DEVELOPMENT OF AN APPROACH FOR WATER QUALITY MANAGEMENT IN URBAN RIVER REACHES

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By

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CANDIDATE’S DECLARATION

I, Nibedita Verma hereby certify that the work which is being presented in the thesis entitled “Development of an Approach for Water Quality Management in Urban River Reaches,” in partial fulfillment of the requirements for the award of the Degree of Doctor of Philosophy, submitted in the Department of Environmental Engineering, Delhi Technological University, is an authentic record of my own work carried out during the period from January 2020 to June 2024 under the supervision of Dr. Geeta Singh and Prof. Naved Ahsan.

The matter presented in the thesis has not been submitted by me for the award of any other degree of this or any other Institute.

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ABSTRACT

The Delhi reach of the River Yamuna stretch is a receptacle of urban liquid waste caused by human interference from domestic and industrial fields and leads to one of the most contaminant reaches of the country. This reach needs a water quality management strategy to directly improve the dissolved oxygen (DO) concentration and decrease the concentration of various undesirable substances, including the biochemical oxygen demand (BOD). This novel study appraised the water quality, assimilation capacity, total maximum daily load, and proposed management strategies by generating scenarios with a receiving water quality model. Multivariate techniques were used to represent the spatiotemporal water quality variations and interpreted a large hourly complex dataset (March 2021-February 2022) obtained from two real-time monitoring stations upstream and downstream of this reach. The increased concentrations of conductivity, BOD COD, TOC, NH_4, and low DO downstream indicated the influence of outfalling drains and diffused sources contributing pollutants into the river stretch. A higher BOD, COD, and TOC concentration was observed downstream in the rainy season, attributed to the organic substance in surface runoff. FA and PCA were implemented in the standardized data set to reveal the correlation between the water parameters. For upstream, factor 1 was strongly positively loaded turbidity, TOC, COD, and TSS for all the seasons except monsoon. For downstream, TOC and COD contributed strongly positive load except in winter. The wastewater treatment plants data for 2020-2022 have been analyzed, and the removal efficiencies of BOD and COD were found between 65%-94%. The BIOFORE technology has shown maximum removal efficiencies, around 94% and 89% for BOD and COD, respectively. The QUAL2kw model was used to predict river quality. The model was calibrated and confirmed in critical flow conditions of pre-monsoon periods. A sharp declination of dissolved oxygen and acceleration of BOD was observed after the outfall of drain1(Najafgarh Drain). In order to evaluate assimilation capacity, four cases with 41 scenarios were studied with varying upstream flow augmentation and BOD load. It has been observed that with 80 cumecs of upstream flow, the reach can assimilate around 30 TPD of BOD and 142 TPD of COD load, maintaining the desired level of DO ($\geq$ 4mg/l) and BOD ($\leq$3 mg/l) throughout the reach. For the Total Maximum Daily Load (TMDL) implementation plan, three scenarios with 10 simulations have been constructed with varying BOD load, upstream flow, and local oxygenation. With 10cumecs upstream flow, the required TMDL was around 7.5 TPD of BOD load to maintain the BOD concentration below 3 mg/l throughout the spread. With the 40 cumecs increment of upstream flow, the TMDL of BOD was found around 14.5 TPD, and DO concentration was more than 2mg/l throughout the reach. Two plans were proposed for water quality management of this polluted reach. In the first plan, 23 scenarios were constructed with varying pollutant load modification and increasing upstream flow. Results indicate that headwater flow management and load modification increase the river water quality. Meanwhile, around 12 km downstream, DO concentration could not reach the desired standard. External oxygenation may be required to achieve the necessary standard of DO. The second plan evaluated the weir function at the critical points to entrap the oxygen and increase the level of DO concentration. It was observed that two weirs, 0.8 and 0.9 m in height after 0.44 km and 10 km downstream, can improve the assimilation capacity of the reach due to flow over weirs producing intense oxygenation through air entrainment.

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LIST OF ABBREVIATIONS

WQMP	Water Quality Management Plan
WQM	Water Quality Model
PCA	Principal Component Analysis
FA	Factor Analysis
CA	Cluster Analysis
DA	Discriminant Analysis
WQI	Water Quality Index
Temp	Temperature
Turb	Turbidity
NH3-N	Amoonia Nitrogen
NO3-N	Nitrate Nitrogen
DO	Dissolved Oxygen
BOD	BioChemi9cal Oxygen demand
CBOD	Carbonaceous Biochemical Oxygen Demand
NBOD	Nitrogenous Biochemical Oxygen demand
BOD_5	5 day BOD
BODu	Ultimate BOD
CBODF	Fast Carbonaceous Biochemical Oxygen demand
COD	Chemical Oxygen Demand
TOC	Total Organic Carbon
TN	Total Nitrogen
TP	Total phosphate
WL	Waste Load
WLA	Waste Load Allocation
TMDL	Total Maximum Daily Load
LA	Load Allocation
MOS	Margin of Safety
MLD	Million liters per Day
MGD	Million Gallons per Day
TPD	Tonnes per Day
STPs	Sewage Treatment Plants
CPCB	Central Pollution Control Board
DPCC	Delhi Pollution Control Committee
DOE	Department of Environment
CWC	Central Water Commission
IF&C	Irrigation and Flood Control Department
E-flow	Environmental flow

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LIST OF RESEARCH PUBLICATIONS

International Journal Publication

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2. **Nibedita Verma,** Geeta Singh & Naved Ahsan. "Water quality management by enhancing assimilation capacity with flow augmentation: a case study for the Yamuna River, Delhi" **"Water Science & Technology" IWA Publication.** September(2023). Vol 88, No 7, 1821 **(SCIE Indexed)** https://doi.org/10.2166/wst.2023.302 **(IF 2.7)**
3. **Nibedita Verma,** Geeta Singh & Naved Ahsan. "Assessment of Spatiotemporal Variations in Water Quality of the Urban River Reach, Yamuna, Delhi" Water, Air & Soil Pollution. , (August 2023) 234:571 **Springer Nature** (**SCIE Indexed)** https://doi.org/10.1007/s11270-023-06569-1 **(IF 2.9)**
4. **Nibedita Verma,** Geeta Singh & Naved Ahsan. "Development of water quality management strategies for an urban river reach: A case study of the River Yamuna, Delhi, India. Arabian Journal of Geosciences, (December 2022) 15:1767, **Springer Nature** (**SCIE indexed during Submission**). https://doi.org/10.1007/s12517-022-11030-4 **(During Submission IF 1.8)**

International Conferences

1. **Nibedita Verma**, Geeta Singh & Naved Ahsan "DO MODELING FOR THE YAMUNA RIVER, DELHI". Presented at "The Third International Conference on Recent Challenges in Science, Engineering, and Technology-2023:: Date:27th,28th, AUGUST-2023".
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CHAPTER 1

INTRODUCTION

1.1 General

The significance of rivers for humans may be appraised by the fact that all advancements of the world have been bloomed at the river banks. The river banks provide fertile soil and water that helps grow crops and increase settlement. Civilizations like Harappa, Nile Valley, Mesopotamia, and the Xia, Shang, and Zhou dynasties have flourished at the banks of the Indus River, Nile River, Tigris and Euphrates Rivers, and Yellow River, respectively. Hence, from the primitive to the modern era, rivers are surrounded by highly populated areas depending on farming and industrial activities as rivers are water suppliers and wastewater acceptors (Othman et al., 2012; Aris et al., 2015). The rivers are pretentious, with water disposed of from various natural and human activities. A river ecosystem can be resilient in modifying and recuperating itself from the transformation enforced by the surrounding pollution. However, the river system can deteriorate with wastewater disposal and a lack of freshwater availability, which lowers the oxygen level and impacts the ecosystem's survival. Therefore, pollutant agglomeration should be maintained at a level that can complement the river's resilience or self-carrying ability. Water resources administration is becoming challenging because of escalating urbanization and industrialization (Hobson et al., 2015; Turner et al., 2009; Brown & Barnwell, 1987). It is the prime prerequisite to managing available water resources in developing countries. The conservation of surface water resources is now a critical issue (Pelletier et al.,2006; Chapra, 2003). Surface water conservation includes preventing pollution if it is already polluted and restoring and enhancing the water bodies (Teegavarapu et al., 2014). Wastewater generated from anthropogenic activities for industrial and domestic purposes is directly or indirectly liberated into the water bodies as point sources after partial or untreated conditions (Mishra & Kumar, 2020; Parmar & Keshari, 2014). Point sources like agricultural runoff, deforestation, and mining activities can also contribute adulterants to the water bodies (Chapra, 2003; Gikas, 2014; Aliffia & Karnaningroem, 2019). India has an area of 3,287,590 sq. km and a 7,500 km coastline with diverse climatic conditions: tropical monsoon in the south and temperate in the north. It has diversified land areas such as upland plain (Deccan Plateau) in the south, flat to rolling plain along the Ganges, deserts in the west, and the Himalayas in the north. The country has several rivers and heavy rainfall; 75% is the southwest monsoon. The country has thirteen major river basins (more than 20,000km^2), occupying 82.4% of the total watershed, contributing 85% of the total surface flow, and housing 80% of the inhabitants (Bhargava, 1985). Significant watersheds are the Brahmaputra, Ganga (including Yamuna Sub Basin), Indus (including Satluj and Beas Sub Basin), Godavari, Krishna, Mahanadi, Narmada, Cauvery, Brahmini (including Baitarni Sub Basin), Tapi, Mahi, Pennar, and Sabarmati (Bhargava, 1985). These rivers cross state boundaries and interstate river basins. These rivers need integrated management systems to incorporate the development of interstate river basins. Every state needs to maintain the river's health by allocating the maximum pollutant load, which can be assimilated to the respective river reach using a water quality-based approach that emphasizes the riverine ecosystem. In this study, the Yamuna River, Delhi stretch is observed to develop a management approach for maintaining the river quality to designated Class “C”. Yamuna River originated from Yamunotri, which is north of Haridwar in the Himalayan mountains, near Bander punch peaks (38^{0}59’ N;78^{0}27’E) in the Mussoorie range of the lower Himalayas at an elevation of about 6387 meters above mean sea level and after flowing total length of 1386 km covering five states Uttaranchal, Uttar Pradesh, Himachal Pradesh, Haryana, Rajasthan, Madhya Pradesh & NCT–Delhi with total basin area around 366000 km^2, its confluence with the river Ganga at Praygraj, Uttar Pradesh (CPCB, 2006). It has five-segment:- Himalayan segment from the origin to Tajewala Barrage, Upper segment from Tajewala Barrage to Wazirabad Barrage, Delhi segment from Wazirabad Barrage to Okhla Barrage, Eutriphicated Segment from Okhla Barrage to Chambal confluence and Diluted Segment from Chambal Confluence to Ganga Confluence. Before reaching the Delhi stretch, the river water is diverted and regulated by a weir to produce electricity in Uttaranchal. In Tajewala/ Hathnikund in Haryana state, the river water is rerouted to the eastern and western Yamuna Canal for agriculture. During the dry season, the river becomes dry in some portions of the Tajewala and Delhi segments and is regained by groundwater discharge and Som Nadi, a seasonal stream (Water Quality Year Book Yamuna Basin, 2015-16). The rivers enter Delhi near Palla village and course through Delhi for about 48 km (DDA, 2014. In Delhi, the river is tapped at Wazirabad through a barrage for drinking water purposes, and no water is allowed to flow downstream during the dry season beyond the Wazirabad barrage to fulfill the water supply requirement in the capital, Delhi (CPCB, 2006). After the Wazirabad barrage, in the Delhi stretch, the river is fed by 16 drains along with the wastewater transfer by the Haryana Irrigation Department from Western Yamuna Canal to Agra Canal via Najafgarh Drain, with partially treated or untreated domestic and industrial wastewater from different places and the reach becomes a sewerage line (CPCB, 2006). In the Delhi stretch, wastewater from the National Capital Region contributes about 80% of the total river length (CPCB, 2006) pollution and becomes unusable. This massive pollution is due to the enormous abstraction of water for irrigation, water supply for drinking and industrial purposes, and the discharge of untreated or partially treated industrial and domestic wastewater. This urban river reach requires an efficient water quality management approach. In this study, QUAL 2Kw, which is reach-based and can use process-based data means measures data, as well as literature-based or calculated data to calibrate and validate water quality parameters, was used to develop a management approach to assessing water quality to maintain the Yamuna River water and assess the assimilation capacity as well as TMDL for BOD of this urban river reach.

