in flow of the river (Table 4.7) also the BOD load contributed by Najafgarh drain decreases but same for the Magzine road drain increases that's why there is very little decreases in the BOD

concentration at Magzine road node despite of increase in river flow. The same goes with the next drain as the flow of the Magzine road drain is also less (Table 4.6) while the BOD concentration of the sweeper colony drain is high dilution capacity further decreases.

2. As for the DO it decreases with the same pace as for previous months but the condition improve less than a little as the DO concentration of the Najafgarh drain become close to standard level.

6.2.3 Variation of DO and BOD in the month of March-2011

The summer period marks its beginning from March and ends till June. In march the inadaptability of the river to handle crises enhanced three-fourth. For the month of March the flow rate of the river is taken as 12.3 m^3/s (Table 4.7) which is just second to minimum as compared to rest months, to meet out the Environmental concern of all the reaches. The following Table and shows the varying profile of DO and BOD for the month of Mar-11.

Table 6.3 Predicted concentration of DO and BOD just d/s of node points for each drains for Mar-2011

Months	Drains	BOD (mg/l)	DO (mg/l)	X (km)
Mar-11	**Najafgarh drain**	61.438	2.33	0.3
	Magzine road drain	59.691	0.9018	1
	Sweeper colony drain	59.501	0.7659	0.1
	Khyber pass drain	57.582	0	1
	Metcalfhouse drain	55.681	0	1
	ISBT + mori gate	55.719	0	1
	Tonga stand	54.187	0	1
	Civil mill	51.405	0	2
	Drain no. 14	51.017	0	0.7
	Power house drain	50.16	0	1.1
	Sen nursinghome drain	47.869	0	1.4
	Barapulla drain	44.01	0	3.6
	Maharani bagh drain	40.671	0	3.5

The predicted result has been compared with the observed values for the above month as shown in the following Figures.

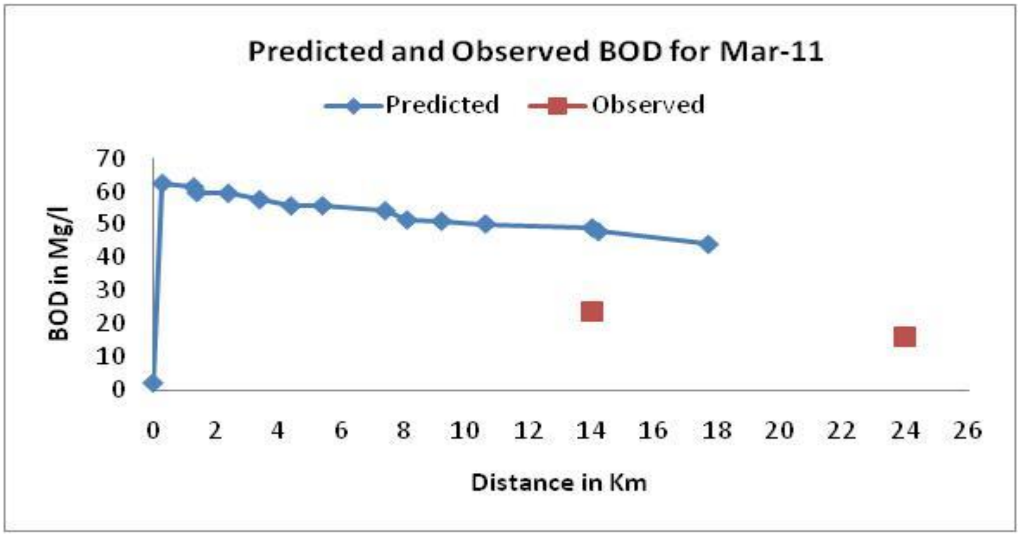


Figure 6.5 Predicted and Observed BOD profile of the river between Wazirabad and Okhla for the month of Mar-11

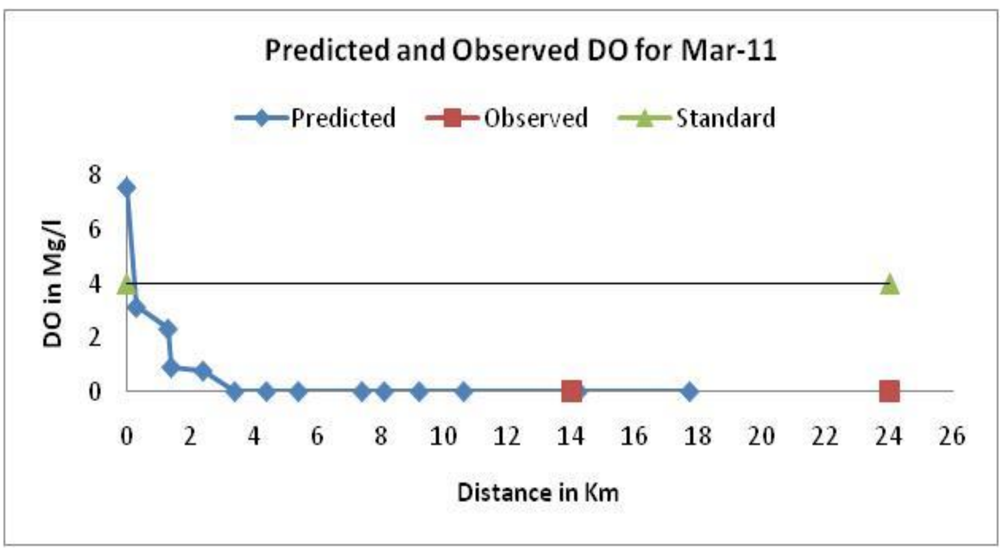


Figure 6.6 Predicted and Observed DO profile of the river between Wazirabad and Okhla for the month of Mar-11

March observes the worst situation with very high BOD load and nil DO throughout the stretch, the points which draws attention here are:

1. As March marks the beginning of Summer season in Northern India (It is the transitioning phase between two season), with its comes the low water discharge as high

demand of water supply is required in the city. Therefore a large part of water is drawn before reaching the Wazirabad barrage inorder to satisfy the increasing demand of the various states. Thus in march Yamuna in Delhi faces the worst case of detoriation.

2. Despite of the fact that flow of the river in this case is considered sufficient to meet out the Environmental concern of the reaches is not justifying its point, this is due very high pollutant load and low water discharge from the drains. Thus it clearly states that along with increasing the flow there should be decrease in pollutant load too, i.e. they ought to be in mutual proportion.

6.2.4 Variation of DO and BOD in the month of April-2011

In April temperature of the atmosphere began to rise. Here the situation is opposite to previous month in terms of river quality. For the month of April the flow rate of the river is taken as 17.6 m^3/s (Table 4.7) to meet out the Environmental concern of all the reaches. The following Table shows the varying profile of DO and BOD for the month of Apr-11.

Table 6.4 Predicted concentration of DO and BOD just d/s of node points for each drains for Apr-2011

Months	Drains	BOD (mg/l)	DO (mg/l)	X (km)
Apr-11	**Najafgarh drain**	27.484	4.0171	0.3
	Magzine road drain	27.213	3.4334	1
	Sweeper colony drain	27.26	3.3726	0.1
	Khyber pass drain	26.402	2.8643	1
	Metcalfhouse drain	25.593	2.411	1
	ISBT + mori gate	25.219	1.9721	1
	Tonga stand	24.964	1.5941	1
	Civil mill	23.702	0.961	2
	Drain no. 14	24.419	0.7381	0.7
	Power house drain	25.073	0.3931	1.1
	Sen nursinghome drain	23.988	0.0504	1.4
	Barapulla drain	22.664	0	3.6
	Maharani bagh drain	21.351	0	3.5

The predicted result has been compared with the observed values for the above month as shown in the following Figures.

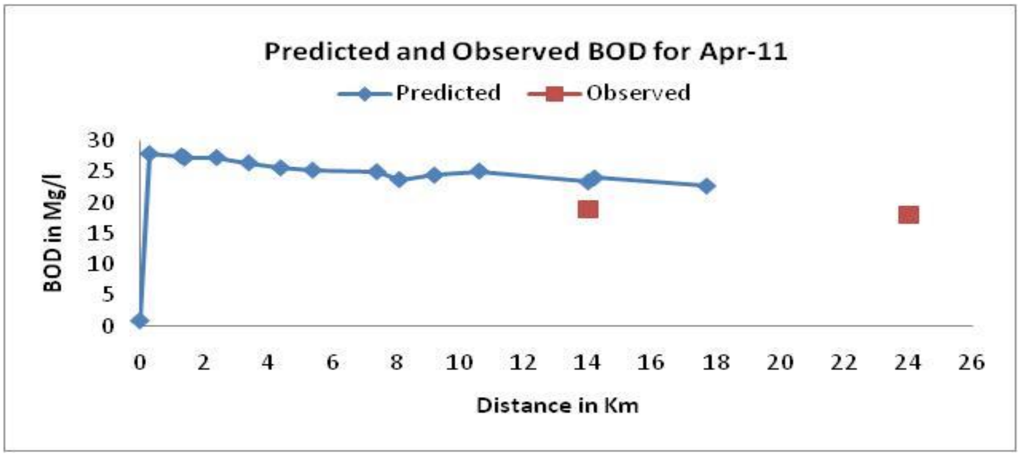


Figure 6.7 Predicted and Observed BOD profile of the river between Wazirabad and Okhla for the month of Apr-11

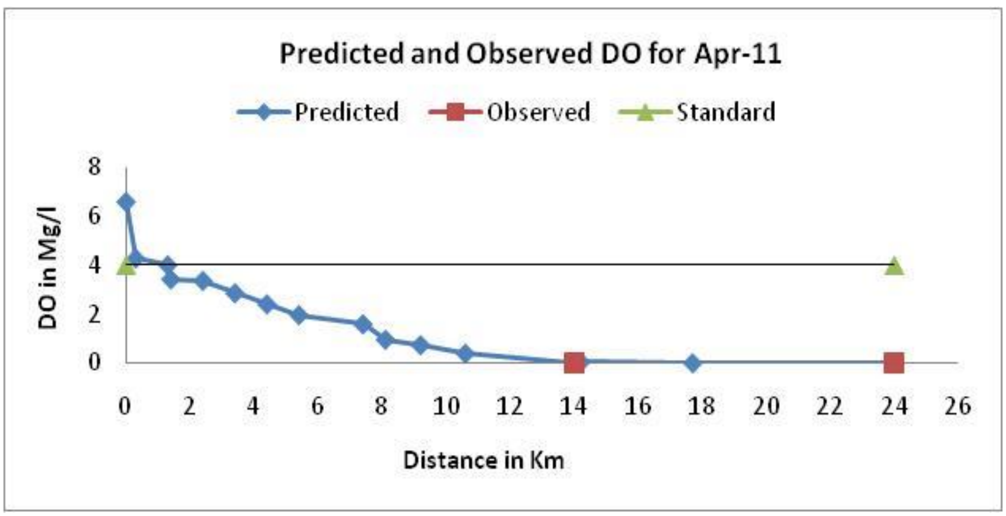


Figure 6.8 Predicted and Observed DO profile of the river between Wazirabad and Okhla for the month of Apr-11

Beginning of April shows a good sign for river as the temperature in the atmosphere increases which brings about melting of ice caps of Himalayas, which inturn regulates the high flow in the river. This high flow inaddition to being sufficient to meeting out high demands of cities also maintain a good discharge d/s the Wazirabad barrage. Besides as seen from the table,

1. BOD load in the season decreases to much lower level as compared to previous month.
2. One of the most important point observed here is that upto Civil mill drain BOD trend is decreasing but it get increased at Drain no. 14 and Power house node then again starts

falling. One of the reason for this difference may be the low water discharge from the Tonga stand drain as well as the Civil mill drain (Table 4.6).

3. Atleast few of the reaches began to touch the level of standard DO. This indicate improvement in the self purification capacity of the river.

6.2.5 Variation of DO and BOD in the month of May-2011

In May temperature of the atmosphere is at peak. Here the situation again get worse . For the month of May the flow rate of the river is taken as 11.6 m^3/s (Table 4.7), which is minimum, to meet out the Environmental concern of all the reaches. The following Table shows the varying profile of DO and BOD for the month of May-11.

Table 6.5 Predicted concentration of DO and BOD just d/s of node points for each drains for May-2011

Months	Drains	BOD (mg/l)	DO (mg/l)	X (km)
May-11	**Najafgarh drain**	42.616	2.3327	0.3
	Magzine road drain	43.093	1.2586	1
	Sweeper colony drain	42.984	1.1566	0.1
	Khyber pass drain	41.586	0.2204	1
	Metcalfhouse drain	40.224	0	1
	ISBT + mori gate	40.734	0	1
	Tonga stand	39.805	0	1
	Civil mill	37.562	0	2
	Drain no. 14	37.305	0	0.7
	Power house drain	37.441	0	1.1
	Sen nursinghome drain	35.781	0	1.4
	Barapulla drain	31.999	0	3.6
	Maharani bagh drain	29.324	0	3.5

The predicted result has been compared with the observed values for the above month as shown in the following Figures.

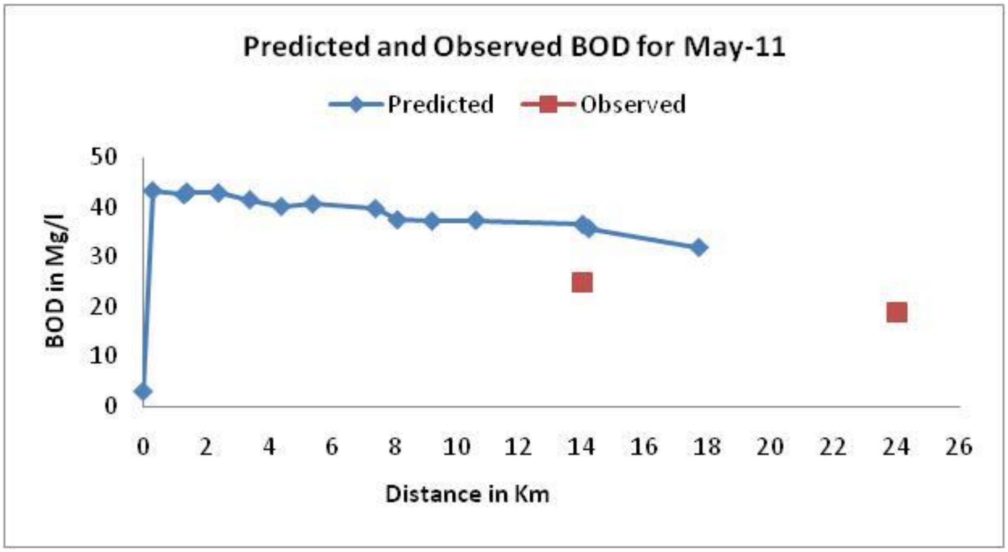


Figure 6.9 Predicted and Observed BOD profile of the river between Wazirabad and Okhla for the month of May-11

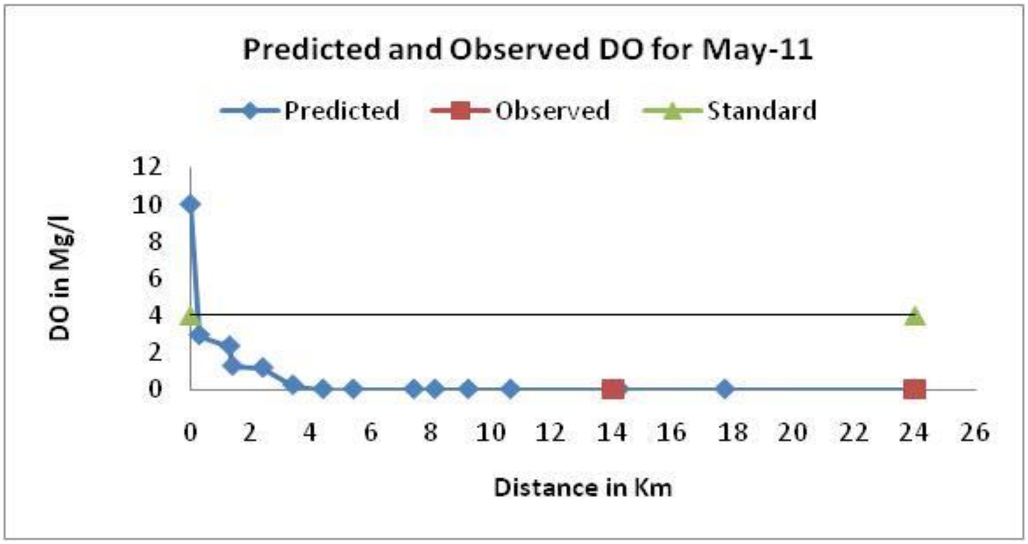


Figure 6.10 Predicted and Observed DO profile of the river between Wazirabad and Okhla for the month of May-11

May being the hottest season again faces the scarcity of water which brings back the demise of the quality of river. Following are the points of observation:

1. Most of the water from the melted ice caps and snow mountains has been exhausted along its path upon reaching the plains to meet out the greater demand of population as well as to the irrigation need. Also the temperature being the highest, accelerate the process of evaporation from the surface of river leaving the high load bringing its dilution capacity to legible range.
2. Thus as seen the BOD level again soars following the old trend and DO level shoots down to again zero.

6.2.6 Variation of DO and BOD in the month of June-2011

In June temperature of the atmosphere began to slow down. Here the situation starts getting better as to marks the end of summer season. For the month of June the flow rate of the river is taken as 15.99 m^3/s (Table 4.7) to meet out the Environmental concern of all the reaches. The following Table shows the varying profile of DO and BOD for the month of June-11.

Table 6.6 Predicted concentration of DO and BOD just d/s of node points for each drains for Jun-2011

Months	Drains	BOD (mg/l)	DO (mg/l)	X (km)
Jun-11	**Najafgarh drain**	19.385	4.0484	0.3
	Magzine road drain	19.328	3.6888	1
	Sweeper colony drain	19.269	3.6506	0.1
	Khyber pass drain	18.634	3.3476	1
	Metcalfhouse drain	18.034	3.08	1
	ISBT + mori gate	18.231	2.7838	1
	Tonga stand	18.343	2.5417	1
	Civil mill	17.661	2.1337	2
	Drain no. 14	20.351	1.8888	0.7
	Power house drain	19.887	1.6011	1.1
	Sen nursinghome drain	19.04	1.3521	1.4
	Barapulla drain	17.765	0.8378	3.6
	Maharani bagh drain	16.478	0.61	3.5

The predicted result has been compared with the observed values for the above month as shown in the following Figures.

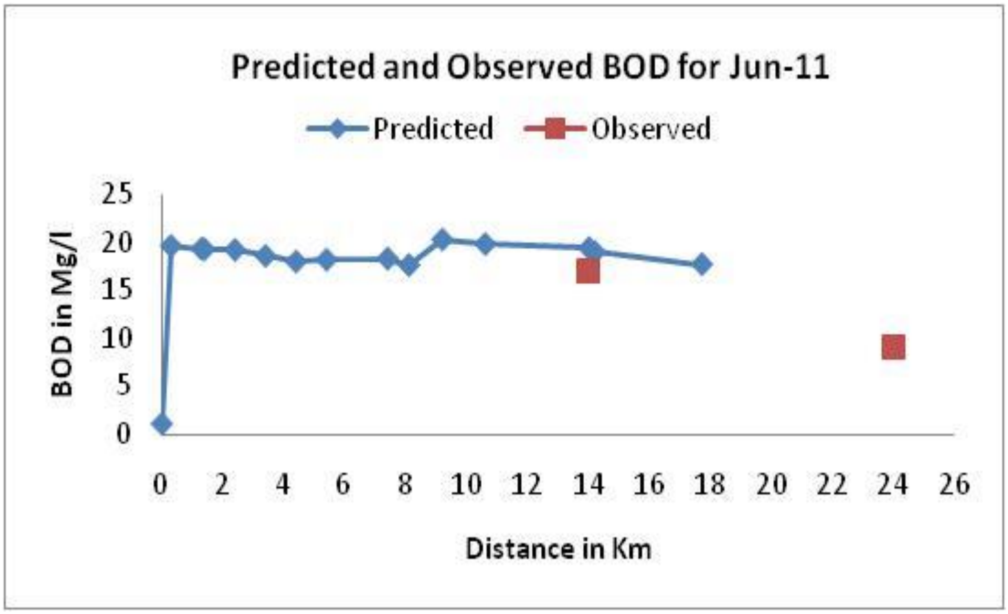


Figure 6.11 Predicted and Observed BOD profile of the river between Wazirabad and Okhla for the month of Jun-11

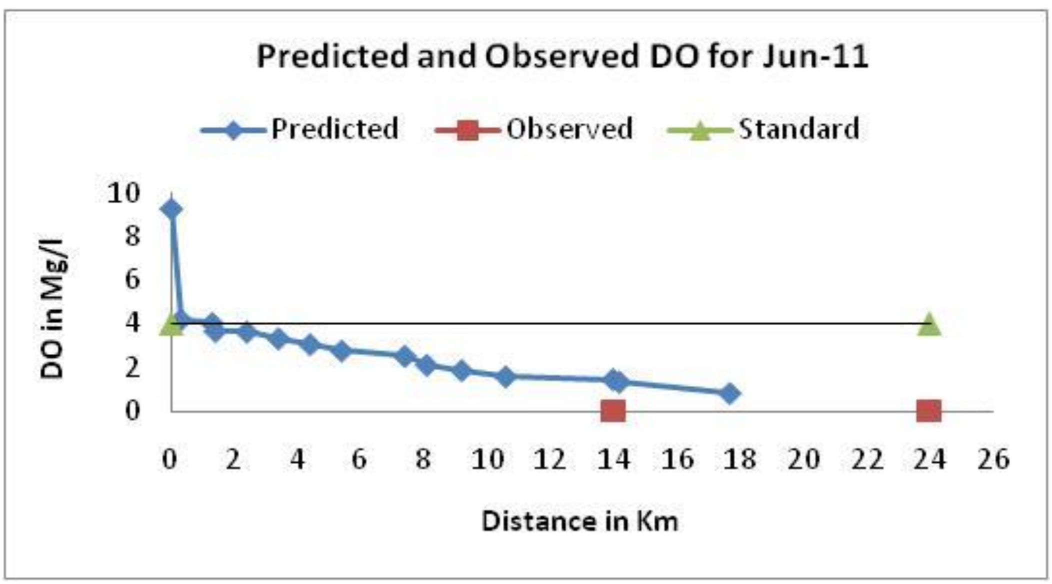


Figure 6.12 Predicted and Observed DO profile of the river between Wazirabad and Okhla for the month of Jun-11

After that comes the monsoon which proves to be boon in restoring the quality of river. From June:

1. The DO of the river starts increasing as the fresh water from rain brings with it the enough DO for the survival of aquatic ecosystem. Also the open drains carries with it storm water due to which discharge from the drains also increases and pollutant load get diluted which contributes lower BOD upon its discharge in the river.
2. Here we can see that as opposed to the general trend of decrease in BOD as we move down the stretch some of the reach shows increasing values. Drain no. 14 reach shows increase in BOD value then again it starts decreasing as observed in the month of April.

6.2.7 Variation of DO and BOD in the month of July-2011

Monsoon period marks its beginning from July and ends till October. The over heated environment get stable with the onset of monsoon. Here the situation changes drastically from worst to nearly best. For the month of July the flow rate of the river is taken as 83.3 m^3/s (Table 4.7) to meet out the Environmental concern of all the reaches. The following Table shows the varying profile of DO and BOD for the month of July-11.

Table 6.7 Predicted concentration of DO and BOD just d/s of node points for each drains for Jul-2011

Months	Drains	BOD (mg/l)	DO (mg/l)	X (km)
Jul-11	**Najafgarh drain**	7.8905	7.5076	0.3
	Magzine road drain	7.8941	7.3503	1
	Sweeper colony drain	7.9026	7.3303	0.1
	Khyber pass drain	7.7517	7.1847	1
	Metcalfhouse drain	7.6073	7.0481	1
	ISBT + mori gate	7.6139	6.8918	1
	Tonga stand	7.5499	6.7666	1
	Civil mill	7.2649	6.5468	2
	Drain no. 14	8.6068	6.3374	0.7
	Power house drain	8.6724	6.1763	1.1
	Sen nursinghome drain	8.4543	6.0119	1.4
	Barapulla drain	8.4191	5.5766	3.6
	Maharani bagh drain	8.0644	5.282	3.5

The predicted result has been compared with the observed values for the above month as shown in the following Figures.

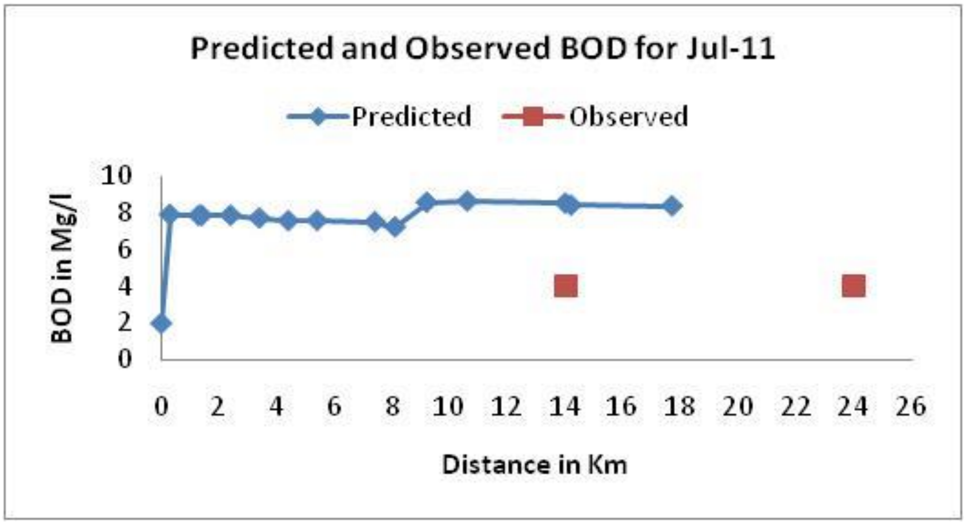


Figure 6.13 Predicted and Observed BOD profile of the river between Wazirabad and Okhla for the month of Jul-11

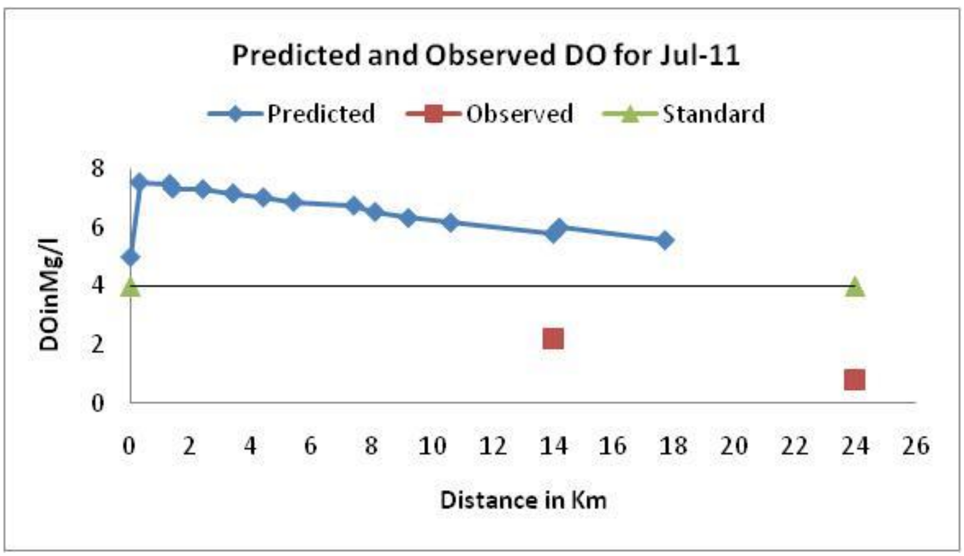


Figure 6.14 Predicted and Observed DO profile of the river between Wazirabad and Okhla for the month of Jul-11

1. Usually in Delhi, monsoon starts in the last week of June or in the beginning of July. The BOD level decreases much below the targets sets by the other months. As seen from the Table 4.6 the BOD contributed by the Najafgarh drain is minimum for this month and after its conflicting with the river due to high water discharge and high DO the BOD

further decreases. Same goes with the other drains also as their condition depends upon this very first drain. Here also after following decreasing pattern Drain no.14 and Power house reach shows increasing values then again it starts decreasing. The point of concern here is that the BOD concentration of Drain no. 14 node onwards is more than even that of Najafgarh node this can be explained by Table 4.6 as one can observe no flow condition observes in civil mill drain, thus according to our assumption the flow of the previous reach is carry forward as it is without increment.

2. As seen here that DO increases at a greater pace. All the reaches have DO well above the standard level.
3. From this month the quality of the river improved much beyond the expected level which remain continued for the entire monsoon period.

6.2.8 Variation of DO and BOD in the month of August-2011

Heavy rain unleashes the limited water discharge boundation during the month of August . Here the situation turns out to be the best in terms of dilution capacity as well as self purification capacity of the river. For the month of August the flow rate of the river is taken as 189.0 m^3/s (Table 4.7) by far the highest ever for any month, to meet out the Environmental concern of all the reaches. The following Table shows the varying profile of DO and BOD for the month of Aug-11.

Table 6.8 Predicted concentration of DO and BOD just d/s of node points for each drains for Aug-2011

Months	Drains	BOD (mg/l)	DO (mg/l)	X (km)
Aug-11	**Najafgarh drain**	7.4422	8.5378	0.3
	Magzine road drain	7.4551	8.402	1
	Sweeper colony drain	7.4513	8.3864	0.1
	Khyber pass drain	7.3491	8.2593	1
	Metcalfhouse drain	7.2489	8.1358	1
	ISBT + mori gate	7.2165	7.9951	1
	Tonga stand	7.1702	7.879	1
	Civil mill	6.9774	7.6663	2
	Drain no. 14	7.9863	7.504	0.7
	Power house drain	8.0585	7.3499	1.1
	Sen nursinghome drain	7.9077	7.2019	1.4
	Barapulla drain	7.7973	6.8144	3.6
	Maharani bagh drain	7.6216	6.5056	3.5

The predicted result has been compared with the observed values for the above month as shown in the following Figures.