1.2 Problem statement

Water quality and pollution are the most common and related issues that are significant concerns for the availability of drinking water in India. Wastewater generated from domestic and industrial sources is disposed of with low or no treatment, a frequent practice in most developing nations and implicated in the deterioration of receiving water bodies instantly and persisting for longer (Ghosh & Mcbean, 1998). The River Yamuna, one of India's most prominent and essential rivers, also has polluted stretches (CPCB, 2006). Big cities like Delhi, Agra, and Mathura are based on this river bank, and they use this river as a source of water supply and the acceptor of wastewater generated from various urban activities. Studies showed that before entering Delhi, the Yamuna River water quality was reasonable for aquatic life and within the desired limits given by CPCB, India (Gupta et al., 2018). After traversing from Wazirabad to Okhla, the river feeds with 16 major drains, and due to a lack of perennial freshwater, the river becomes ecologically inoperative (Sharma & Kansal, 2011; Singh et al., 2007). Furthermore, according to the Sewage Treatment Inventory Report (CPCB,2021), against the 3330 MLD generated sewage, the actual utilized capacity of sewage treatment plants is 2412 MLD. Also, the effluent standards of the 34 STPs are not compiled with the standards (STP reports DPCC domain). Hence, wastewater has been disposed of partially or without treatment in the river. Delhi Pollution Control Committee (DPCC) (1034b379dc3af99c6346443e7a948d4b.pdf (delhigovt.nic.in)) monitors river water quality at Palla, Wazirabad, ISBT bridge, ITO bridge, Nizamuddin bridge, Okhla barrage, Agra canal at Okhla barrage, and River Yamuna at Asgarpur monthly. Fig 1.1 shows that after Wazirabad, the river exceeded water quality standards. Minimum 10 cumecs of E-flow for dilution of polluted water in river Yamuna in Delhi is required to meet desired water quality levels in river Yamuna for bathing purposes, i.e., BOD < 3 mg/l & DO >5 mg/l (GONCT, Delhi, DOE, 2022). To assess the minimum necessary E-flow of river Yamuna for the stretch between Hathini Kund to Okhla, a comprehensive study was assigned by NMCG to the National Institute of Hydrology (NIH), Roorkee, on 24.12.2018. E-flow of 23 Cumecs (437 MGD) in lean season (May) has been recommended in the NIH study, and the BOD level would come down from 25 to 12 mg/l (Ideal BOD≤3 mg/l) (GONCT, Delhi, DOE, 2022). Hence, more upstream water flow is required to maintain the designated water qualities. The Yamuna Action Plan I, the most significant water quality restoration project adopted for Yamuna River management, started in 1993 and was adopted to restore this polluted reach. However, it has been observed that after the completion of the Yamuna Action Plan I (YAPI) (1993-2003) and YAPII (2004-2013), the river quality did not improve. Ongoing YAP(III) (2012-ongoing), which is comprised of the construction of sewage treatment plants and rehabilitation projects, the BOD load is constantly increasing (Srivastava & Prathna 2021). Figs 1.1 and 1.2 show the present water quality conditions of the river reach. Much study has been done on this river's reach, including the water quality index and monitoring.

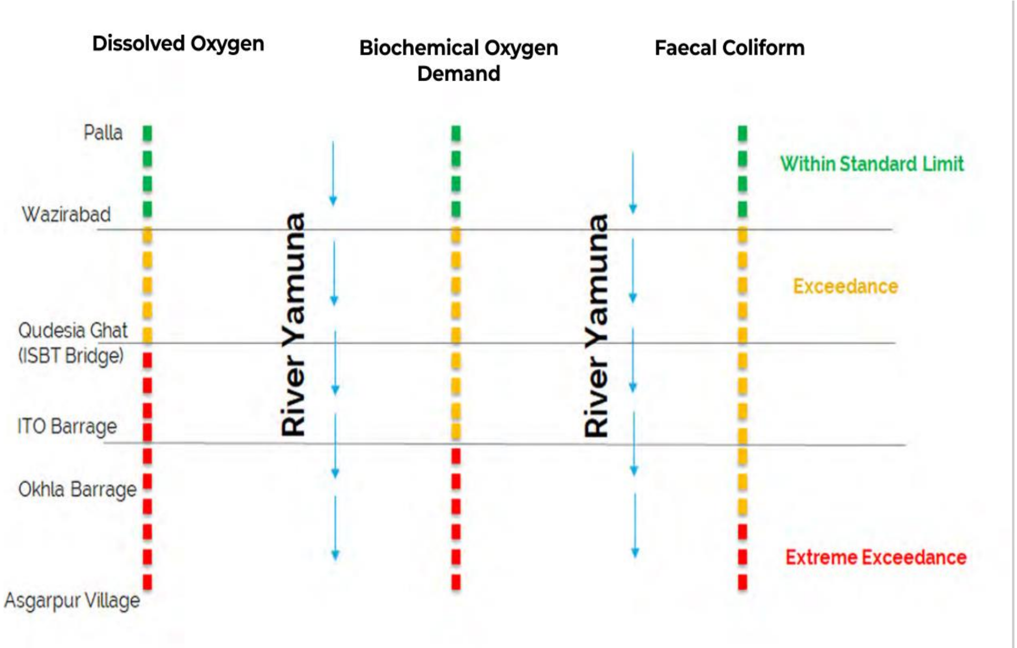


Figure 1.1. Water Quality of the Delhi stretch of River Yamuna (Source: Progress in Rejuvenation of River Yamuna, December 2022 (DOE, 2022).

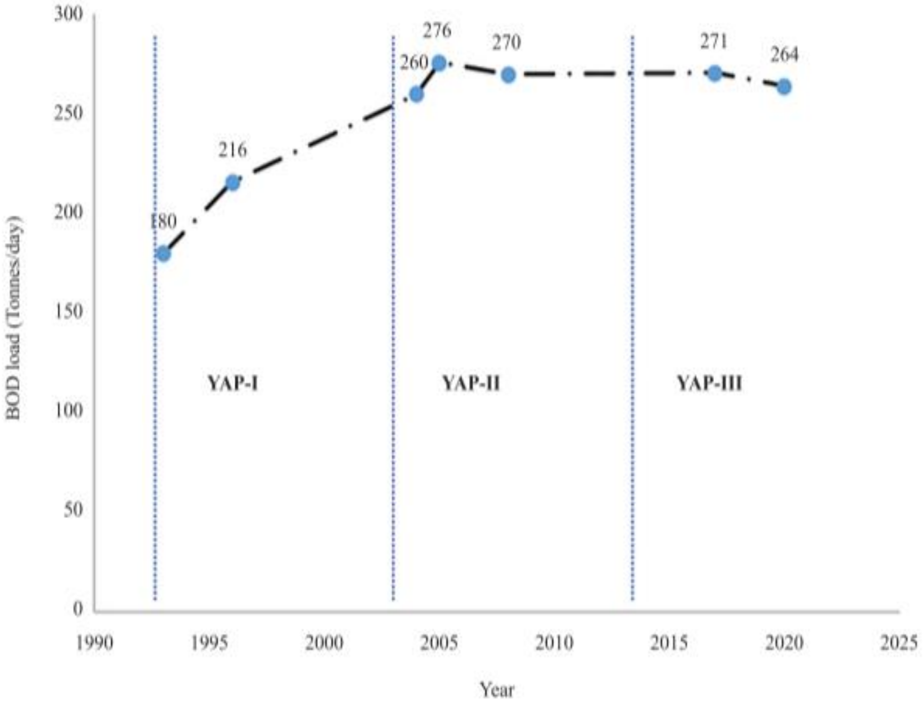


Figure 1.2. Pollutant load reaching the River Yamuna during the YAP (Srivastava & Prathna, 2021)

A study was conducted by Virginia University in collaboration with the Delhi Jal Board in the year 2016 to investigate Delhi's Yamuna River water quality. It was stated that the river water quality is acceptable at Palla, and a sharp deterioration happened after adjoining Najafgarh and supplementary drains carrying huge amounts of domestic and industrial wastewater (Lung,2022). The study also concluded that COD and BOD5 concentrations are low at Palla but increase sharply by Nizamuddin with maximum levels reaching 144 mg/L and 80 mg/L, respectively (Lung, 2022), Whereas the DO concentration was high at Palla, it declined below 1 mg/l at Nizamuddin and river reach becomes anaerobic (Lung, 2023). Furthermore, the concentration of oxygen-demanding substances has increased with time as industries and urbanization have developed tremendously. Therefore, a complete study, including water quality assessments and total maximum daily load allotment with creating an integrated management approach to the river reach, is required, which has not yet been done. The water quality model can predict the fate of the pollutant load disposed into the river. Hence, these models can evaluate the quantity of load that should be disposed of into a stream to maintain the river's health ecologically fit. This study proposes a development approach to support the urban river reach of Yamuna, Delhi, focusing on the BOD, COD, and DO to achieve the desired class "C".

1.3 Objectives of the Study

The main objectives of this study are as follows:

a) To assess the existing water quality and waste inputs through various point and nonpoint sources in the urban reach of the river.
b) To simulate an urban river reach using the QUAL2Kw model and to determine the self-assimilation capacity of the river with existing conditions.
c) To determine the total maximum daily load allocation for the river reach and predict its water quality for different management scenarios.
d) To develop a suitable plan for the long-term sustainability of urban reaches.