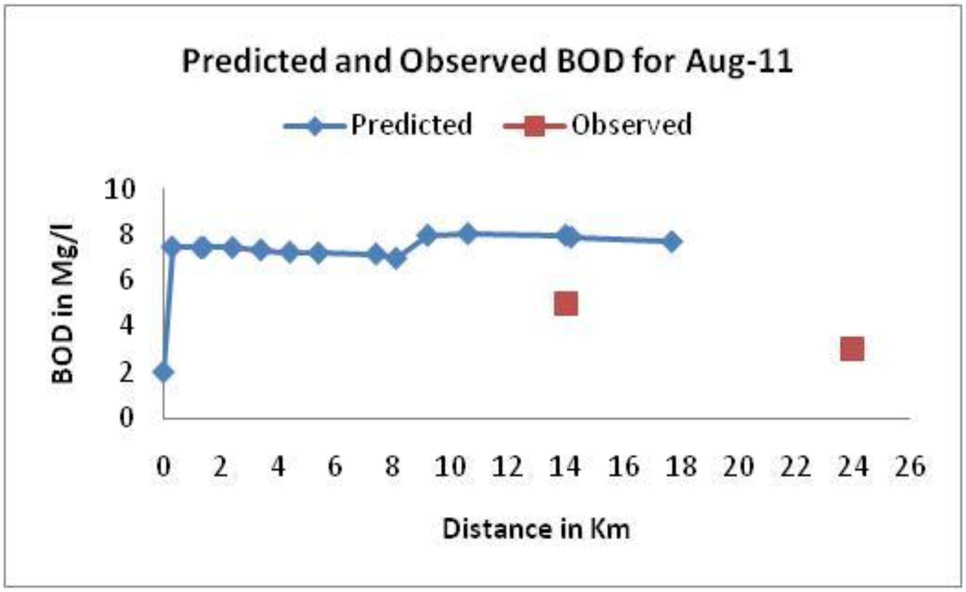


Figure 6.15 Predicted and Observed BOD profile of the river between Wazirabad and Okhla for the month of Aug-11

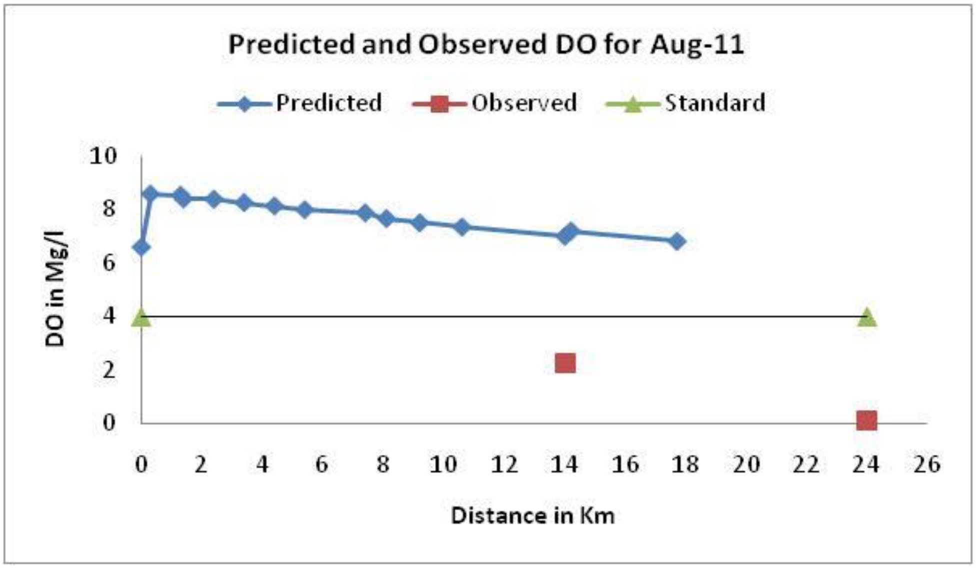


Figure 6.16 Predicted and Observed DO profile of the river between Wazirabad and Okhla for the month of Aug-11

This is the best period in the whole monthly cycle of the variation of river quality. Important points which marks the difference here are as follows:

1. The BOD level reaches to its minimum the value being close to standard level as set by CPCB.
2. The self purification capacity of the river greatly improved bringing back the zone of self purification in proper sequence.
3. The DO level of the river shoots up and shows its all time high value.
4. Its shows the best time of the year for the flourishment of aquatic life.

6.2.9 Variation of DO and BOD in the month of September-2011

The month of September too maintain river quality fairly well. The monsoon began to retrace its path. For the month of September the flow rate of the river is taken as 162.0 m^3/s (Table 4.7) to meet out the Environmental concern of all the reaches. The following Table shows the varying profile of DO and BOD for the month of Sept-11.

Table 6.9 Predicted concentration of DO and BOD just d/s of node points for each drains for Sept-2011

Months	Drains	BOD (mg/l)	DO (mg/l)	X (km)
Sep-11	**Najafgarh drain**	6.9214	8.3351	0.3
	Magzine road drain	6.9261	8.2145	1
	Sweeper colony drain	6.9343	8.1994	0.1
	Khyber pass drain	6.8325	8.089	1
	Metcalfhouse drain	6.7344	7.98	1
	ISBT + mori gate	6.6935	7.8577	1
	Tonga stand	6.62	7.7599	1
	Civil mill	6.4314	7.5769	2
	Drain no. 14	7.0181	7.3464	0.7
	Power house drain	7.0415	7.2178	1.1
	Sen nursinghome drain	6.896	7.0991	1.4
	Barapulla drain	7.453	6.6485	3.6
	Maharani bagh drain	7.2141	6.4008	3.5

The predicted result has been compared with the observed values for the above month as shown in the following Figures.

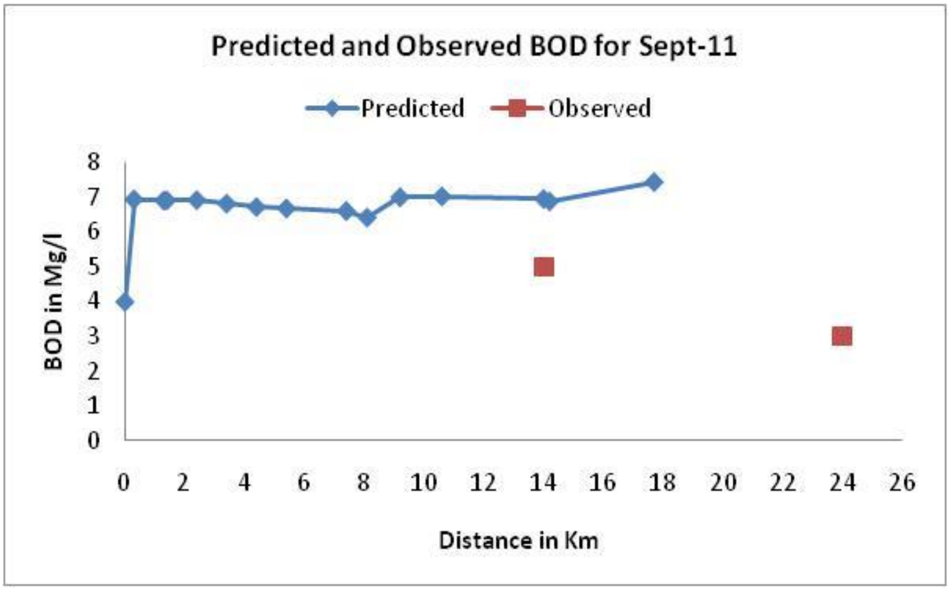


Figure 6.17 Predicted and Observed BOD profile of the river between Wazirabad and Okhla for the month of Sept-11

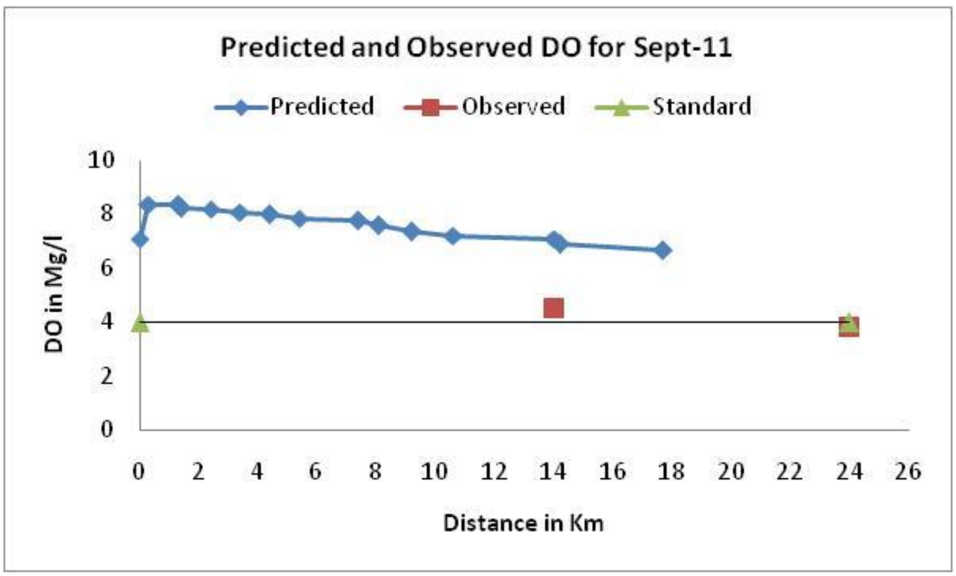


Figure 6.18 Predicted and Observed DO profile of the river between Wazirabad and Okhla for the month of Sept-11

The months September too enjoy the healthy and favorable condition to aquatic ecosystem. Again the stretch faces the vigorous condition with DO touching the saturation value and BOD close to standard value both satisfying the more than normal condition which provides an excellent quality to the water of Yamuna river.

6.2.10 Variation of DO and BOD in the month of October-2011

October is the last month of monsoon period. In this month little or no rain has been observed. For the month of October the flow rate of the river decrease to much lower level as compared to monsoon months, is taken as 36.4.0 m^3/s (Table 4.7), to meet out the Environmental concern of all the reaches. The following Table shows the varying profile of DO and BOD for the month of Sept-11.

Table 6.9 Predicted concentration of DO and BOD just d/s of node points for each drains for Oct-2011

Months	Drains	BOD (mg/l)	DO (mg/l)	X (km)
Oct-11	**Najafgarh drain**	14.561	5.682	0.3
	Magzine road drain	14.43	5.4249	1
	Sweeper colony drain	14.446	5.3965	0.1
	Khyber pass drain	14.077	5.1654	1
	Metcalfhouse drain	13.718	4.9534	1
	ISBT + mori gate	13.663	4.7286	1
	Tonga stand	13.362	4.5504	1
	Civil mill	12.706	4.2451	2
	Drain no. 14	16.02	3.8203	0.7
	Power house drain	15.851	3.5645	1.1
	Sen nursinghome drain	15.302	3.3329	1.4
	Barapulla drain	15.23	2.7433	3.6
	Maharani bagh drain	14.593	2.3537	3.5

The predicted result has been compared with the observed values for the above month as shown in the following Figures.

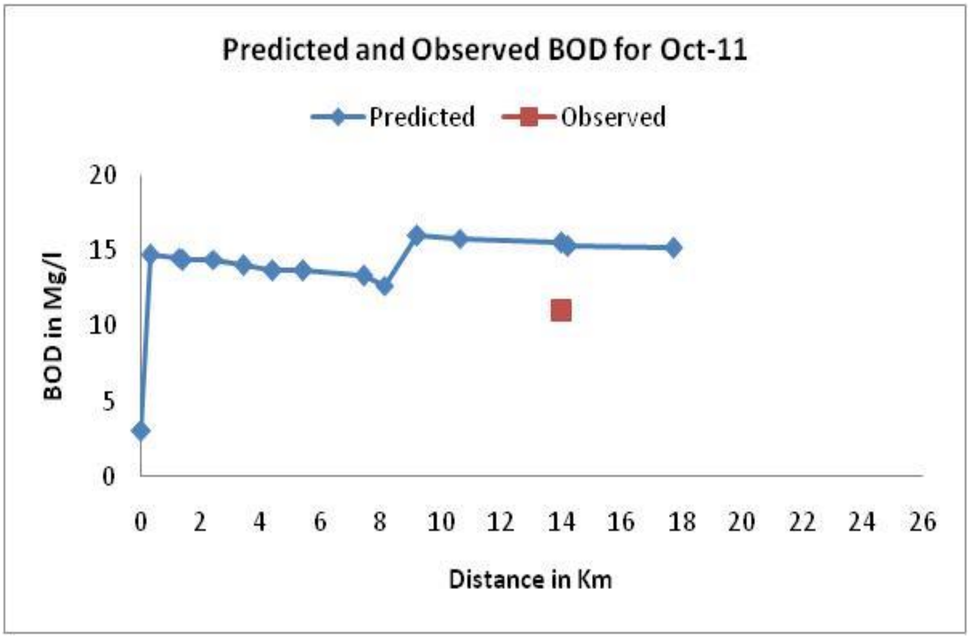


Figure 6.19 Predicted and Observed BOD profile of the river between Wazirabad and Okhla for the month of Oct-11

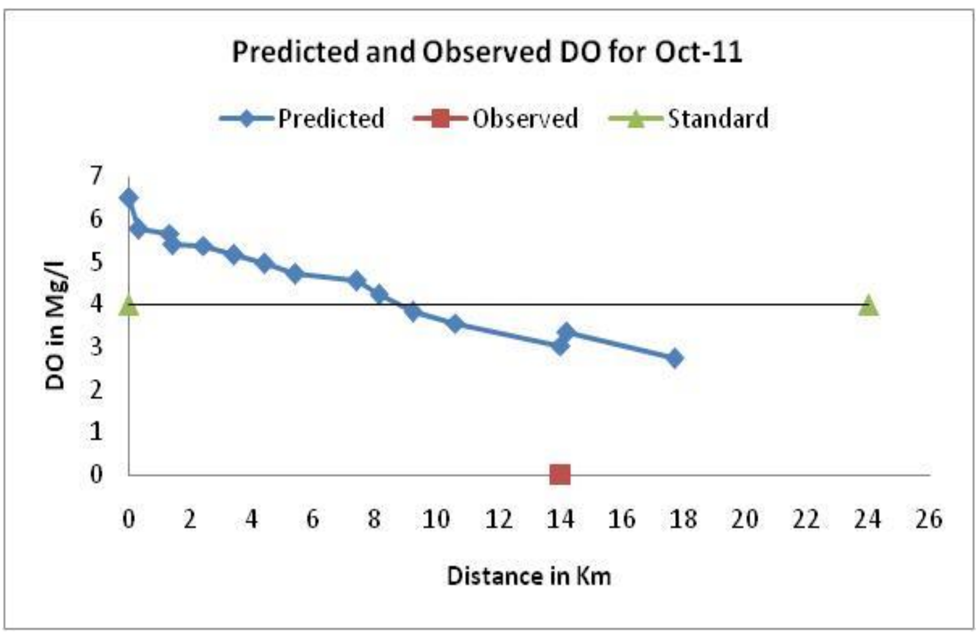


Figure 6.20 Predicted and Observed DO profile of the river between Wazirabad and Okhla for the month of Oct-11

October again is the transitioning month from monsoon to winter. The following points makes existence here are:

1. DO starts decreasing and the BOD starts increasing but still the river's condition is satisfying. From Najafgarh to Civil mill reach the trend remain intact then there is sharp increase in the Drain no. 14 reach again there is decrease till the Maharani bagh reach. While the DO follow continuously decreasing pattern.
2. Once again the DO level for lower reaches decreases to below standard level which indicates the problematic phase of the river soon going to be start.

6.2.11 Variation of DO and BOD in the month of November-2011

November marks the beginning of winter period. The temperature began to fall, the ice caps and the Himalayas get covered with the snow. For the month of November the flow rate of the river, is taken as 22.4 m^3/s (Table 4.7), to meet out the Environmental concern of all the reaches. The following Table shows the varying profile of DO and BOD for the month of Nov-11

Table 6.11 Predicted concentration of DO and BOD just d/s of node points for each drains for Nov-2011

Months	Drains	BOD (mg/l)	DO (mg/l)	X (km)
Nov-11	**Najafgarh drain**	22.043	4.5254	0.3
	Magzine road drain	21.696	4.1461	1
	Sweeper colony drain	21.632	4.1079	0.1
	Khyber pass drain	21	3.7803	1
	Metcalfhouse drain	20.396	3.4857	1
	ISBT + mori gate	20.146	3.1962	1
	Tonga stand	19.689	2.9582	1
	Civil mill	18.863	2.5428	2
	Drain no. 14	22.281	2.1753	0.7
	Power house drain	22.242	1.8846	1.1
	Sen nursinghome drain	21.362	1.5989	1.4
	Barapulla drain	19.7	1.0422	3.6
	Maharani bagh drain	18.452	0.7403	3.5

The predicted result has been compared with the observed values for the above month as shown in the following Figures.

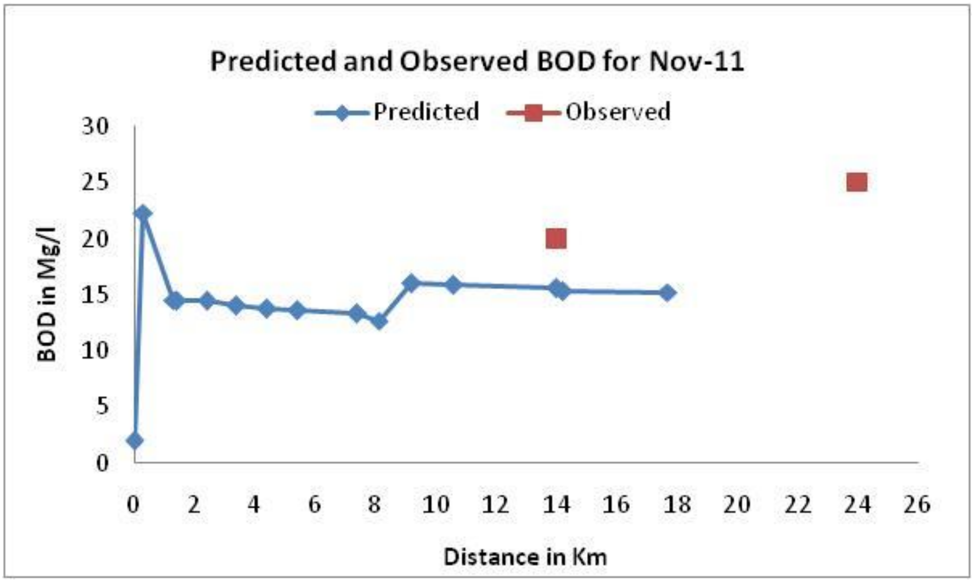


Figure 6.21 Predicted and Observed BOD profile of the river between Wazirabad and Okhla for the month of Nov-11

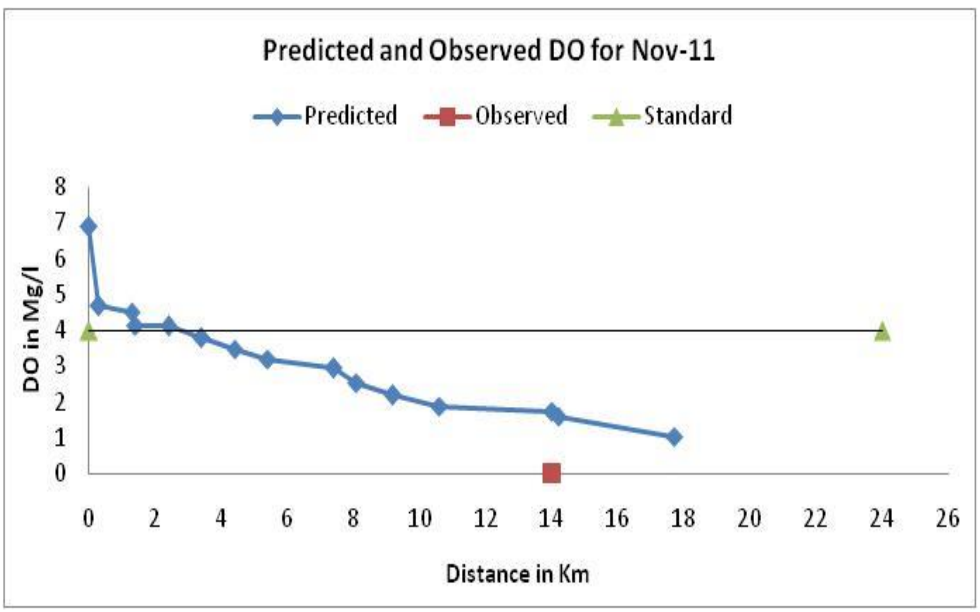


Figure 6.22 Predicted and Observed DO profile of the river between Wazirabad and Okhla for the month of Nov-11

The important points which marks existence here are the same observed in the beginning of the monthly cycle but here still the condition remain poorly well as the DO level does not have shown nil value. We can say that it is the stating phase which is slowly pushing the river into its worst state in the subsequent months.

6.2.12 Variation of DO and BOD in the month of December-2011

December being the coldest month of the year further brings down the temperature to negative level in the Himalayas. The only discharge received d/s is through the canals and tributaries of Yamuna. For the month of December the flow rate of the river, is taken as 15.0 m^3/s (Table 4.7), to meet out the Environmental concern of all the reaches. The following Table shows the varying profile of DO and BOD for the month of Dec-11

Table 6.12 Predicted concentration of DO and BOD just d/s of node points for each drains for Dec-2011

Months	Drains	BOD (mg/l)	DO (mg/l)	X (km)
Dec-11	**Najafgarh drain**	47.98	3.0681	0.3
	Magzine road drain	47.356	2.0041	1
	Sweeper colony drain	47.209	1.9024	0.1
	Khyber pass drain	45.743	0.9722	1
	Metcalfhouse drain	44.297	0.1423	1
	ISBT + mori gate	42.922	0	1
	Tonga stand	41.723	0	1
	Civil mill	39.916	0	2
	Drain no. 14	41.445	0	0.7
	Power house drain	42.423	0	1.1
	Sen nursinghome drain	40.684	0	1.4
	Barapulla drain	37.309	0	3.6
	Maharani bagh drain	33.776	0	3.5

The predicted result has been compared with the observed values for the above month as shown in the following Figures.

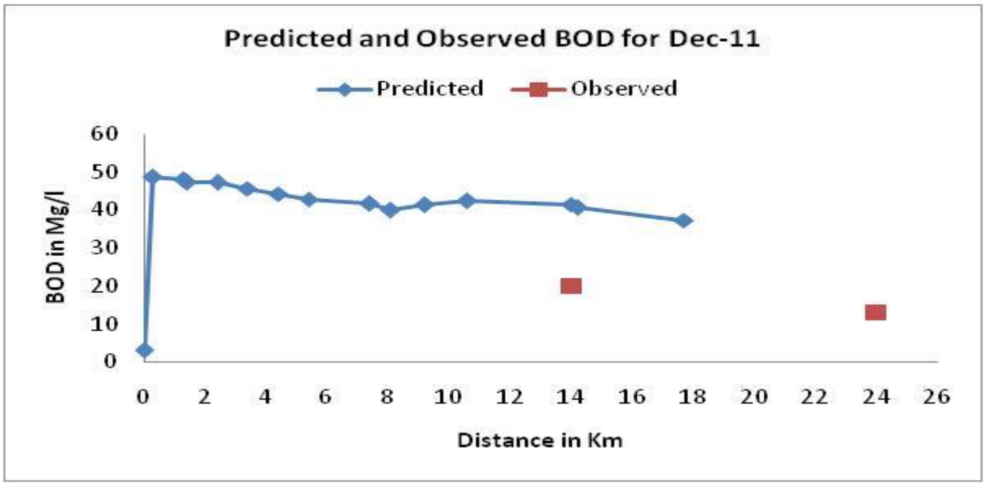


Figure 6.23 Predicted and Observed BOD profile of the river between Wazirabad and Okhla for the month of Dec-11

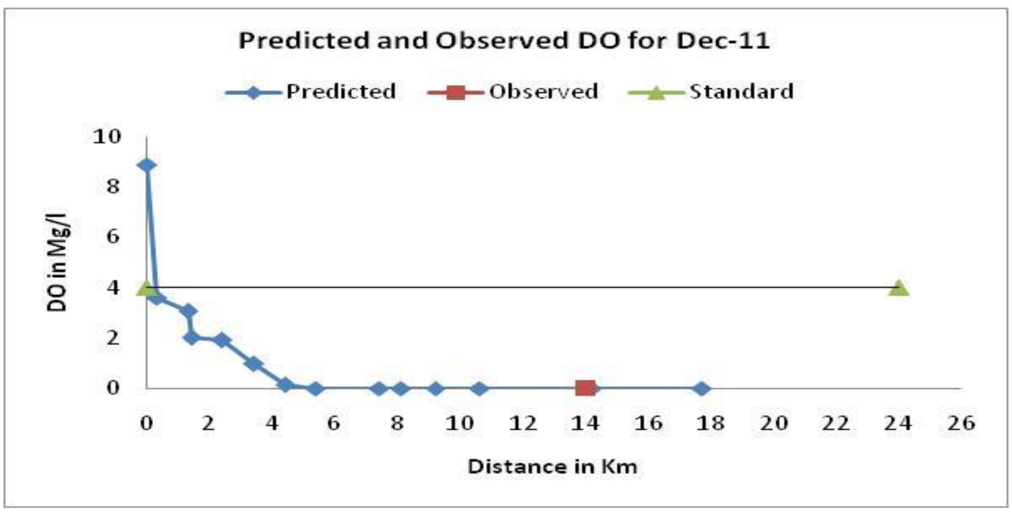


Figure 6.24 Predicted and Observed DO profile of the river between Wazirabad and Okhla for the month of Dec-11

As seen from the above Table and Figures, again the condition of river starts detoriating. In Dec DO concentration for most of the reach become nil showing incapability of the river to self purificate due to heavy pollutant load. Again the cycle is ready to replicate for the next year. The reason for this is the unproportioned balance between discharge of waste and flow of fresh water. Once again the river began to show decreasing dilution capacity.

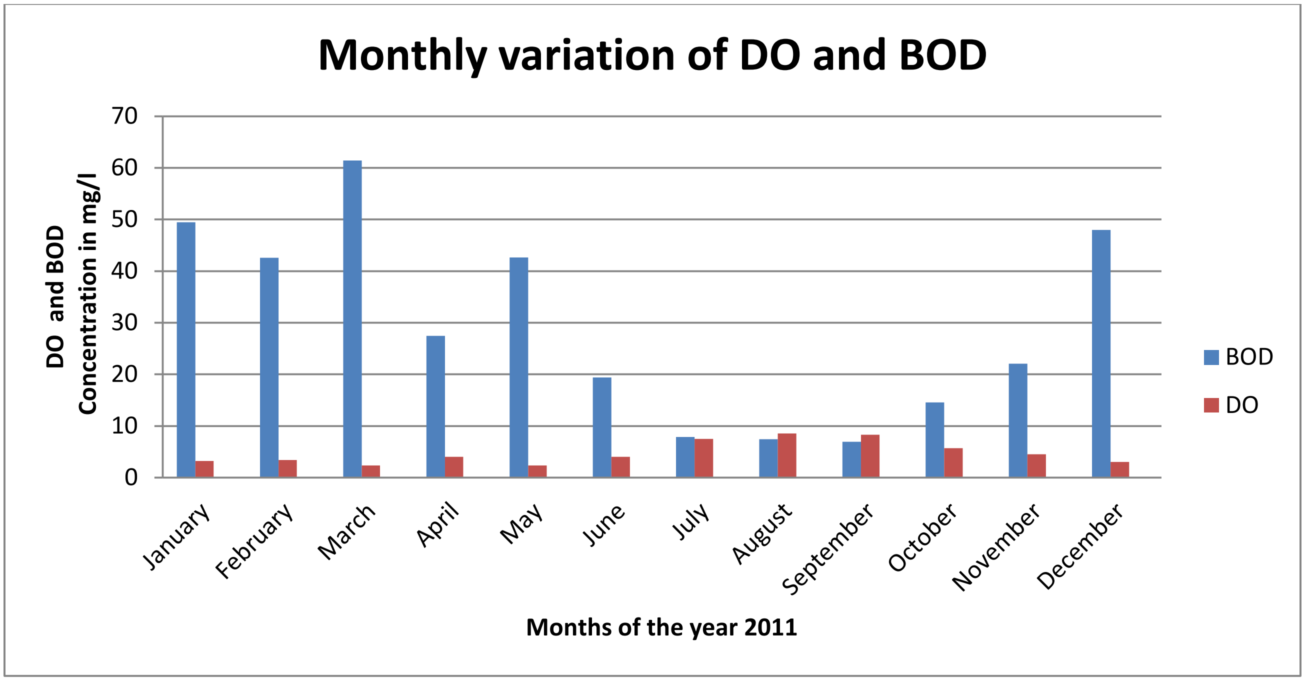


Figure 6.25 Bar graph showing comparison of the monthly variation of DO and BOD at a distance 0.3 km from Wazirabad barrage