1.4 Significance of the Study

The strength of this research lies in its specific focus on determining the maximum allowable BOD loads into the Urban River reach of Delhi by using the QUAL2Kw framework and developing a management approach to keep the required DO throughout the reach. The study carried on the maximum allowable BOD load is significant for this reach, as this reach is highly polluted with organic oxygen-demanding substances due to the high volume of wastewater containing heavy pollutant load after entering Wazirabad (Arora & Keshari, 2021b). The spatiotemporal assessment of water quality for the upstream and downstream also requires knowing the pollutant qualities and quantities added to this river reach. A principal components and factors analysis is necessary to identify the considerable parameters and causes of pollution. Self-resilience capacities must also be estimated to evaluate the allowable maximum load. This river reach is a primary water source for the mega metropolitan of Delhi. The river reach becomes a sewer line for high pollutant load and low base flow. Therefore, the study area is very significant in terms of ecology as the mortality rate of fish is very high in this reach. The present work has contributed to developing a management approach by collecting secondary data from CPCB, DPCC, CWC, and I&FC. The wastewater input drain data were also collected from the DPCC domain. Wastewater treatment plant efficiencies have also been tested, and options for their improvement have also been highlighted. Scenarios have been developed to study the assimilative capacity of this reach with flow augmentation and load reductions. The TMDL approach for this reach is highly recommended, as several action plans could not achieve the required water quality of this reach. The scenarios have been developed with flow variation, load reduction, and local oxygenator. The development approach with a soft tool like QUAL2Kw is suggested in the present study to determine the maximum allowable load into this polluted reach to attain the desired water quality standard. The TMDL implementation plan for the urban River Delhi reach will benefit the administrative authorities in overcoming and encountering pollutant load in the river. Furthermore, this study also suggested a suitable improvement in effective monitoring strategies and time frame for the TMDL implementation for the Yamuna River in Delhi and other rivers in India.

1.5 Scope of the Study

This study will help to understand the water quality parameters of the Yamuna River, Delhi Stretch, and to attain a cost-effective method to manage the pollution of this segment. The results of this study of this segment will provide the information that permits rational decisions to be made on the following:

i. The spatiotemporal variations of water quality of Yamuna River and the reason for pollution
ii. Sources of pollutants
iii. The self-assimilation capacity of the river with existing hydrological and meteorological conditions
iv. Use of a Mathematical model to simulate the water quality parameters such as BOD, DO, pH, alkalinity, and ammonia
v. Developing and implementing a water quality model under different scenarios to determine the assimilation capacity
vi. Total maximum daily load is a successful and cost-effective method of management procedure of BOD by studying the conditions a) reducing waste load by treating it before discharging, b) diversifying the drain, and c) using the flow augmentation process.
vii. Develop a water management policy to maintain the health of the river body.

1.6 Research Gap

According to the findings of the comprehensive literature review for the Urban River reach of Yamuna, Delhi, the following research gaps are noted:-

1. Using real-time water quality data, assessing the spatiotemporal variations of water quality parameters for different seasons and determining the hidden factors describing the large data sets and impacts of probable water pollutant sources for current geomorphological and meteorological conditions, such as PCA and FA.

2. The spatiotemporal variations of water quality parameters, mainly DO, BOD, COD, NH_4, NO_3, etc., require assessment upstream and downstream of the reach.
3. Using water quality models such as QUAL2Kw to assess the river's assimilation capacity by generating different scenarios with varying load and flow enhancement.

4. Considering COD in modeling, in addition to BOD, as COD is very high in the study reach.

5. Determination of the total maximum daily load, which includes the load from point and nonpoint sources and the margin of safety.

6. Development of a water quality management plan to control waste inputs from different sources of pollutants and maintain the river's ecological health through flow augmentation, load modifications, and external reaeration. Construction of a series of weirs to improve the reaeration at the critical points and increase the DO concentration.

1.7 Research Hypothesis

Hypothesis for developing a water quality management approach for the conservation of Urban River reaches are as follows:

- Null Hypothesis(H0): There is no significant relationship between the stream water quality and the use of an effective approach for the management of stream quality using a water quality model.

- Alternative Hypothesis (H1): There is a significant relationship between stream water quality and the use of an effective approach for the management of stream quality using a water quality model.

CHAPTER 2

LITERATURE REVIEW

2.1 General

Developing a management strategy for urban river ecosystems can positively influence the country's socio-economic conditions and environment. Establishing a robust infrastructure for wastewater treatment plants and sewerage lines, while initially impacting the economy and the livelihood of the surroundings, can lead to significant long-term benefits. Therefore, a management approach must be formulated to restore the degraded urban river reach by revitalizing the baseline ecosystem with biotic and abiotic components. The increasing global awareness of the importance of water body management and the subsequent introduction of new rules aimed at restoring the ecology is expected to strike a balance between short-term socio-economic concerns and long-term investments in water quality (Willis et al., 2002). The implementation of sustainably managed policies will involve a series of comprehensive decisions (McIntyre, 2004). Water quality management aims to regulate the quality of aquatic bodies within permissible limits and offers a promising path forward. There are two approaches for managing waterbodies: technology-based, which assumes aquatic bodies have sufficient dilution capabilities and limited contaminant loading, and water-quality-based approaches, which design the discharge permit to maintain the receiving water quality (Creek, 2004). The aims of water resources management are threefold: i) restoration of modified or exploited water bodies, ii) conservation of sensitive waterbodies from actions that are deteriorating them, and iii) intensification of the waterbodies' aquatic bodies by modifying characteristics (Elshorbagy et al., 2005). The best management plan is the approach that implies one or more of these objectives. Water quality management approaches such as the TMDL process and water quality models can predict pollutant load (Chapra, 2003). Technological and computation systems have improved, and models have become more intricate and diversified (Thomann, 1998). These models are coordinated with a decision tool to assist in adopting measures for water quality management (Chapra, 2003). This study established a water quality development plan using flow augmentation and load modifications with a water quality model. This chapter includes an overview of the water quality assessment, Reviews of water quality models, assimilation capacity, TMDL assessment, and water quality management plan.

2.2 Literature Review on Water Quality Assessment

Rivers are the most sensitive natural resources, carrying domestic, industrial, and agricultural runoff from the large watershed (Zhang et al., 2009). The river conditions rely on natural and anthropogenic activities such as precipitation, erosion, municipal waste, land use patterns, urbanization, industrialization, agricultural flow, and mining (Yilma et al., 2019). The combined effect of these activities deteriorates the surface water bodies, which need (Wang et al., 2013) appropriate management options. Vegetation, topography, geological characteristics of the catchment area, seasonal variation of the precipitation levels, surface runoff, ground surface interaction, interception, and abstraction promote a water body's water quality parameter (Avtar et al., 2013). The spatiotemporal assessment of river water quality requires regular and continuous monitoring programs to estimate and maintain (Singh et al., 2004). This monitoring creates vast and complex data matrices composed of many physicochemical constituents, which are challenging to interpret and conclude (Singh et al., 2004; Bonansea et al., 2018). A reliable river quality assessment framework is required to minimize the impacts of pollutants and protect a river's ecological health and sustainable expansion (Arora & Keshari, 2021b). Nowadays, principal component analysis (PCA) and factor analysis (FA) are widely used to assess river characteristics by simplifying complex data, removing spare information, and keeping valuable information (Bonansea et al., 2018). Multivariate statistical techniques create a matrix from acquired data to assess relation, likeness, and unlikeness (Singh et al., 2004) among the constituents and their origin (Achieng' et al., 2017). The PCA and CA help to distinguish potential pollutant sources affecting water resources and provide a unique understanding of the relation between different pollutants (Lkr et al., 2020; Wang et al., 2013). These methods are essential to verifying spatiotemporal variation generated by various natural and manmade factors (Shrestha & Kazama, 2007; Vega et al., 1998). PCA/FA is used to assess river quality, identify pollutant sources, and as a tool for water resource management (Atakoglu & Yalcin,2022; Dehghanzadeh et al., 2015). PCA reduces the dimensionality of factors and keeps all related information of corresponding constituents (Singh et al., 2004).

Kannel et al. (2007) used water quality indices and DO as the benchmark for identifying the quality of the Bagmati River, Nepal, for 1999-2003 and assessed the impact on urban areas. A data matrix was obtained from five years of data, and the water quality index and effective WQI identification were examined, as well as the spatiotemporal variation of water quality parameters. Four well-managed seasons have been adopted. Song and Belin (2008) Studied the number of factors in FA for data with missing values. Models AIC and BIC were combined to develop a factor model, select the number of factors, and estimate the parameters. Developed and existing methods were compared for an actual data set with known factors. It was concluded that the developed model showed the corrected number of factors with known factors. Koklu et al. (2010) assessed the water quality of the Melen River of Turkey using multivariate techniques. Twenty-six parameters from five monitoring points of 1995-2006 were collected. PCA, FA, DA, and multiple regression analysis were applied to assess the relationship among the parameters, extract significant parameters, and expose the factors. Fulazzaky et al. (2010) assessed the Selangor River, Malaysia's river status, using WQI. The river water has been degraded due to wastewater from poultry, municipalities, and industries. Data collected from nine stations showed that the river is highly polluted. The study was done to find vulnerable parameters and sources of pollutants and recommend the required measures to be contemplated by the local authorities. WOES has been used for this purpose, transforming the data into a working form and indicating the level of deterioration. Bu et al. (2010) evaluated the water quality of the Jinshui River, China, using cluster analysis (CA), Discriminant analysis (DA), and factor analysis (FA). The study concluded the spatial variation of physical and chemical characteristics discriminant variables and identified the factors responsible for water contamination. Twelve sampling locations were placed, and four samples were collected. Three clusters were generated during CA. Three discriminated groups were generated from nine variables. Cluster 1 has the upper stream locations, and Clusters 2 and 3 have the middle and lower locations. Clauter 3 has only one station where wastewater from bankside eateries was presented and ascribed that treatment without treatment. Results obtained from DA also agreed with the same as those of CA. Three zones mentioning no pollution, moderately polluted, and highly polluted areas have been identified. The five varifactors explained 90.01 % of the variance, including chemical components, oxide-related processes, natural weathering, and decomposition processes. The study concluded the importance of multivariate techniques for water quality management.