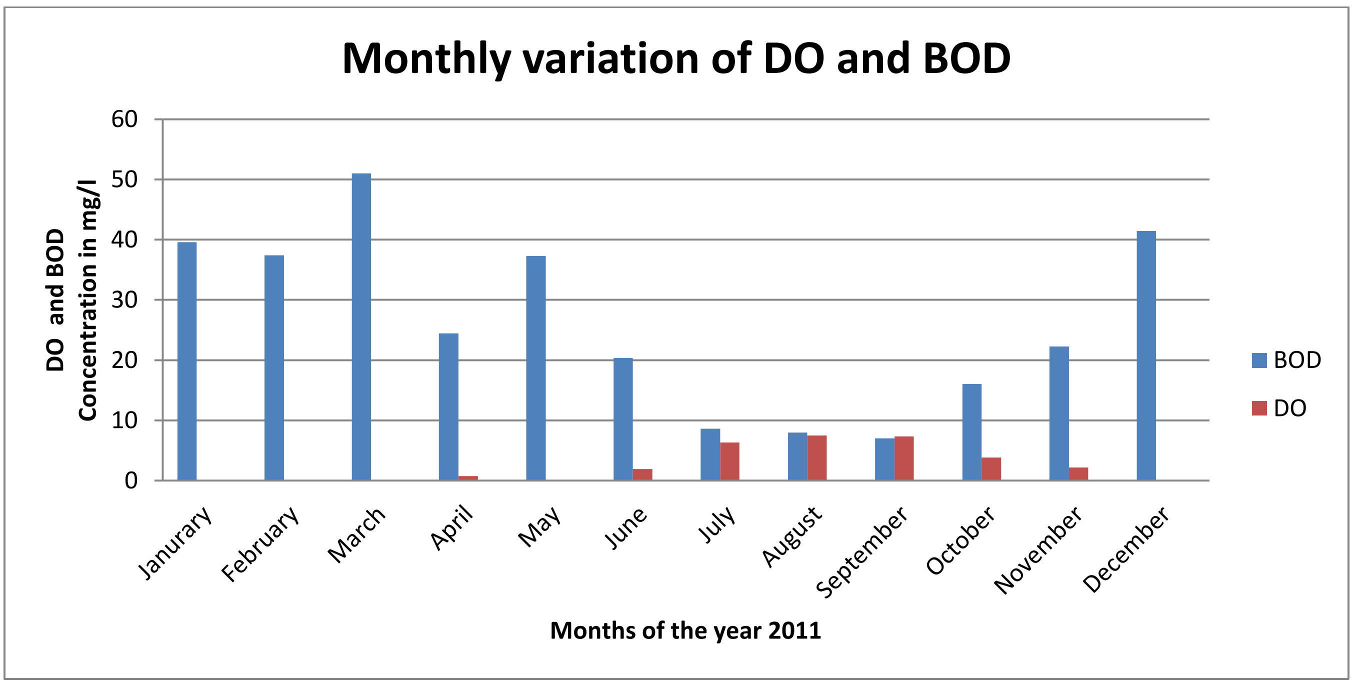


Figure 6.26 Bar graph showing comparison of the monthly variation of DO and BOD at a distance 8.1 km from Wazirabad barrage

The following are the summarization of the points as obtained from the analysis of predicted results:

1. The above results indicate that maximum BOD has been observed for Najafgarh drain the reason being explained earlier then afterwards the BOD starts decreasing. The comparison of monthly variation of DO and BOD at Najafgarh node has been shown in the Figure 6.25 whereas Figure 6.26 shows the comparison at Drain no. 14 node which shows an increasing BOD opposite to the trend as obtained at other nodes.

2. As seen from the Figure 6.25 and Figure 6.26, the monsoon period from July till September shows the extraordinary recovery of the river from high to low BOD and from nil to saturated DO. March represent the worst situation followed by the winter months.

3. Although the DO concentration at Najafgarh reach is good enough to support aquatic ecosystem especially in the months from July to Nov due to the sufficient discharge of water downstream as provided by monsoon (As predicted by Rai's model, 2011).

4. The DO in the months from Dec to Apr is nil for some reaches and in the month of May is nil for most of the reaches due to low water discharge provided by summer season.

5. As compared with the observed values obtained at sampling station the predicted value differed, the reason for this is that the observed values are noted for actual case where little discharge is allowed d/s of Wazirabad as most of the water is drawn out at Wazirabad water works. Also this model is developed taking in account pollution from point sources only besides certain assumption which are taken due to inadequacy of data further effect the results.

Thus by these prediction one can conclude that if sufficient discharge is allowed to be maintained along with the controlled discharge of pollutants then river gain its self purification capacity easily. Despite this fact it is very difficult to fetch Yamuna water towards the city to maintained the sufficient water supply throughout the year.

6.3 Yearly Variation of DO and BOD over 22 km stretch of Yamuna at Delhi

The yearly data for the year 2011 has been calculated by averaging the data obtained for all the months of the year 2011 as given in Table 4.8 and Table 4.9. As seen from these tables the maximum pollutant load is contributed by the Magzine road drain along with little flow and lowest being that of Khyber pass drain. The yearly variation has shown for the remaining two cases but applied differently. The output obtained in Table 6.13 and Table 6.14 are the two different scenario for the same case B. Table 6.13 gives the results for actual set of input data whereas Table 6.14 gives results for input data taken from Rai's model prediction by averaging the monthly data. The results obtained has been compared by plotting the two with distance for the 22 km stretch of Yamuna for the justification of the fact that if sufficient water is allowed d/s keeping in mind the Environmental flow requirement of the subsequent reaches then the condition of the river get improved along with the controlled discharge of untreated waste.

6.3.1 Yearly variation of DO and BOD in the actual scenario

As stated above the yearly variation has been predicted for the actual scenario as witnessed by the Yamuna river where little water is available for discharged d/s the Wazirabad barrage which become negligible in the dry period. The following Table shows the real picture where DO and BOD are being predicted just u/s and d/s of the nodes for the year 2011.

Table 6.13 Predicted concentration of DO and BOD for the actual case of low water discharge d/s of Wazirabad barrage for the year-2011

Drains	BOD (mg/l)		DO (mg/l)	
	U/s	D/s	U/s	D/s
Najafgarh drain	48.3892	53.4233	0.6287	0
Magzine road drain	51.5916	50.7174	0	0
Sweeper colony drain	50.5424	49.173	0	0
Khyber pass drain	47.5121	45.6343	0	0
Metcalfhouse drain	44.1087	45.7708	0	0
ISBT + mori gate	44.335	43.1715	0	0
Tonga stand	41.8292	40.8676	0	0
Civil mill	38.4272	41.2945	0	0
Drain no. 14	40.4663	38.6604	0	0
Power house drain	37.5353	35.9289	0	0
Sen nursinghome drain	34.6197	35.9385	0	0
Barapulla drain	33.0595	34.7162	0	0
Maharani bagh drain	32.0878		0	

The profile of the river for the scenario has been shown in the following figures

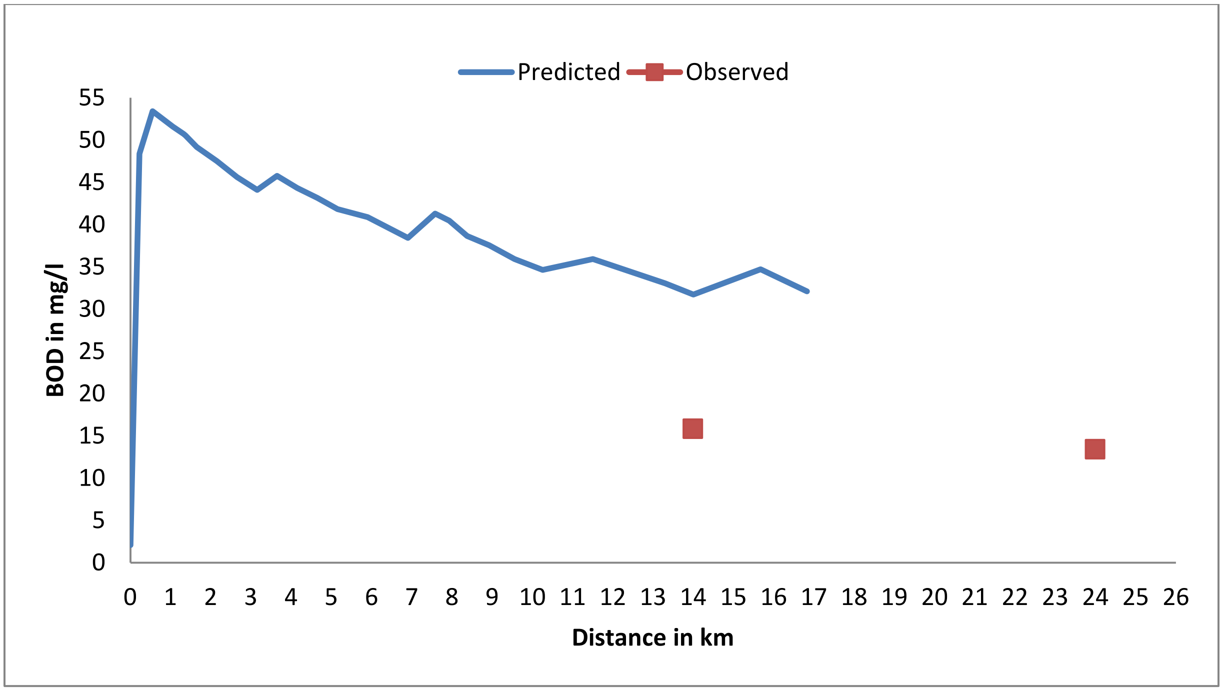


Figure 6.27 BOD profile of the river for the actual scenario

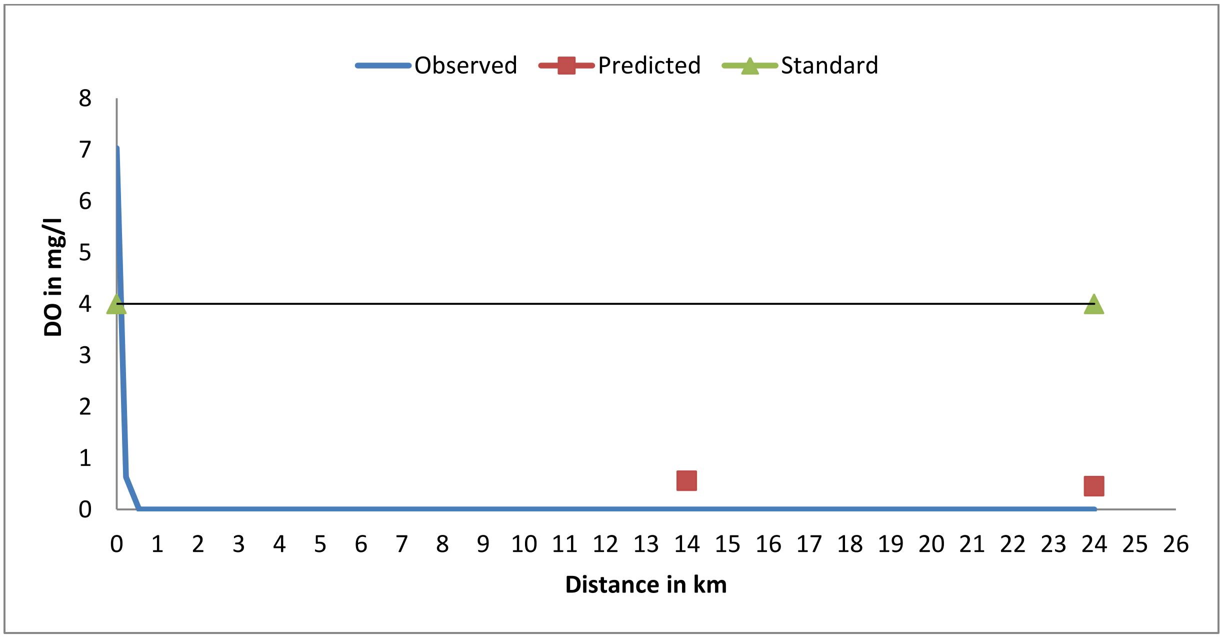


Figure 6.28 DO profile of the river for the actual scenario

The following points has been observed from the above Table and Figures:

1. The above table shows that BOD concentration just u/s of Najafgarh node is less than just d/s this is because of the high load contributed by Najafgarh drain.
2. The same situation is observed at Metcalfhouse, Civil mill, Sen nursing home and Barapulla node though by little amount only concentration d/s is more.
3. Although the major BOD load has been contributed by Magzine road drain the BOD after discharge get lower than u/s the node, the reason being the same of increasing quantity of water added to its floe by previous reach.
4. By considering this actual case it has been predicted that the condition of the stretch is pathetic as there is no DO at all, left in the river. This is detrimental to aquatic ecosystem as well as to human ecosystem. One of the solution to this situation is given in the next section.

6.3.2 Yearly variation of DO and BOD in the hypothetical scenario

This hypothetical scenario is formed by again using the Rai model prediction. The following Table shows the hypothetical picture for providing the better solution in improving the quality of Yamuna, where DO and BOD are being predicted just u/s and d/s of the nodes for the year 2011.

Table 6.14 Predicted concentration of DO and BOD for the hypothetical case in which sufficient water discharge is allowed d/s of Wazirabad barrage for the year-2011

Drains	BOD (mg/l)		DO (mg/l)	
	U/s	D/s	U/s	D/s
Najafgarh drain	32.9376	33.3271	5.3116	3.4639
Magzine road drain	33.0596	32.945	3.674	4.8288
Sweeper colony drain	32.9185	32.7521	4.8084	4.6932
Khyber pass drain	32.4895	32.2261	4.4955	4.2965
Metcalfhouse drain	31.9679	32.1447	4.1094	3.8874
ISBT + mori gate	31.8887	31.6734	3.7085	3.5292
Tonga stand	31.4213	31.1878	3.3599	3.1003
Civil mill	30.6946	30.9646	2.7881	2.5577
Drain no. 14	30.7934	30.6005	2.4544	2.2906
Power house drain	30.3373	30.011	2.1381	1.9657
Sen nursinghome drain	29.6834	29.8542	1.7862	1.4281
Barapulla drain	29.0383	28.9971	1.0223	0.6493
Maharani bagh drain	28.2299		0.3187	

The profile of the river for the scenario has been shown in the following figures