Chigor et al. (2012) studied water quality assessment for surface area sources of Zaria, Nigeria, for March-December of 2002, and 228 samples were collected from 12 monitoring locations. The population of this area is habituated with open defecation, and domestic sewage is disposed of without treatment, resulting in surface runoff with contaminants disposed of into the river. The coefficient correlation was derived. Students t-test was applied parameters. The polluted segments of the river reach contain foul odors, rubbish, effluents with color, and waste from surface runoff. High temperatures are found during the wet and dry season. No correlation was found between fecal coliform and temperature, mentioning low coliform count. Low pH value observed in the dry period. A low pH value was observed in one place due to acidic discharge from a fisherman's cottage. The Samaru stream, ABU dam, and Kubanni River were polluted by fixed and diffused sources. Avtar et al. (2013) assessed the groundwater quality of Bundelkhand by using PCA and FA. Heavy construction works have changed the land use pattern, water flow, and ecological balance. Groundwater qualities and soil chemistry must be investigated before constructing an intertwined canal between the Betwa and Ken Rivers. Therefore, this study evaluated the significant ions present in the groundwater with multivariate statistics to evaluate boundary conditions, flow paths, and hydrogeochemical substances. Grids have been generated according to sample collection activities. Samples were collected from different wells and identified locations using GPS III, Garmin. A portable Orion Thermo water analyzing kit (Model Beverly, MA, 01915) with a precision of 1 % was selected for all on-site evaluations. Multivariate analysis was done with SPSS, and water type was determined with AqQA. Overall, groundwater conditions were acceptable, excluding a few points with high nitrate and fluoride. PCA concluded that the reason for the presence of metals and ions in the groundwater is agricultural and industrial activities, which are manmade actions, and geological effects, which are natural processes. Heavy metals infiltrated during recharge, and high Ca ions were present due to carbonate weathering. Aquifer conditions have been analyzed using sediment chemistry. It has been concluded that significant geochemicals occurred due to weathering, ion exchange, oxidation-reduction, and dissolution. Gupta et al. (2013) analyzed the water quality of the Godavari River basin by applying CA, DA, FA, and PCA to provide details of the water quality parameters and the sampling sites. Water quality data and seven parameters were collected from 78 stations for 2007-2009. Except for 2 stations, the WQI of all the stations was average to excellent. CA developed four clusters, and group 4, comprising 27 stations, was cleaner as BOD and coliform were lower. PCA recognized three factors. DA concluded pH and BOD were significant parameters. Venkatramanan et al., 2014, demonstrated the Nakdong River (Korea) quality using CA, FA, WQI, and correlation analysis. PH, DO, BOD, COD, TP, TOC, TSS, NH_4-N, NO_3-N, PO_4-P, Chl.α, and C were studied for fourteen river locations. The study assessed the correspondence of these parameters with the possible source of pollutants. The high nutrients found downstream reveal agricultural and industrial activities near the area. Due to high BOD, NH_4-N, and PO_4-P, the DO (Song & Belin, 2008) is depleted fast and creates anaerobic conditions. A positive correlation between the parameters showed that their source of origin was similar, and a negative correlation between DO and temperature indicated that if temperature is high, a reduction of DO is happened in the water. The river's water quality was suitable for industries and irrigation only. The FA and CA studies concluded that the sources of pollution are surface runoff, erosion, microbial activities to increase BOD, direct dumping of waste, and industrial wastewater increased BOD, COD, and NH_4-N. Gupta et al. (2014) assessed the water quality of the Mandakini River in India through multivariate statistics, which is the significant river of Chitrakoot, fulfilling the water demand for the locality. The temperature was higher than 26 degrees and showed less DO concentration. pH value was more elevated, and it was concluded that alkaline water. Turbidity was mainly within the permissible limits except in some cases. HCO_3 ion was highest, and F ion was lowest in concentration. Hardness was higher. Nitrates and DO values were within the permissible level. BOD was more elevated at RG ups and RG down. Calcium cation was the highest. The study concluded that bathing and domestic sewage were the leading causes of water pollution. Parmar & Bhardwaj (2014) ARIMA model and statistical analysis were applied to manage the water quality of the Yamuna River at Hathnikund, Haryana, India, for the 10 years of data collected from CPCB. Predicted data from the model has been compared with the observed data. Temperature and pH were higher than the WHO limits. Achieng' et al. (2017) used multivariate techniques to predict the water quality of physiochemical parameters for the River Sosiani, Kenya, dry and wet seasons. Besides pH and DO, all the parameters' concentrations grew high downstream. Cluster analysis and factor analysis have been done to determine the reason for pollution, and nutrients and organic pollution are assessed. Numerous effects of contaminants, environmental changes, and complex behavior of waterbodies generating data could be evaluated with multivariate techniques. Singh et al. (2020) assessed the spatiotemporal variation of Kali River water quality using the multivariate statistical method and water quality index to ascertain the pollution sources. Seventeen sampling stations were set, and it was found that the first eight stations' water quality was less polluted. Pollution started from s9 and severely increased after s13 due to wastewater from Sugar mills and other industries in Muzaffarnagar. Using R software, the principal component analysis, Pearson correlation, cluster analysis, water quality index, comprehensive pollution index, and Numerous indexes were used to determine the physiochemical and metal pollution. Downstream water quality was deplorable, and corrective measures must be adopted to upgrade the water quality. Tyagi et al. (2020) depicted the water quality index (WQI) as a decision-making tool for water quality assessment and determined the required treatment for getting the desired criteria. This paper reviewed the developed WQI and highlighted the requirements for a new, simplified WQI. The strengths and limitations of some WQI have been analyzed and, based on required improvements, have been suggested.

Kaur et al. (2021) assessed the water quality of the Yamuna River in the Panipat district, Haryana, to identify the footprint of wastewater generated from the urban area disposed into the river. The study used CCME-WQI, NSF-WQI, and HCA methods to recognize the vulnerable zones. Points sources have been attributed to this study. River quality and the Panipat drain quality were assessed for the further use of irrigation and industrial purposes. Urban land use patterns deteriorated the river quality. The Panipat drain pollutes 31.8% of the stretch of the river. Before entering the Panipat drain, the river water is suitable for irrigation. Due to high corrosivity, the river and drain water were unsuitable for industries. In dry seasons, due to low flow, water was unacceptable. Khullar & Singh. (2022) assessed the water quality of River Yamuna in Delhi using the deep learning method. A Bi-LSTM model has been developed, which can produce missing data. Statistical accuracy was checked, and forecasting was done using the monthly data of different locations in Delhi for the monthly data of 2012-2019. The study aimed to assess the water quality by collecting samples from other places, dealing with the missing values, initiating a new LSTM framework comprising an optimization system to reduce the missing value errors, and examining the strength of the new framework. This research implements a time series of single one-dimensional constituents. The study concluded that the developed model could be included with a water quality model and forecast the constituents more correctly.

2.3. Literature Review on Water Quality Models

Predictive reliabilities of water quality models are gravely constrained in ascertaining the intricate environmental functions (McIntyre, 2004; Chen et al., 2007). Excessive nutrients, organic matter, toxic chemicals, and heavy metals from adjacent watersheds destroy water sources. Water quality models assist in understanding the loading of the pollutants and can express the fate of the contaminants with time and distance. Water quality models integrate physical, chemical, and biological information related to loadings (Chapra, 2011). These models help to understand the systems' environmental and conceptual parts. Moreover, it can visualize water bodies internally to provide management decisions (Knightes et al., 2019). Starting from Streeter Phelps (1925), the water quality model evolution is divided into four phases (Chapra, 2011). The first stage of water quality modeling began from 1925 to 1960. The first water quality model originated to assess the water quality of the Ohio River of the USA, to assess the dissolved oxygen concentration for point sources, and to determine the relationship between wastewater loading and accumulation in receiving water. In this stage, one-dimensional steady-state flow with bacteria and BOD loading were considered an analytical method to determine dissolved oxygen depletion. The second phase was from 1960 to 1970; due to the inventions of computers, complex numerical models were developed for 1 and 2-dimensional systems like streams and estuaries for primary and secondary effluent. The third phase was from 1970 to 1977 when multidimensional systems with high nutrient loading assessed eutrophication. The last stage was from 1977 to 1990 when toxic and acid rain-related pollutants simulated the multi-systems particle water and water-food interactions. These models addressed numerical and analytical solutions. After these four phases, more comprehensive and interlinked water quality models with scientific and computing advances developed. These models can simulate loads from point sources with a well-defined entry point, such as drains and tributaries. Additionally, non-point sources do not have identified entry points, such as atmospheric deposition and surface runoff. With improved computer technology and widespread internet facilities (early 2000 to present), models analyze temporal and spatial environmental variations with the accessibility of more data, more complex water bodies, and the maximum number of pollutants (Wool et al., 2020). Currently, water quality models have improved with the advancement of technology. The receiving water quality models link watershed models, mainly simulating non-point source loads (Camacho et al., 2015). Different governmental organizations have developed these models, teamed with educational and consulting agencies. However, selecting a model is problematic due to the need for an adequate understanding of the numerical and analytical conditions, data necessity, strength, assumptions, and constraints of the available models. The development of modeling techniques has been reviewed by (Camacho et al., 2015). Olowe & Kumarasamy. 2018, reviewed principles of different water quality modeling and their aspects for waterbody conditions. Cox (2003) has reviewed six water quality models, SIMCAT, TOMCAT, QUAL2E, QUASAR, MIKE-11, and ISIS, and checked the potentiality of these models for the simulation of dissolved oxygen in low-land rivers (Cox, 2003). At the same time, Kennel et al. (2011) reviewed SIMCAT, TOMCAT, QUAL2Kw, QUAL2EU, WASP7, and QUASAR for rivers. Sharma and Kansal (2013) also discussed models and provided comprehensive approaches for selecting a model. Among these models, BLTM, SIMCAT, QUAL2EU, WQRRS, and QUASAR are rarely employed in recent water quality management research. Costa et al. (2019) listed AQUATOX, EFDC, QUALS, SPARROW, SWAT, and WASP as being widely used for the last 21 years. Camacho et al. (2019) reviewed the models evaluating dissolved oxygen availability, dynamics of phytoplankton, and eutrophication, including carbon and nutrient cycling processes, and simulated the fate and transport of toxics (Camacho et al., 2019). The present study reviewed some water quality models implemented to measure waste load and TMDL analysis studies in recent years. EPA (2019) (TetraTech Inc., 2018) selected some water quality models as a mechanism for the total maximum daily load assessment. These are AQGNPS, AQUATOX, BASINS, BATHTUB, CE-QUAL-W2, CE-QUAL-ICM, EFDC, HEC-RAS, MIKE11, QUAL2KW, SIMCAT, SPARROW, SWAT, SWMM, SW TOOLBOX, TOMCAT, VISUAL LUMES, WASP, and WQRRS. TOMCAT and SIMCAT. These models can assess point and diffused sources of contamination, whereas AQNGPS can assess agricultural non-point sources. The AQNGPS model helps with management options for reducing soil erosion and controlling floods and droughts (Jirasirichote et al., 2021). AQUATOX can simulate nutrients, sediments, algae, aquatic vegetation, fish, and invertebrates. The model can assess parameters like DO, pH, temperature, solids, nitrogen, and phosphorous (Jirasirichote et al., 2021). BATHTUB simulates morphologically complex reservoirs and lakes, predicting current water quality and determining TMDL for lakes (Region et al., 2013). However, BATHTUB cannot indicate the water quality for surface water bodies. At the same time, QUAL2Kw is more suitable for streams as it can interact with macrophytes and decayed algae to carbonaceous biochemical oxygen demand (Ranjith et al., 2019). QUAL series models are also easily accessible, frequently upgraded, and simulate the maximum number of parameters (Sharma & Kansal, 2013). However, extensive data has been required for AQUATOX, QUAL2Kw, and WASP (Sharma & Kansal, 2013). Additionally, AQUATOX establishes pollutants' direct and indirect effects on organisms (Ejigu, 2021). EPD-RIV1 has the most comprehensive water quality algorithm, but it does not include sediment transport (Sharma & Kansal, 2013), which influences the dissolved oxygen of the stream water (Park et al., 2013). The USEAPA declared the EFDC model a water quality management tool (Wang et al., 2013). QUAL-ICM can simulate biochemical, oxygen, nitrogenous, and phosphorous cycles, but it cannot simulate the hydrodynamics of a waterbody (TetraTech Inc., 2018). However, CE-QUAL-ICM can incorporate CH3D and EFDC and compute 36 water quality parameters (Camacho et al., 2019). BASINS is an integrated system for simulating all pollutant sources (Wang et al., 2013). SWAT, AQUATOX, PLOAD, and HSPF. MIKE models are used for all types of water bodies, whereas the QUASAR model is appropriate for the DO simulation for large rivers (Wang et al., 2013). SIMCAT needs limited data, but sediment oxygen demand, photosynthesis, and temporal variability are not accommodated (Ranjith et al., 2019). CE -QUAL-W2 is a 2- dimensional model assuming lateral homogeneity suitable for long, narrow rivers, lakes, and estuaries (TetraTech Inc., 2018). EFDC includes hydrodynamics, toxic contaminant transport, water quality, and the eutrophication model (Chen et al., 2017; Wu & Xu, 2011). However, it has been used successfully for TMDL analysis (Seo et al., 2010; Chen et al., 2017). Sparrow incorporates point sources, soil type, and land use patterns by utilizing the multivariable regression method to analyze the water quality. However, the SPARROW model helps assess the transport and fate of nutrients and hydrological and biogeochemical effects (Saleh & Domagalski, 2015). SWAT is an agricultural watershed management tool that evaluates soil erosion, control, and input non-point sources. However, SWAT cannot assess the maximum daily flow and runoff (Olowe & Kumarasamy, 2018). Although there are some limitations, all of these models are used worldwide. This study discussed some models depending on their uses and the management of different water bodies, and these water quality models are AQUATOX, QUAL2Kw, WASP, CE-QUAL-W2, EPDRIV1, MIKE11, and HEC-RAS. Reviewed water quality models are public domains and primarily mechanistic. These models are used for stream and river management projects and TMDL analyses.

2.3.1 MODEL REVIEWS

2.3.1.1 AQUATOX

Model development

AQUATOX is a simulation tool to evaluate the destiny of pollutants and ecological risk assessment for water resources (Park et al., 2008) and better understand an ecosystem's physical, chemical, and biological relations. AQUATOX is the newest version of the water quality model, starting with the ecosystem model CLEAN and incorporating algorithms from models like CLEANER, LAKETRACE, MACROPHYTE, PEST, and TOXICARE PART (Clough, 2014). 1990his model was linked to the Microsoft Windows interfaces, providing more flexibility and user-friendliness (Clough, 2014). In 2002, EPA first released AQUATOX 1, and then after more development, a new version of AQUATOX 3.2 was available by adding more variables. AQUATOX 3.1 plus was formed in 2014 and included external nutrient limitations(Clough, 2014). AQUATOX 3.2 is freely available on the EPA websites developed in 2018 (EPA Website, 2021)and can simulate twenty parameters (Olowe & Kumarasamy, 2018).

Model process

AQUATOX can compute biomass transfer from one compartment to another and simulate multiple environmental stressors (organic loadings, nutrients, sediments, temperature, and toxic chemicals) and their effects on aquatic biota such as macrophytes invertebrate, algal, and fish communities. The model predicts the relationships between the physio-chemical environment and biological processes. It represents all surface water bodies. The model requires loading characteristics data, general site characteristics including hydraulic and hydrological data, biological characteristics of the aquatic plants and animals, and chemical characteristics of any organic toxicant. The model uses the principle of Runge-Kutta integration methods to correct the error in the fourth-order resolution and differential equations of the fifth-order. The model assumes that the water body comprises different well-mixed parts and average flow data is used for analysis (Olowe & Kumarasamy, 2018). Fig. 2.1 shows the conceptual Model for AQUATOX.

Strength

This model analyses the aquatic system with minimum site-specific information and represents the system successfully (Akkoyunlu & Karaaslan, 2015). It can describe the conditions and impacts of toxic organic chemicals, conventional pollutants, and attached and planktonic algae. This model uses a daily timescale to analyze physical conditions such as flow, light, and sediment for aquatics. The environmental threat assessment model considers the sorption and bioaccumulation of organic toxicants (Clough et al., 2017). It simulates up to 20 organic chemicals simultaneously. AQUATOX simulates toxins, nutrients, biomass, aquatic living organisms, TSS, BOD, DO, bioaccumulation factors, and food webs as indirect effects (Akkoyunlu & Karaaslan, 2015; Zhang & Liu, 2014). It is freely available (Clough, 2014) and creates an integrated part of the BASINS system.

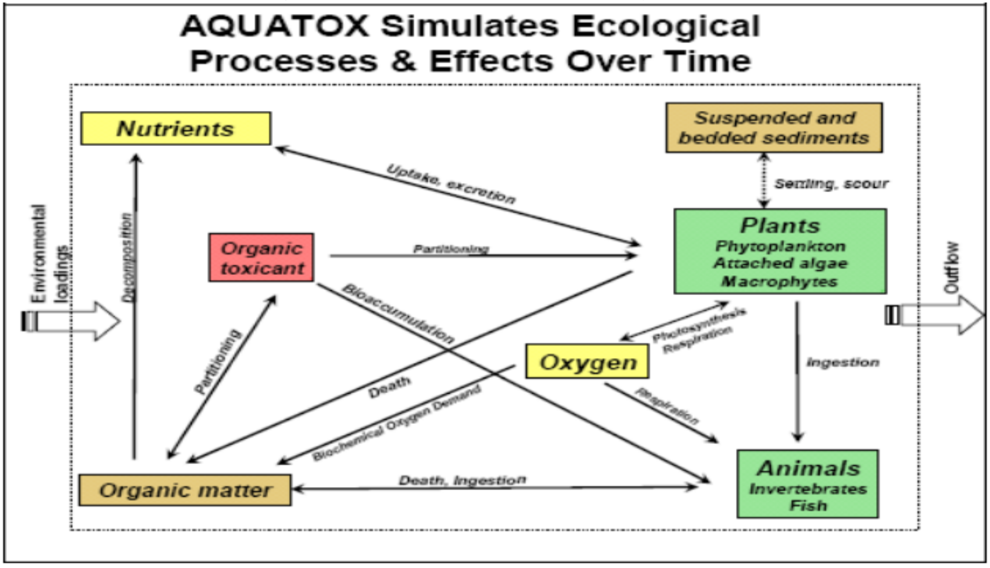


Figure. 2.1 Conceptual Model for AQUATOX (AQUATOX 3.1, 2014)

The newest version, AQUATOX 3.1, includes the nominal range of the sensitivity analysis range as a built-in. Sensitivity analysis is compared using an automated "tornado diagram," which is examined by a reverse tornado diagram (EPA website, 2021). AQUATOX also quantifies and evaluates model uncertainty by varying the values or statistical distribution of multiple input parameters. Coupled with other hydrological and hydrodynamic models, AQUATOX simulates more complex aquatic systems (Niu et al., 2016). This model is used for TMDL determination and water quality management. This model treats biota-integrated parts of the environmental system of water bodies and hence models the bioaccumulation of toxicants and their effects on biota, which is not accumulated in other water quality models. AQUATOX is the only model simulating the response of periphyton to nutrients, flow, and grazing (EPA).

Assumptions and limitations

AQUATOX assumes that each segment is well mixed and has an identical set of state variables. Linkages between elements are considered either unidirectional or bidirectional. The model has many parameters and requires extensive calculations and time (Niu et al., 2016). It is unsuitable for fully ionized substances (Lombardo et al., 2015) and cannot simulate metals and organometals. Moreover, the assumption is a unit volume while simulating the water body's nutrients, sediments, and other chemicals (Olowe & Kumarasamy, 2018). Overall, AQUATOX requires high data, and it is a complex box-type model where interactions are not visible (Clough, 2014). In addition, detritus matter is defined together with non-living organic matter and decomposers (Costa et al., 2021).

Applicability

The model is used to manage the ecosystem and evaluate the causes of biological impairment by predicting and assessing the effects of toxic substances. The model improved the water quality for Megan Lake, Turkey, and analyzed the future scenario of the conventional parameter to improve the water quality (Akkoyunlu & Karaaslan, 2015). The Mississippi trustees used this model to evaluate ecosystem impairment and recovery quantitatively (Clough et al., 2017). Additionally, this model was used to control the water quality of a lake (Zhang & Liu, 2014) and it was concluded that it could warn early about the fate of pollutants and help manage the water bodies. The model can simulate nutrients, organic waste, toxic sediment substances, macrophytes, and periphyton (Olowe & Kumarasamy, 2018; Anyadike, 2013). The model was used for the Vimtim stream in Nigeria and stated that it is quite applicable to analyzing water quality. Moreover, it has been used successfully in streams, rivers, lakes, estuaries, and ponds. Rashleigh. (2003) applied AQUATOX to Contentnea Creek in the coastal plain, North Carolina, assessed the stream ecosystem for some pollutants, and suggested using the model in other areas. The AQUATOX model simulated landscape lakes in Tianjin, China, and evaluated the management options for different scenarios (Niu et al., 2016). Hence, the model is suitable as a river management tool. Overall, this model is ideal for simulating the pollutant stressors in different water bodies.

2.3.1.2 WASP

Model development

Hydroscience, Inc. developed the model WASP in 1970, and the Large Lakes Research Station (LLRS) of the US Environmental Protection Agency later adopted it for the Great Lakes assessment. After 50 years of development, WASP8 is available freely on the USPEA website. The model can simulate the physicochemical parameters of large rivers, lakes, and estuaries (Wool et al., 2020) with interlinking hydrodynamic, eutrophication, and toxic chemical modules. It can simulate sediment transport, water transport, macroalgae, periphyton, eutrophication, pH, alkalinity, water temperature, and light. The model includes two modules to analyze conventional and toxic pollutants. Since its development, the model has been used worldwide to manage water bodies and for research purposes (Ambrose & Wool, 2001; Wool et al., 2003).