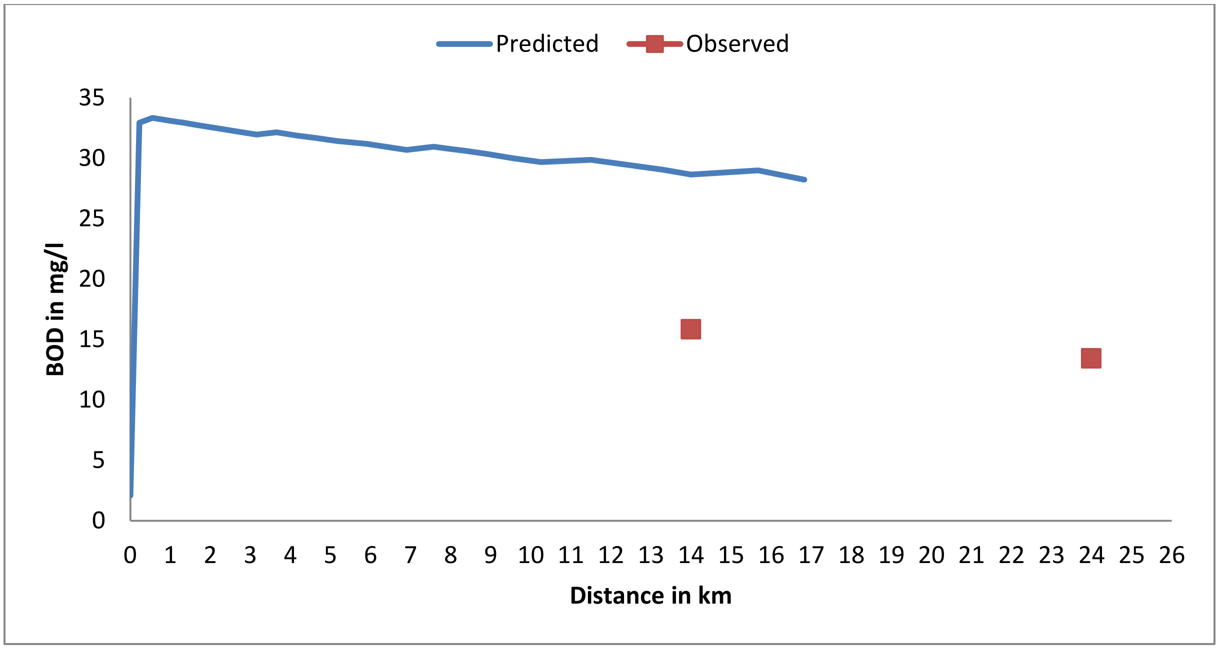


Figure 6.29 BOD profile of the river for the hypothetical scenario

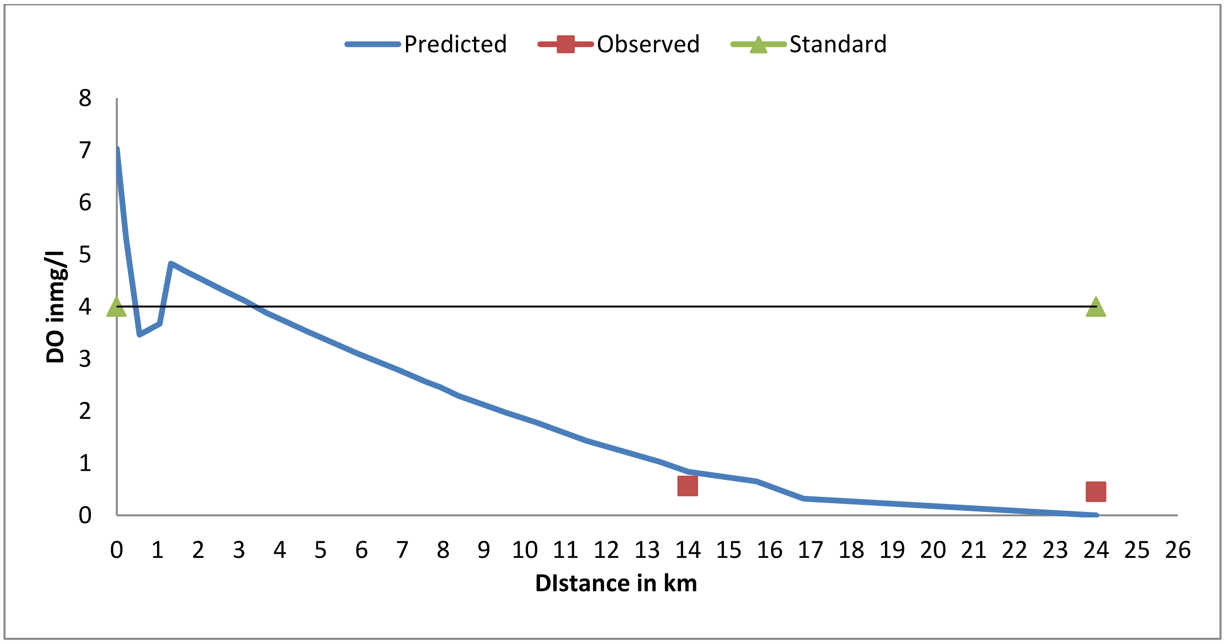


Figure 6.30 DO profile of the river for the hypothetical scenario

The following points are of importance from the above Table and Figures:

1. Maintaining water flow throughout the stretch is the primary need of the stretch. The upper half reaches maintains standard DO level but still lower half requires other measures to be taken into account. BOD concentration also decreases from the actual case but still it require more decrement for maintaining healthy environment.
2. If we consider the previous case where monthly variation is taken the condition of river stands good in the monsoon season where DO level touches the saturation mark. From here we can see that average BOD for most of the stretches remain above standard level, in addition to it if untreated waste could have become restricted to be discharged into the river then the results will reach upto the saturation level.

Summarizing the important points of observation:

1. As Observed from the above figures, 6.26, 6.28, 6.29, 6.30, the actual case is the worst scenario which is prevailing in the river according to current situation.

2. The DO concentration of whole of the stretch is nil which is depicting the extremely poor self purifying capacity of the river, which is also matching the observed value.

3. The BOD load although decreases as its distance from the source increases but not in a significant way.

4. Some other factors which might not be taken into account for this modeling study are seems to be responsible along with the pollutant load consider here for the detoriating condition of the river in this stretch.

5. In comparing with the hypothetical case where just sufficient water is allowed to flow through to meet out the environmental flow requirement of each reach, the segment of the river is regaining its quality. Thus it seems quite necessary that the pollutant load and the background discharge of the river should be in proper proportion for maintaining the healthy quality of river.

6. The deviation from the observed value is due to the assumption consider for the development of the Model, the non-point pollutant source has not been considered here, besides due to lack of data regarding the parameters the calibration has not done for the model.

6.4 Yearly Variation of DO and BOD at each reach

As explained earlier the terminology regarding the model, a reach is the path between two node along the river whereas a node is the point of confluence of drain with the river. In this case the yearly data has been taken from the actual data for the year 2011. Table 6.15 and 6.16 below shows the obtained results for BOD and DO respectively.

6.4.1 Yearly variation of BOD at each reach

BOD as represented by 'L' is calculated at five points of equal intervals designated as L_0 to L_4. L_0 is the point just d/s of starting node of a reach and L_4 is point just u/s of the ending node of the same reach. The variation of BOD as recoded from the results obtained from the model are as follows:

Table 6.15 Predicted BOD concentration of reaches calculated at five points for each reach

Drains	L_0	L_1	L_2	L_3	L_4
Najafgarh drain	49.1707	48.9088	48.6483	48.3892	48.1315
Magzine road drain	54.3634	53.4233	52.4995	51.5916	50.6994
Sweeper colony drain	50.8052	50.7174	50.6298	50.5424	50.4551
Khyber pass drain	50.0251	49.173	48.3354	47.5121	46.7028
Metcalfhouse drain	46.4168	45.6343	44.865	44.1087	43.3651
ISBT + mori gate	46.506	45.7708	45.0472	44.335	43.6341
Tonga stand	43.8587	43.1715	42.495	41.8292	41.1737
Civil mill	42.1454	40.8676	39.6286	38.4272	37.2622
Drain no. 14	41.7149	41.2945	40.8783	40.4663	40.0584
Power house drain	39.2356	38.6604	38.0937	37.5353	36.9851
Sen nursinghome drain	36.602	35.9289	35.2682	34.6197	33.9831
Barapulla drain	37.4707	35.9385	34.4689	33.0595	31.7076
Maharani bagh drain	36.1101	34.7162	33.3762	32.0878	30.8492

The profile for each reach of BOD variation are shown in the following figures:

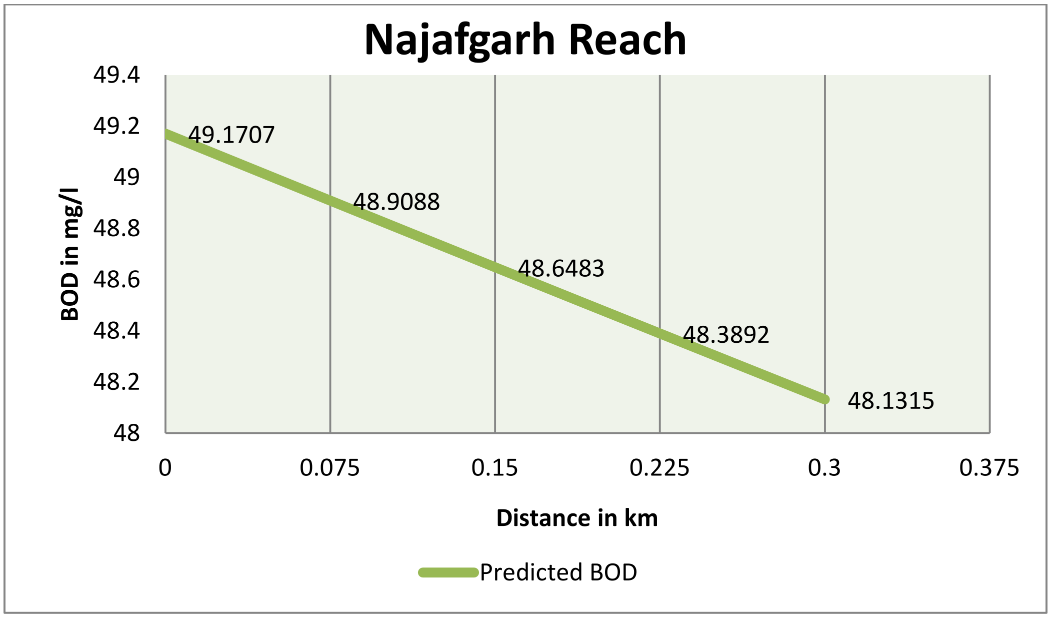


Figure 6.31 BOD profile of Najafgarh reach

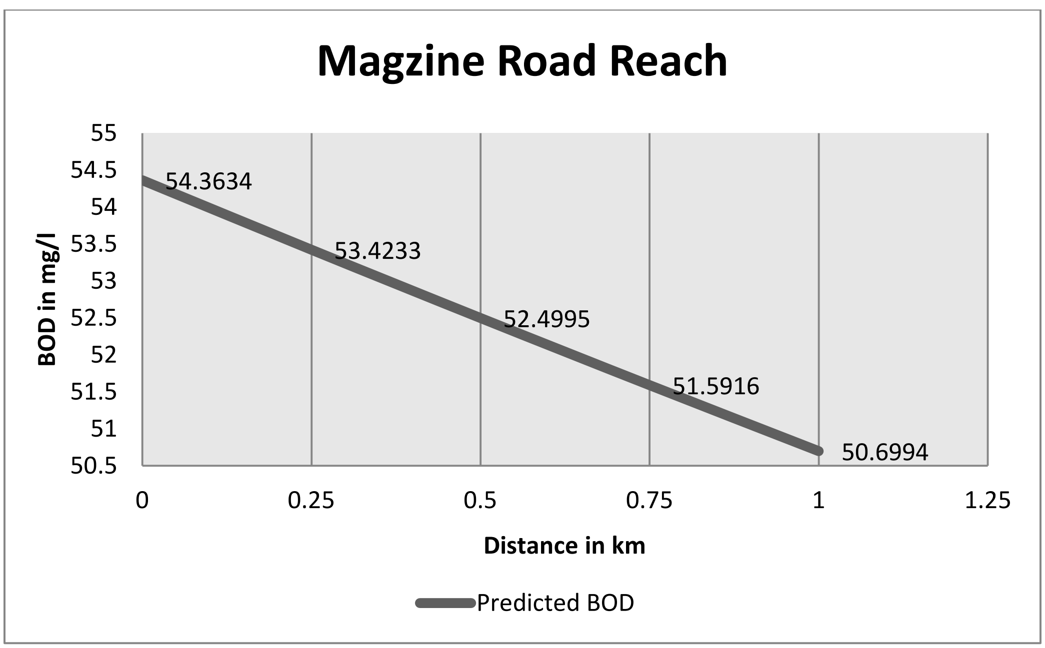


Figure 6.32 BOD profile of Magzine road reach

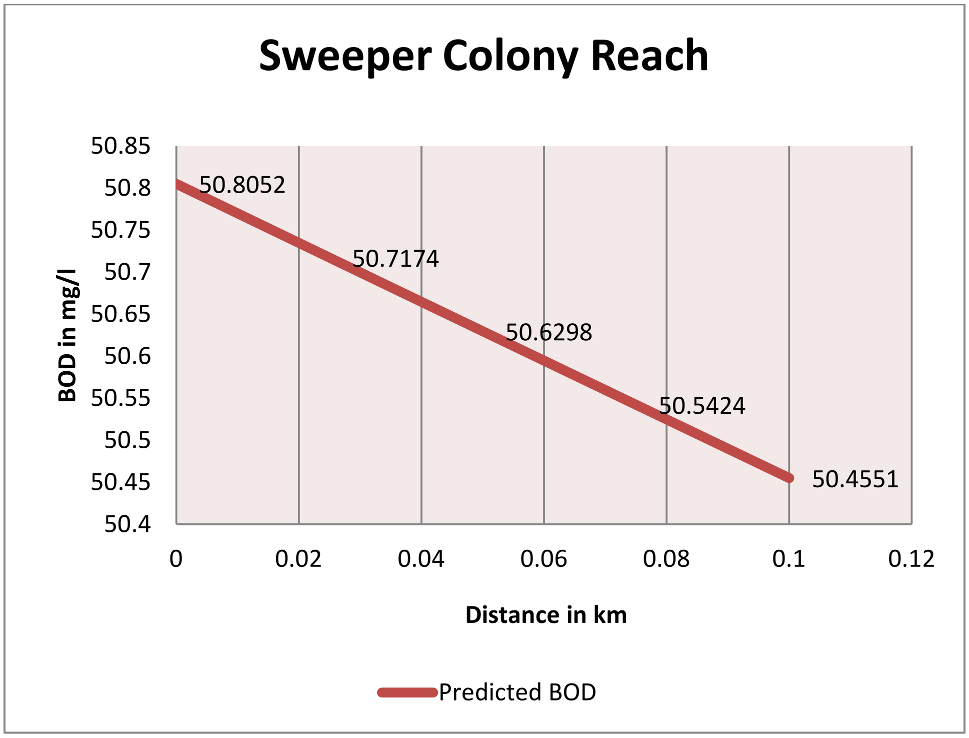


Figure 6.33 BOD profile of Sweeper colony reach

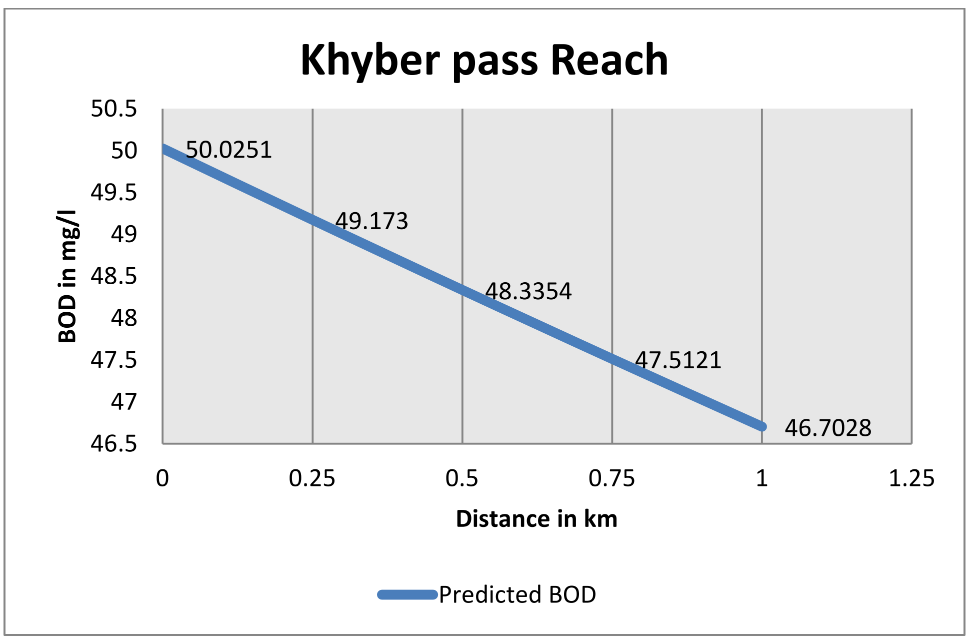


Figure 6.34 BOD profile of Khyber pass reach

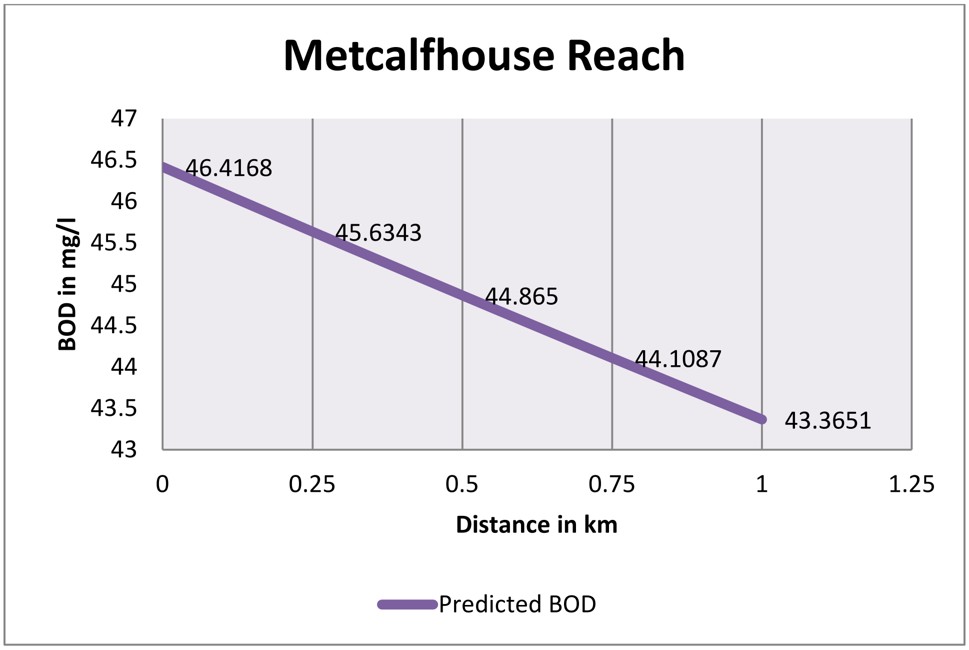


Figure 6.35 BOD profile of Metcalfhouse reach

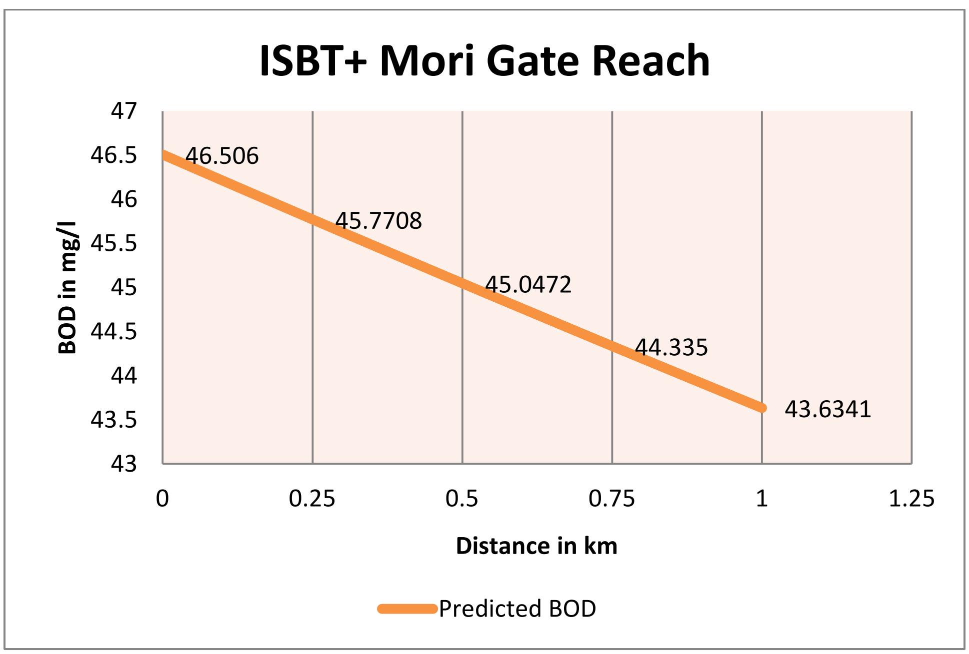


Figure 6.36 BOD profile of ISBT + Mori gate reach

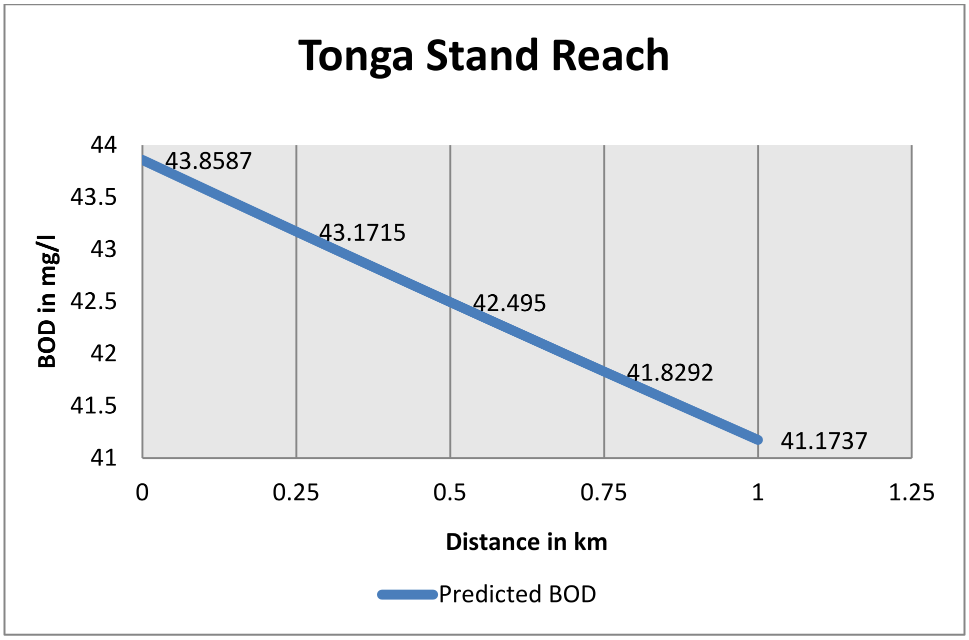


Figure 6.37 BOD profile of Tonga stand reach

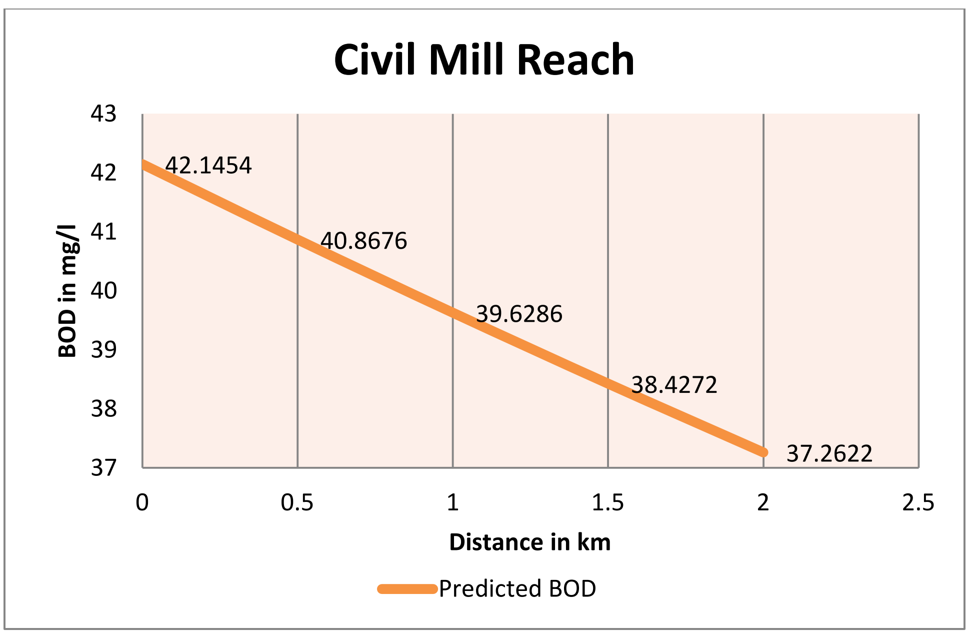


Figure 6.38 BOD profile of Civil mill reach

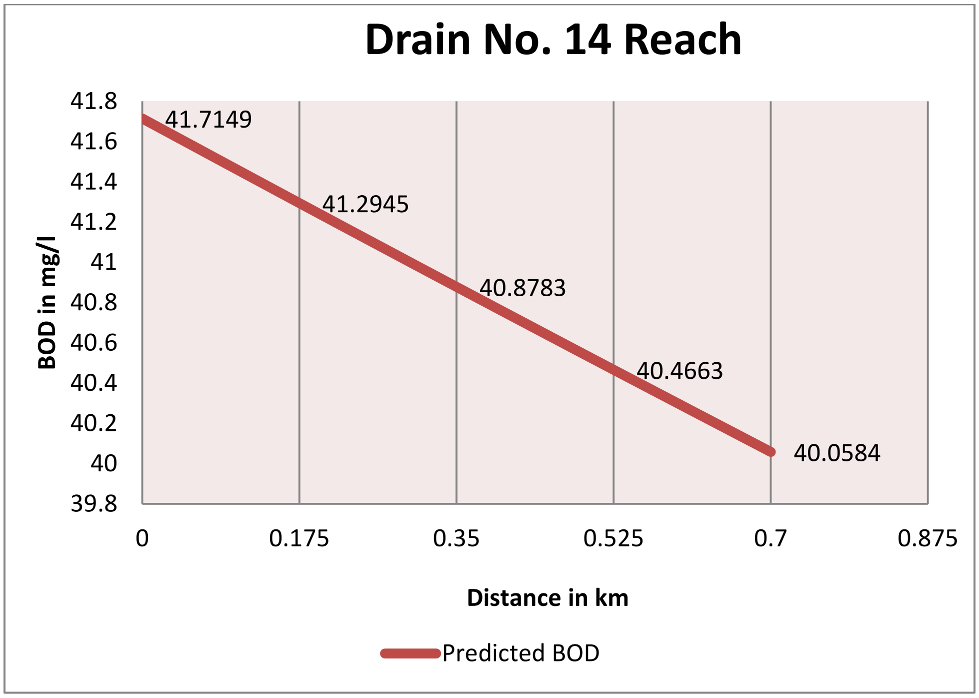


Figure 6.39 BOD profile of Drain no. 14 reach

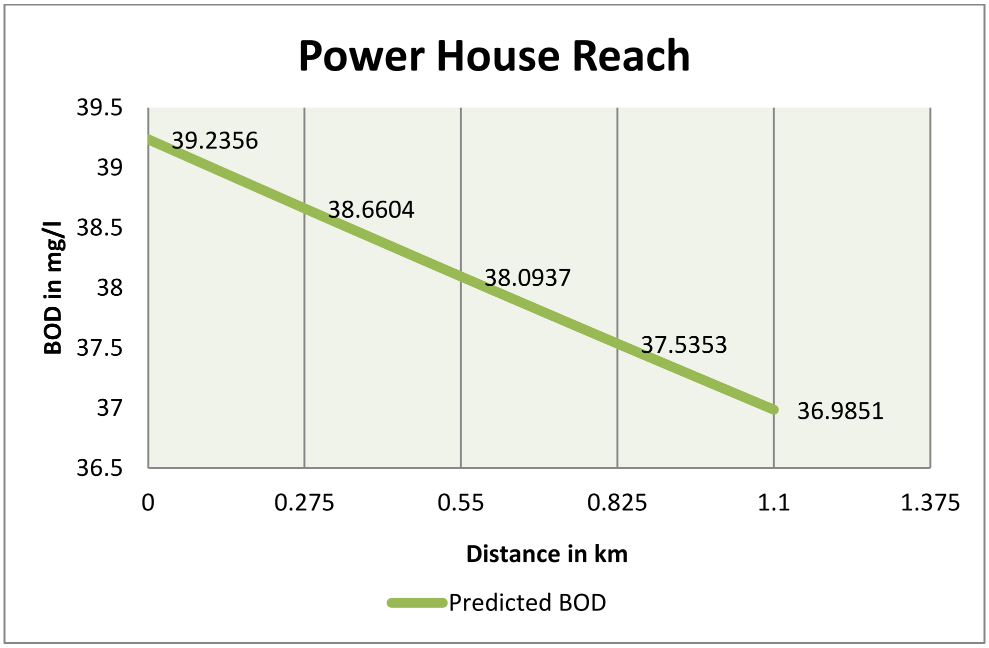


Figure 6.40 BOD profile of Power house reach

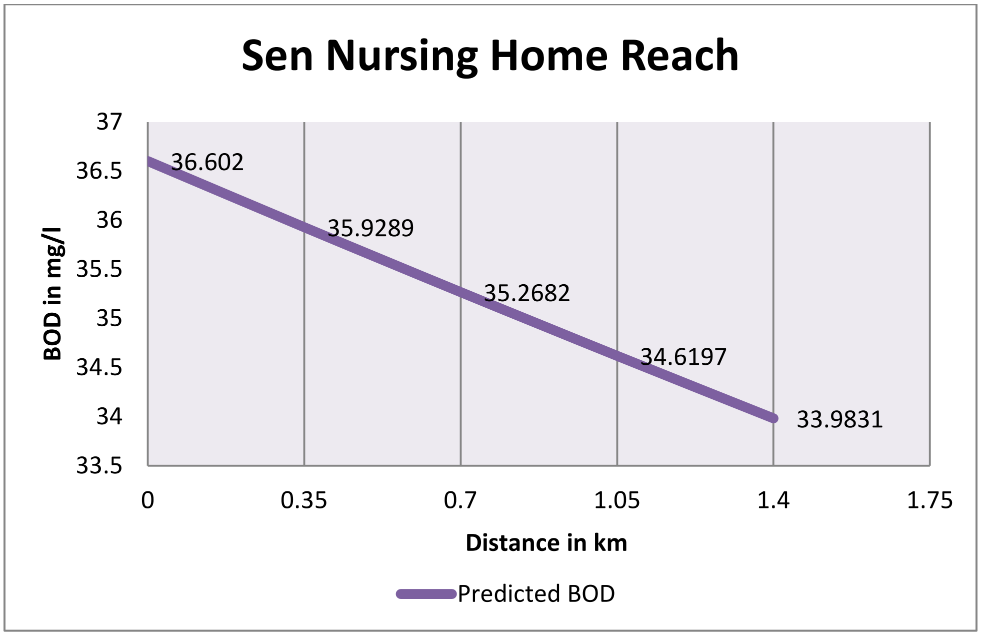


Figure 6.41 BOD profile of Sen nursing home reach

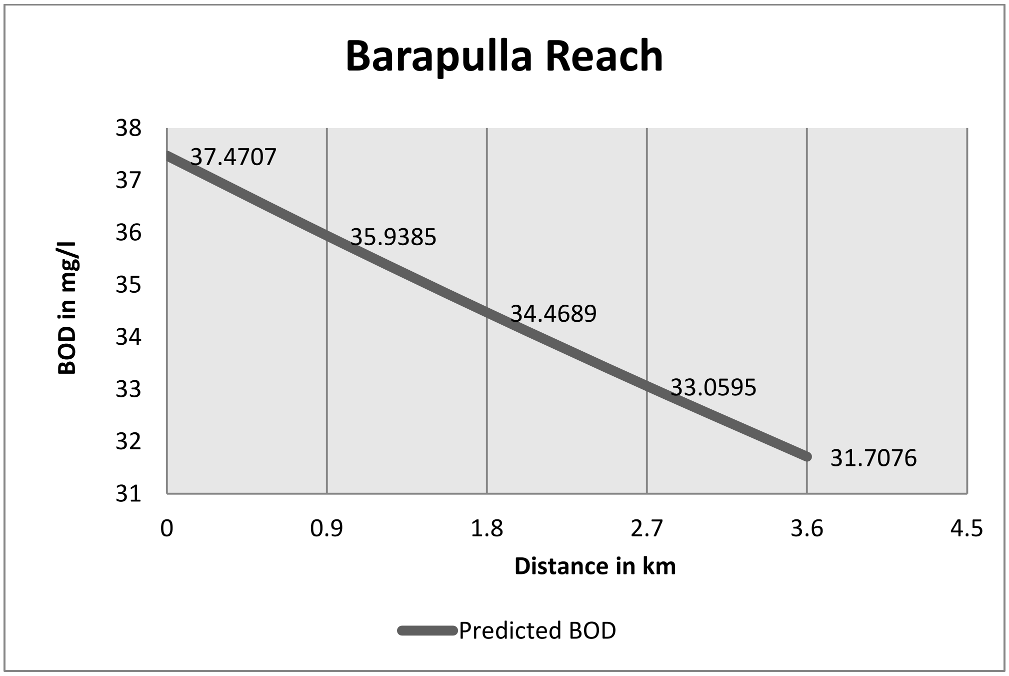


Figure 6.42 BOD profile of Barapulla reach

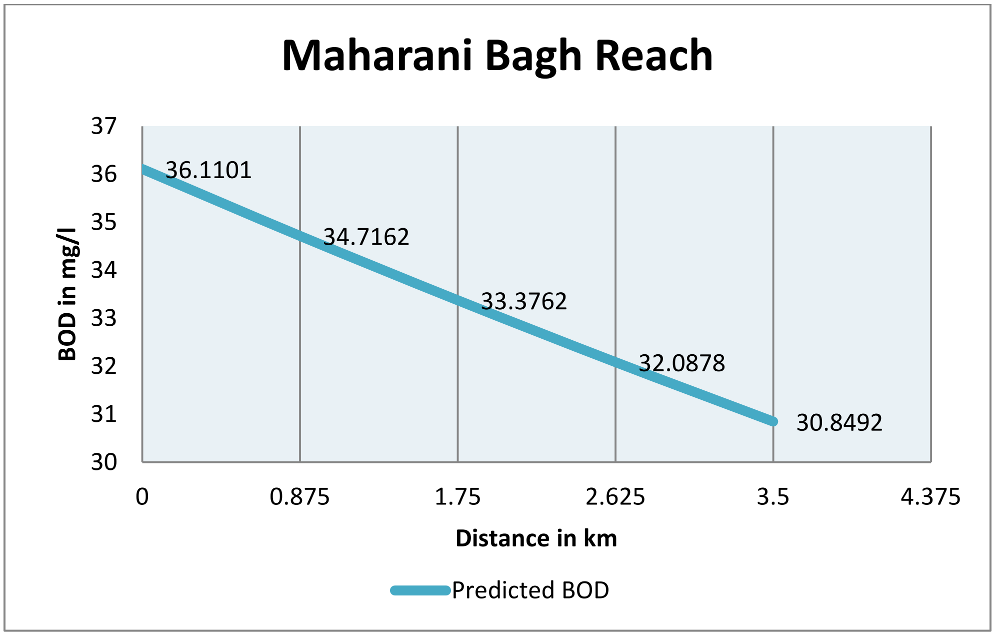


Figure 6.43 BOD profile of Maharani bagh reach

The following are the points of discussion here:

1. As seen from the above graphs, the BOD profile follows almost a linear trend as it has been calculated over a short distance at equal intervals.

2. The facts lies that BOD decreases as the distance from the source increases which also goes with the theory. Sweeper colony reach shows the highest BOD that is the contribution by the Magzine road drain along with the Najafgarh drain as self purification capacity of the river is nil. BOD decreases as move down due to little dilution by the river water.

3. As the distance between the two nodes is quite small the largest being of Barapulla reach that is 3.6 km and smallest is of sweeper colony reach 0.1 km, the variation along these reaches are very less.

6.4.1 Yearly variation of BOD at each reach

DO has also being calculated at five points of equal intervals designated as DO_0 to DO_4. DO_0 is the point just d/s of starting node of a reach and DO_4 is point just u/s of the ending node of the same reach. The variation of DO as recoded from the results obtained from the model are as follows:

Table 6.16 Predicted DO concentration of reaches calculated at five points for each reach

Drains	DO_0	DO_1	DO_2	DO_3	DO_4
Najafgarh drain	1.1625	0.9813	0.8034	0.6287	0.4573
Magzine road drain	0.4423	0	0	0	0
Sweeper colony drain	0	0	0	0	0
Khyber pass drain	0	0	0	0	0
Metcalfhouse drain	0	0	0	0	0
ISBT + mori gate	0	0	0	0	0
Tonga stand	0	0	0	0	0
Civil mill	0	0	0	0	0
Drain no. 14	0	0	0	0	0
Power house drain	0	0	0	0	0
Sen nursinghome drain	0	0	0	0	0
Barapulla drain	0	0	0	0	0
Maharani bagh drain	0	0	0	0	0

The profile for each reach of DO variation are shown in the following figures:

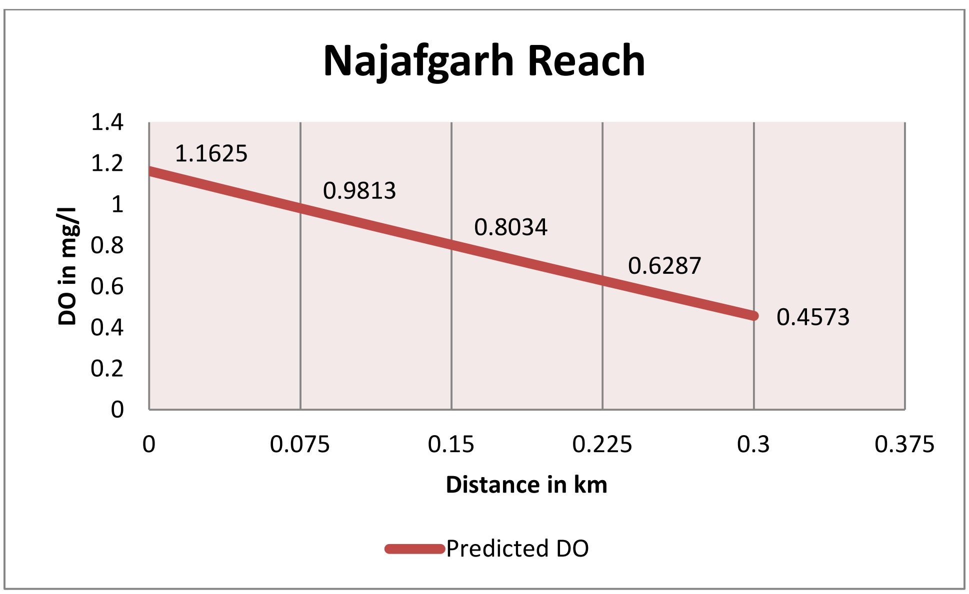


Figure 6.44 DO profile of Najafgarh reach

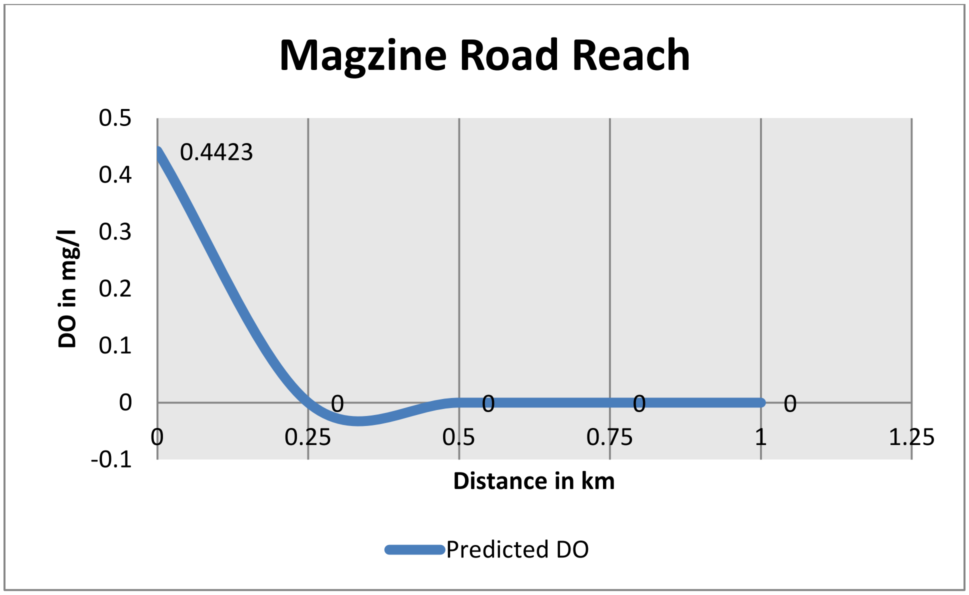


Figure 6.45 DO profile of Magzine road reach

Following points have been observed from the above Table and Figures

1. The DO profile of the reaches as shown in above is very poor, only Najafgarh reach shows some DO concentration left in the river although far below the standard level. The rest of the reaches contain nil DO which depicts the extravagantly low self purifying capacity of the river.

2. DO concentration for the entire stretch is nil which has already being depicted in the case B. The DO profile for the stretch is drawn here only for two reaches which atleast shows some integer value while all the other shows a straight line at x=0 and y=0.

3. Nothing much of significant has been observed here, the results obtained is quite enough to declare it as a dead river.

For the purpose of presenting the result the negative value for the DO concentration as obtained from the model prediction here is taken as zero. Also the Model had predicted the critical value of DO, the critical distance at which DOcrit occur as well as the critical time, tcrit. But these results are not mentioned in this report as they are insignificant for the purpose of study because for almost all the reaches DOcrit is predicted as negative which is obtained at the critical distance beyond the distance of that particular reach.

CHAPTER – 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

The study presented in this report briefly describes that MATLAB as a programming tool can be used to develop a Water Quality Model. Although to make it compatible with the real situation it has been required to have a large set of background data collection. In the work presented here an effort has been made to successfully implement the DO-BOD model at 22 km stretch of river Yamuna with limited data provided by CPCB, India. The performance of model could have been significantly enhanced if more ground observations were available. Following conclusions can be drawn based on the study:

1. Once recognised as a holy mightiest river, is now facing a dreadful situation with almost zero level of DO and significant level of BOD concentration.

2. The self purifying capacity of river become nil due to its over exploitation. The river is highly polluted due to the discharge of various treated as well as untreated waste**.** The maximum BOD concentration has been observed just d/s of Najafgarh drain node.

3. One of the measure suggested in the study which can be used to cope-up with the problem to some extent is maintaining the continuous flow of water d/s the Wazirabad barrage, although it has been difficult to maintain such flows especially during dry period, thus in addition to this certain other measures should have to be adopted.

4. It has also been concluded that despite being the major pollutant contributing drain, the DO after Najafgarh node, i.e. Magzine road reach never arrived at zero value this is due to the flow of less polluted water from Wazirabad barrage which on confluencing with the drain directly dilute the pollutant load to some extent which saves it from facing nearly zero condition but the later reaches have to bear its consequences.

5. The monthly variation of DO and BOD shows that the river completely regain its quality in the monsoon months if sufficient discharge of water is available d/s whereas March followed by May and winter months faces the devastating situation.

6. Model is very user-friendly, once developed it can be applied for any river for any time period just requiring the change in the input matrix and value of constants. Data input can

be done in a very systematic and coherent manner. Less number of hydrological parameters and topographical conditions are required to carry out simulations in MATLAB, contrary to other models. The effects of measurement errors can be minimized by optimizing data-collection procedures like collecting data in most sensitive locations and by collecting optimum number of replicates.

7.2 RECOMMENDATIONS

For regaining back the quality of river Yamuna rigorous methodologies should be adopted. Following recommendations are made from the study:

1. One of the solution already explained in the previous section is maintaining continuous flow in the stretch. This can be achieved by tapping water after Hathnikund barrage to restrict the draining of whole of the water in the WYC and EYC. The water here is diverted for irrigation purpose for the state of Haryana so that little or no water is left for discharge after the diversion.

2. The water can also diverted by constructing canal from some other nearby sources and by means of small tributaries. Another best way of receiving water is by means of ground water discharge. Special attention should be given for replenishment through ground water recharge. Programmes should be needed to collect flood water for recharging ground water and filling water bodies.

3. There should be control on the discharge of untreated waste of high organic content. Treated water must not be mixed with untreated water. Additional ETP's should be constructed along side the drains which contribute high pollutant load. Further parallel drains along Yamuna should be constructed to prevent entry of waste into the river.

4. Provision of conveying storm water to the river also help in recharging of river. Storm water can be collected or directly allowing it to enter drains can be a feasible option.

5. Encroachment on Yamuna bed need to be removed so that recharging of river can take place.

6. Artificial aeration is also an excellent option for maintaining the healthy quality of river by regaining purification non-naturally.

7. If none of the option seems feasible inorder to achieve DO upto standard level the waste discharge and water discharge should be in proportion so that proper dilution of waste can take place.

Papers Published

1. "Assessment of the impacts of point load on River Yamuna at Delhi stretch, by DO-BOD Modeling of river, using MATLAB Programming", published in International Journal of Engineering and Innovative Technology, ISSN: 2277-3754 (Online), Vol. 2 issue 10, April-2013.
2. "DO-BOD Modeling of River Yamuna for Delhi Segment Comparing the Actual Case of Low Water Discharge with that of the Flow Required to be Maintained to Meet Out Environmental Flow Concern of Various Stretches", published in International Journal of Innovative Research in Science, Engineering and Technology, ISSN: 2319-8753 (Online), Vol. 2, issue 5, May-2013.

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