Model system

WASP understands and predicts the future conditions of pollutants using a mass balance framework occurring in waterbodies from natural and anthropogenic activities occurring in water bodies. This model can simulate various pollutants in 1D, 2D, and 3D systems. The fundamental strategy includes time-varying advection and dispersion processes, mass loading for point and diffused sources, boundary exchange with the variable compartment, and spatial and temporary mass conservation. Fig. 2.1 represents the mercury conversion of the water column and sediment. The WASP has a graphical user interface with a preprocessor, creates input datasets for multisession and run-time diagnosis, and automatically imports hydrodynamic model interface information (Ambrose &Wool, 2017). It also has a postprocessor system to visualize output results and analyze or compare field values and simulation values for confirmation testing. WASP 8 contains two water quality modules to simulate contaminants: the Advanced Eutrophication module and the Toxicant Module. The Advanced Eutrophication module analyses all conventional pollutants, such as dissolved oxygen, nitrogen, and algae. At the same time, the Advanced Toxicant module can simulate dissolved substances, nanomaterials, organic carbon, mercury, temperature, salinity, and bacteria. WASP can interlink with a hydrodynamic model such as EFDC (3D), DYNHYD (1D, branching), RIVMOD (1D, no branching), CE-QUAL-RIV1 (1D, no branching), SWMM (1D, branching) and avail the transport or hydrodynamic variables information (Cope, 2019). To simulate the impact of hydraulic changes in surface water flow on groundwater flow, this model adds MODFLOW and MT3D (Jia et al., 2015).

Strength

WASP has an adjustable modeling system that can predict water quality in 1D/2D/3D. Users can configure the particular problems with available input data and simulate conventional and toxic pollutants (Wool et al., 2006). The model analyzes the fresh and saline water quality. The volume control structure enables the mass conservation principle and links with hydrodynamic and watershed models. WASP8 lets the modeler inspect the results when the model runs (Wool et al., 2020) and has a plug-in with QGIS. The model downloads data to the preprocessor and assists the BASINS systems.

Assumptions and limitations

The mass balance equation used in this model framework represents finite difference methods. A wholly mixed finite segment is adopted, called the integrated standard volume (Sharma & Kansal, 2013). Transport information produces and requires linkage with external hydraulic and hydrodynamic models. The model cannot analyze mixing zones near fields and sinkable or floating materials. (Kannel et al., 2011). In addition, sediment flux is simplified and cannot simulate periphyton and macroalgae (Costa et al., 2021). WASP requires a hydrodynamic model plug-in to affect the flow and ample time to calibrate.

Applicability

The WASP can simulate fresh and marine water resources with highly complex systems. The model supports TMDL studies and is the world's most commonly used waste load and TMDL allocations model. Some applications are assessing nutrient pollution in Tampa Bay, Florida (Wang et al., 1999); nitrogen and phosphorous compounds in the Neuse River Estuary, North Carolina (Wool et al., 2003) are the other scientific studies instead of the USA. This model can simulate solids for the Cape Fear River, Carolina. Chemicals and nanoparticles (Knightes et al., 2019). WASP determined the ammonia nitrogen decomposition rate for the Pusu River in Malaysia and successfully addressed maintaining river water quality (Nuruzzaman et al., 2018). Seo & Kim (2011) applied EFDC and WASP7 to Lake Yongdam, Korea. This model has been successfully used with an integrated HSPF model for the Feitsui reservoir in Taiwan for catchment reservoir management (Chen et al., 2021).

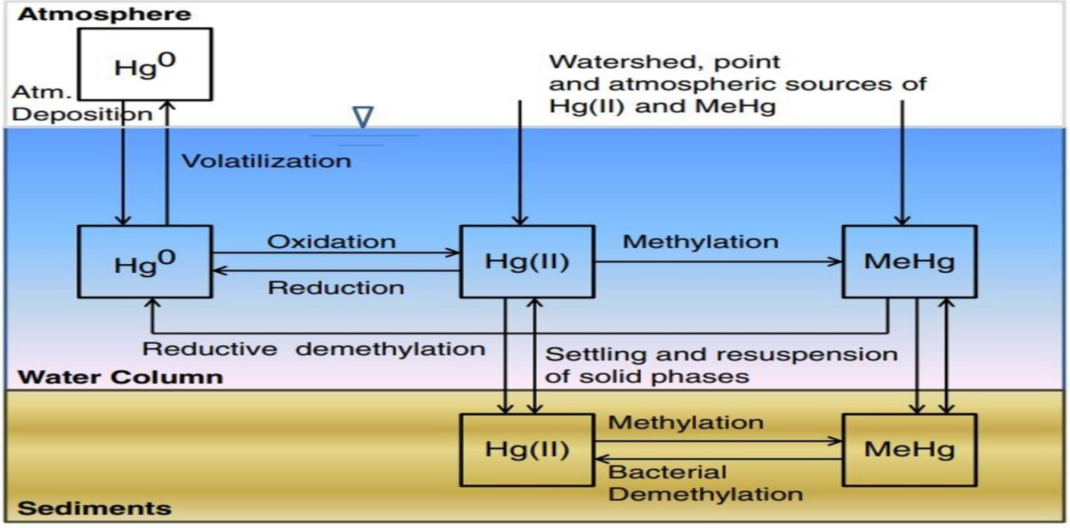


Figure 2.2 Mercury conversion of the water column and sediment (Camacho et al., 2019)

2.3.1.3 CE –QUAL W2

Development

CE-QUAL-W2 is a 2D hydrometric framework coupled with a water quality model. It is suitable for prolonged, thin water systems with longitudinal and vertical variations (Cope, 2019). The initial model, developed in 1975, was named the LARM (Laterally Averaged River Model). Extending from the 1.0 version, version 4.5 is now available (user manual CE-QUAL -W2 Version 4.5).

Model process

This model's data requirements are geometric information, boundary information, hydraulic and kinetic parameter values. The longitudinal and vertical spacing, segmental length, cross-sectional width, and slope of the waterbody specify a computational grid. Boundary conditions data assess the model during calibration. Estimating the quantity and types of data necessary to adequately represent and comprehend waterbody conditions and develop the required database to support the model is needed. Earlier versions of CE-QUAL-W2 simulated the flow and temperature, nutrients, and algal conditions and allowed 20 water qualities, including concentration, flow patterns, hydrodynamics, and temperatures (Martin, 1988). In recent versions, inorganic solids, particulate biogenic silica, degradation of generic elements, total dissolved gases (TDG), tiny aquatic organisms, nonconservative alkalinity, and a sediment diagenesis model (Kannel et al., 2011) can be simulated. Moreover, Cope (2019) outlined that the current version permits the selection of the volume and types of algae and adds parameters for periphyton and macrophytes. Epiphyte growth rate multipliers can be computed based on light availability, phosphorus, nitrogen, and silica. The Epiphyton biomass includes the light-limited self-shading Epiphyton, and the rate shows both natural and predator mortality. This periphyton growth is a function of biomass limitation conditions and is limited to being exceeded by the nutrient supply over a given timestep. These periphytic burial rates also represent the dead cells' burial in the organic sediment compartment. In CE-QUAL-W2, the macrophyte model represents multiple submerged species by allowing nutrients from the water or sediments. Ammonia, nitrate-nitrogen, and inorganic phosphorus are the nutrients simulating in CE-QUAL-W2. Additionally, phytoplankton respiration and dissolved organic matter (DOM) decay are also included in the source term. Fig. 2.3 represents the CE-QUAL-W2 Kinetics.

Strength

The model applies to waterbody segments by identifying upstream or downstream boundary states with multiple branching algorithms for complex aquatic bodies (Cole & Wells, 2011). The CE-QUAL-W2 model simulates hydrodynamic constituents such as elevations, speed, temperatures, and water quality parameters (Cole & Wells, 2011). Water surface elevation is computed with varying cells in a compartmental grid. Grid works as a fully 2D mixed reactor for different timesteps; multiple branches and cells represent complex water bodies (Edinger, 2003). Hydraulic structures, such as spillways and pipes, can also be analyzed. The model can simulate river and reservoir systems (Masoumi et al., 2016).

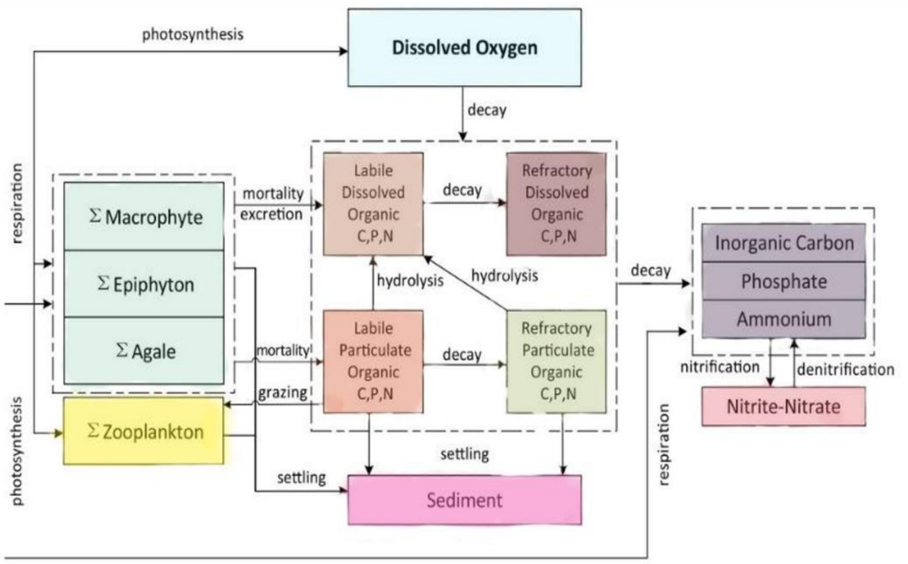


Figure 2.3 Representation of CE-QUAL-W2 Kinetics (Pdxscholar et al., 2003)

Limitations and Assumptions

The model assumes the variations of characters in the longitudinal and vertical directions and neglects lateral movements (Cole & Wells, 2011). These assumptions apply to relatively long and narrow water bodies. For hydrodynamics, equations assume as laterally. Variations in constituents such as velocities and temperatures are negligible. These assumptions are not suitable for waterbodies with lateral variations. Eddy coefficients model turbulence is user-friendly, and the user should decide on the required applications accordingly. The computations for upright momentum exclude and are inaccurate in waterbodies with acceleration or turbulence (Cole & Wells, 2003). The model is inapplicable for simulating Zooplankton and macrophytes, including sediment oxygen demand (Edinger, 2003). This framework assumes well-mixed in the lateral direction with a quasi-3-D mode by incorporating other models (Cole & Wells, 2011). Moreover, Sadeghian et al. (2018) concluded that the algal simulation quality was compromised due to oversimplified algal growth mechanisms.

Applicability

The model has been used in the USA and other countries (Camacho et al., 2019). The model links multiple optimization algorithms for maximizing the waste loading of the Karkheh River, Iran (Masoumi et al., 2016). It is a framework to assess the impacts of different factors, including temperature, nutrients, and organic in aquatic systems (Bowen & Hieronymus, 2003). Furthermore, CE-QUAL-W2 was used to predict the water quality of Lost Creek Lake, Oregon (Smith et al., 2012) and Applegate Lake, Oregon. Portland University reports that many countries' researchers use this model, and over 2300 documented applications are available (Cope, 2019).

This model was used to simulate the Pischin reservoir in Iran (Khodabandeh et al., 2021) coupled with an artificial neuron network and calculate the highest average amount of phosphate limits from three points. The model was used to simulate the water elevation and temperature for the Karkheh Dam reservoir in western Tehran and was found to have high potential use (Masoumi et al., 2021).

2.3.1.4 MIKE-11

Model Development

Danish Hydraulic Institute (DHI) developed MIKE11 in 1972 and distributed it as a modular package. The model is used worldwide for modeling flows, flood warnings, water quality, and sediment transfer in estuaries, rivers, and irrigation channels (Camacho et al., 2019).

Model system

MIKE-11 is a window-integrated graphical user interface that forecasts flood control, impacts of pollutant loadings, morphological changes due to sediment deposition, and the concentration of pollutants (MIKE-11 documentation). The model is a one-dimensional dynamic tool for managing and planning complex, straightforward waterbodies. MIKE-11 is an integrated structure with the hydrological module, advection-dispersion module, cohesive and noncohesive sediment transport modules, and various aspects of water quality. It is widely used for flood defense and as a water quality model for urban pollution management. MIKE-11 can be integrated with other DHI software and perform different modeling activities. To model a 2-dimensional system, it can also link with MIKE 21, and for surface water- groundwater modeling, MIKE SHE (Système Hydrologique Européen) can be integrated. In MIKE-11, water quality simulation occurs at six different levels, including first-order decomposition of BOD, DO; sediment exchange and oxygen demand; ammonium and nitrate balance excluding denitrification; added to the oxygen demand for nitrification, denitrification, delayed oxygen demand due to settled BOD; cohesive and noncohesive sediment processes (Cox, 2003)

Strength

MIKE-11 incorporates modules that simulate dynamic flows in waterbodies and apply them to branched and looped networks (Cox, 2003). MIKE-11 simulates the time series of flow, depth, and concentrations. The hydrodynamic module predicts flows in rivers and estuaries. Additionally, it simulates the solute transportation and transformations in complex river systems. The model simulates solute transport and changes in complex waterbodies. An advection-dispersion module simulates the transport of solutes, solving the equation of conservation of mass. The advection-dispersion module is also capable of simulating first-order decays of determinants. This application includes water quality modules for DO, BOD, ammonium, nitrate, nitrification, denitrification, eutrophication, heavy metals, nutrient transport, and wetlands. Modules can include sediment processes or exclude sediment processes.

Limitations and Assumptions

MIKE-11 is a 1D model assuming the flow is homogeneous throughout the water body. The flow is modeled using hydrodynamic equations. Data requirements are higher and more complex than a steady-state model(Panda et al., 2010). The model requires high time to run, is not straightforward, and needs extensive data. With limited data, MIKE-11 runs at different levels of water-quality complexity.

Applicability

In the United States, MIKE-11 is used along with MIKE SHE to predict minimum flow requirements, surface water-groundwater interactions, and ecosystem restoration (Camacho et al., 2015). MIKE-11 analyzes the tidal section, DO, BOD, sediment gas exchange, coliform bacteria, ammonia, and nitrate balance without denitrification (Tsakiris & Alexakis, 2012). Furthermore, the model can be used for point load, and a hydraulic model can be used for flood analysis and control using advection and dispersion equations (Tsakiris & Alexakis, 2012). Kazmi & Hansen. (1997) simulated BOD and DO for the Yamuna River in northern India. This model was also used for eutrophication problem analysis (Cook, 2012). Liang et al. (2015) assessed the groundwater interaction with the surface water with this framework.

2.3.1.5 HEC-RAS

Model Development

Hydrologic Engineering Center (HEC)- River Analysis System (RAS) is a software developed by USACE for 1D and 2D steady and unsteady flow measurement (HEC-RAS_6.0_Users_Manual, 2021). Since being publicly released in 1995, the model has been used in various studies. The model was developed to predict hydraulic simulation for an open channel network and different hydraulic structures, like bridges, culverts, spillways, and weirs. This model is freely accessible on the USACE HEC website.

Model Process

The HEC-RAS model is a tool that integrates a graphical user interface, separate interpretation components, data storage capacities, management processes, and mapping systems (User manual). Fig. 2.4 shows the kinetics of model HEC-RAC. This model has five modules consisting of 1-dimensional steady water flow, 1D and 2D unsteady flow modules, a movable unsteady sediment transport, and a water quality module. These modules can adopt geometric data representing the unvaried geometric and hydraulic computation routine. The steady flow module determines the surface profiles for the single gradual and steady river reach or a complete network of channels for the critical, supercritical, subcritical, and mixed flow. Energy and momentum equations are used in the model to calculate the energy losses and effects of bridges, culverts, dams, weirs, and other structures. The unsteady flow component simulates 1D, 2D, combined 1D, and 2D unsteady flow through an open channel network and floodplains for different water profiles and incorporates steady-state computations. The sediment transport component simulates 1D and 2D sediment transport and movable boundary calculations. The Water Quality Module performs detailed temperature analysis and water quality, including algae, dissolved oxygen, CBOD, dissolved orthophosphate, dissolved organic phosphorous, ammonium nitrate, and nitrate. Water quality modules are designed to calculate the effects of sinks and sources.

Strength

The steady-state module assesses the change in water surface profiles caused by channel modification, levees, and hydraulic structures at the water body. The unsteady components can analyze dam break and operation, levee breaching, and pumping stations. Water quality submodules such as nutrient simulation modules-NSM1 and NSM11 can be plugged in and simulate many water quality constituents. HEC- RAC can handle an extensive data set in an aquatic environment. The model simulates aquatic dissolved oxygen, algae biomass, nitrogen and phosphorous cycles, organic nitrogen, ammonium and nitrate-nitrite, and carbonaceous biochemical oxygen in a simple way with minimum state variables.

Limitations

The HEC-RAC model sometimes creates unstable numerical analysis during unsteady flow analysis for highly dynamic streams and rivers with steep or nasty slopes. It requires modules and submodule plug-ins for multidimensional aquatic systems. HEC-RAS NSM1 can simulate the transport of suspended sediments and only the net settling process (Zhang & Johnson, 2014).

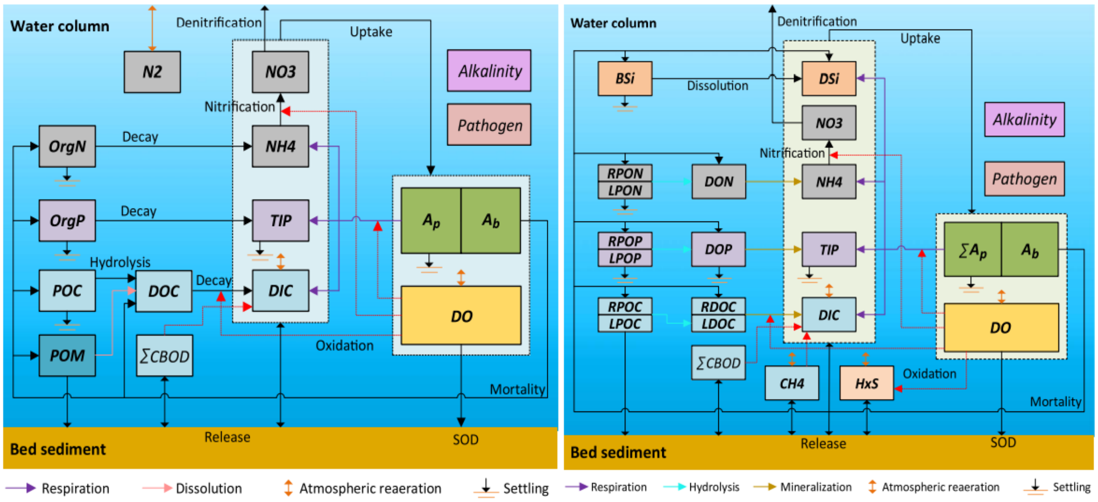
Applicability

The HEC-RAS water quality model analyzes water quality and TMDL. It is applicable in environmental-impact statement studies for the Ljungan River, Sweden, where flow variation dependence on aquatic species such as salmon was measured (Bustos et al., 2019). This model was used to predict water quality for the lower Minnesota River (Zhang & Johnson, 2014).

2.3.1.6 EPD-RIV1

Model development

The Environment Protection Department- One dimensional River (EPD-RIV1) is a cross-sectionally averaged, hydrodynamic framework. Ohio State University developed this model to predict the fate of stormwater runoff. The Environmental Protection Division (EPD), Georgia, reviewed the water quality models during the Chattahoochee River Modeling Project (CRMP), and the CE-QUAL-RIV1 model was selected. After many changes, the newer CE-QUAL-RIV1 improves capabilities by adding new features; exceptionally, to estimate the waste load allocations, the EPD- RIV1 model is established (Camacho et al., 2019).



(a) (b)

Figure 2.4: Water quality kinetics for (a) NSMI and (b) NSMII (Camacho et al., 2019)

Model Process

EPD-RIV1 is a 1-dimensional framework with two codes: hydrodynamic (RIV1H) and water quality code (RIV1Q), where the hydrodynamic code simulates water transport, and then the water quality model simulates the sixteen variables. This model predicts the flow and quality of highly unsteady one-dimensional streams and rivers. The model is based on the S.T. Venants equations, which consider the four points of the implicit finite difference method.

Fig. 2.5 shows the steps involved in the model process. The RIV1H code calculates river hydraulics in this model using geometric properties and boundary conditions. Using the RIV1H output, the RIV1Q code analyzes the water quality parameters. RIV1Q simulates up to 16 parameters. The model illustrates the interrelationship between these variables, outsider state variables, and highly unsteady flow (Olowe & Kumarasamy, 2018). Sharma & Kansal. (2013) concluded that it could simulate multiple branches and in-stream hydraulic structures to analyze the existing water body states, waste load allocation, and total maximum daily load allocation. The computer-based software has a computer system shell and preprocessor. It can analyze the longitudinal variations in hydraulic and water qualities and apply them to small lateral and vertical parameters. Additionally, the model solves the differential equations representing the variables as a time step of the day.

Strength

The model simulates hydraulic characteristics with flexible geometric specifications and time series. It simulates temperature, nitrogen, phosphorous, DO, CBOD, iron, manganese, algae, and coliform bacteria. The model analyzes the impacts of macrophytes on the oxygen level and nutrient cycle (Sharma & Kansal, 2013). Also, it explores water bodies with multiple branches, in-stream hydraulic control structures, waterways locks, dams, and regulating barriers with flexible time series input. It also simulates fixed and diffused sources by adding flows and constituent loading with the impact of withdrawals or diversions. Moreover, this model represents the recycling and combination rates of nutrients and the effects of toxic substances in aquatic systems.

Limitations and Assumptions

The model equations are considered cross-sectionally averaged, and lateral and vertical gradients are small and negligible. It applies to 1-D rivers with limited branches and highly changeable dynamic flow (Camacho et al., 2019). The assumptions are that cross-sections, bottom configurations, point source flows, diffused source flows, and concentrations of parameters are known. The model cannot analyze sediment transport and its influences on water quality. It assumes homogeneity in the cross-sectional area, which is rarely possible. The 1-dimensional assumption is invalid in regions without complete mixing. The model does not apply to sediment transport, toxins, or metals (Camacho et al., 2019). The model cannot simulate sediment transport processes and requires expert personnel to use the model effectively (Olowe & Kumarasamy, 2018).

Applications

The EPD-RIV1 is a 1-dimensional river system simulating fixed and distributed sources with highly dynamic flows. The model also simulates rivers' physical, chemical, and biological processes. It applies to predicting water quality constituents, including thermal stratification, macrophytes, and algae growth (Olowe & Kumarasamy, 2018). The Alabama Department of Environmental Management used the EPD-RIV1 model to determine TMDL in the Cahaba River (Creek, 2008).

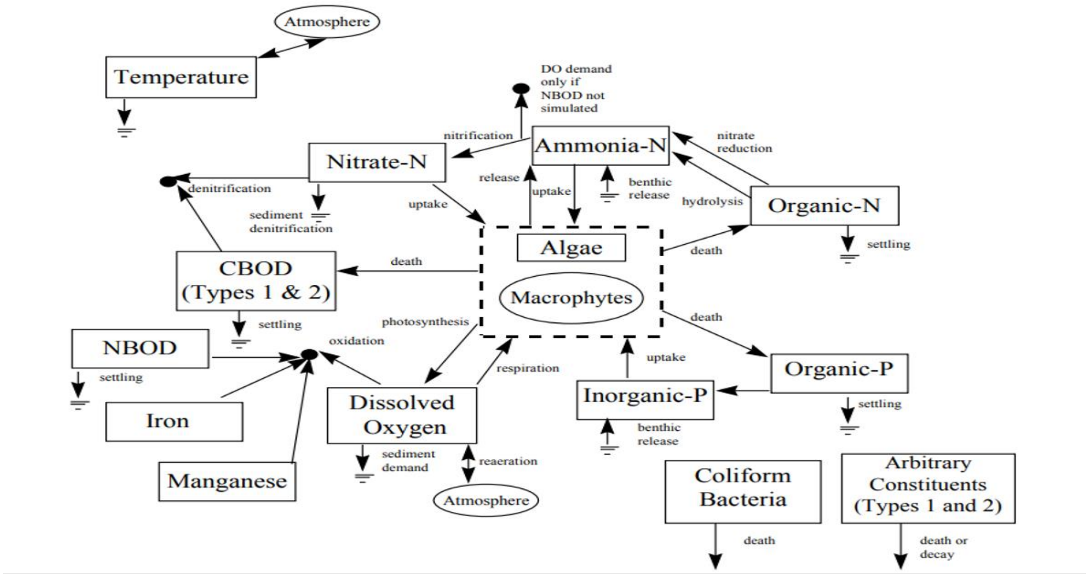


Figure 2.5 Conceptual model for EPD-RIV1(Burke & Martin,1990)

2.3.1.7 QUAL2Kw

Model Development

QUAL2Kw (Q2Kw), an advanced version of QUAL2E, started to develop in 2004 after modifying QUAL2K version 1.4. The latest version, 6 is available on the EPA website. Development is assisted by the Washington State Department of Ecology, parallel to the QUAL2K development (Cope, 2019). Park and Lee (2002) developed the QUAL2K model as an advanced version of QUAL2E to eliminate the shortcomings of QUAL2E (Park & Lee, 2002), where most model equations are unchanged, excluding equations for DO, BOD, and nitrate. QUAL2Kw (W for Washington) is the latest and most advanced version of QUAL2K, developed by Pelletier et al., 2006. It simulates bottom algae and the hyporheic zone. These two factors are essential factors for analyzing shallow rivers. For TMDL studies, Q2Kw is used as one of the leading modeling frameworks in Washington state for the temperature and nutrients of rivers (Carroll & O'Neal, 2006). Other states in the USA also adopted this model (Turner et al., 2009) to assist the TMDL programs.

Model process

QUAL2Kw version 5 is a model with 1-D, steady-uniform hydraulics, heat budget, kinetics, point sources, non-point sources, and abstractions included for simulation (Pelletier & Chapra, 2008). The newest version, 6, consists of a nonuniform unsteady flow system (Cope, 2019). QUAL2Kw version 5 follows one-dimensional, steady-uniform hydraulics. Heat budget, water kinetics, point and non-point sources, and abstractions include simulation (Pelletier & Chapra, 2008). The newest version, 6, consists of a nonuniform unsteady flow system (Cope, 2019). **T**he model can also use kinematic wave flow routing. Calibration is challenging in modeling, but QUAL2Kw has an autocalibration facility utilizing a genetic algorithm called PIKALA and automatically calibrates kinetic rate parameters within user-defined ranges (Pelletier & Chapra, 2008). Dynamic water quality kinetics with diurnal variables allow more accurate simulations of biochemical systems (Turner et al., 2009). In eutrophic systems, bottom algae and phytoplankton are essential to define water quality criteria, and QUAL2Kw can simulate both organisms(Turner et al., 2009). The model has the capabilities for Monte Carlo uncertainty and sensitivity analysis simulation by adding software YASAlw or Oracle Crystalball. Fig. 2.6 shows the steps involved in the model process.

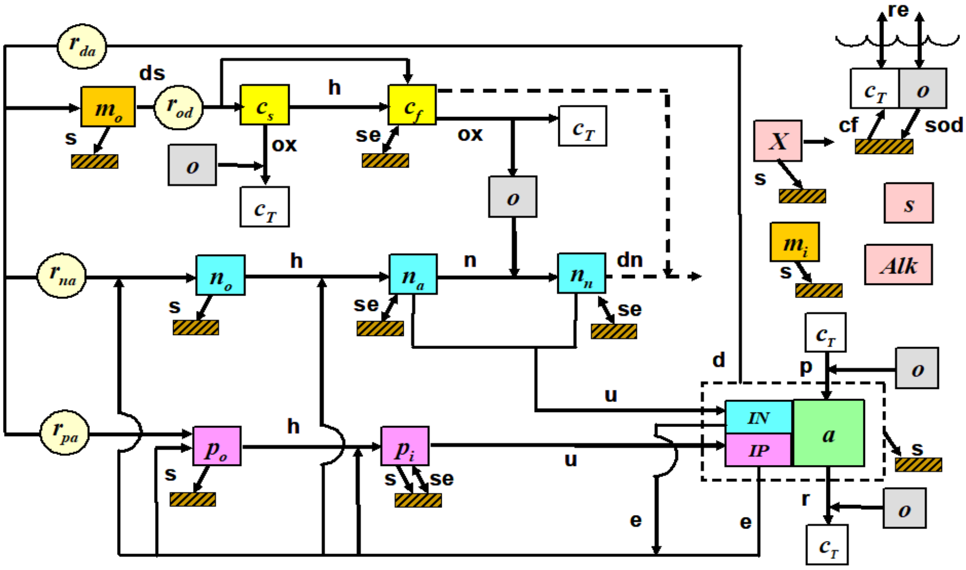


Figure 2.6 Conceptual model for QUAL2Kw (Qual2kw5_theory, 2008)

Strength

The framework predicts slow and fast CBOD. It satisfies anoxia by reducing oxygen levels to nil. Sediment oxygen demand and nutrient fluxes, bottom algae, light extinction, generic pathogens, and reach specific kinetic parameters are analyzed. Effects on gas transfer due to weirs and waterfalls can also be determined. It examines the water trading between the water column and the hyporheic zone. The model simulates the river with equal and unequal segmenting, sediment water flow for nutrients, and DO (Sharma & Kansal, 2013). Detritus inorganic solids and algae are assigned as predictors for light extinction. The system has an automatic calibration process.

Limitations and Assumptions

Although QUAL2Kw has a sound capability to simulate natural aquatic systems (Kannel et al., 2007), this model has limitations. One of the significant limitations is nonuniform mixing (2D or 3D); the model is one-dimensional, so it assumes a laterally and vertically mixed system. This model does not simulate metals, toxic substances, Zooplankton, macroinvertebrates, or ichthyoids. It does not analyze the adsorption and desorption of metals in the sediment zone and simulates only the river's main stem. The model uses time variation in water quality over diel cycles; otherwise, it is persistent all day. The model does not have a separate macroalgae routine. It does not simulate a reservoir system.

Applicability

QUAL2Kw is a water quality assurance tool that interacts with algal growth, nutrients, dissolved oxygen, and sediment oxygen demand. The model analyzes boundary conditions and nonconservative constituents with input-output consideration for steady and dynamic states and uncertainty analysis (Pelletier & Chapra, 2008). Moreover, it is a deterministic tool for waste load allocation and total maximum daily load analyses (Hobson et al., 2015). Although this model has some limitations, the application of QUAL2Kw is quite palpable in simulating water quality parameters like BOD, COD, DO, NH_3-N, organic-inorganic phosphorous, TSS, and temperature. Waste load assignments for BOD, CBOD, NH_3-N, PO_4, and DO have been evaluated. Countries like the U.S.A, Iran, Italy, China, Portugal, Nepal, South Korea, China, and India have used the QUAL2Kw model to conserve river water (Costa et al., 2019). This model reduced the treatment cost by integrating the nondominated sorting genetic algorithm II and determined the waste load allocation (Farjoudi et al., 2021). QUAL2Kw 6 is used to manage the downstream water by regulating the flow of a dam, and sensitivity analysis with YASAIw (Khonok et al., 2021) and BOD, conductivity, and pH are more responsive for the Sefid Rud River. This model has been used to develop reaeration constants for river Yamuna, Delhi (Arora & Keshari, 2021a).

2.3.1.8 Summary

In this study, seven water quality models were reviewed. The models are advanced for particular geographical regions and conditions; thus, their applicability is limited to other areas. However, these models are crucial for analyzing the water resources' physical, chemical, and biological qualities and predicting the change in the ecological parameters of the systems when specific boundaries or primary conditions are altered. At the same time, these models are applicable in other geographical regions by calibrating, validating, and sensitivity analysis. These models give different levels of complexity. MIKE-11, HEC-RAS, EPD RIV1, and QUAL2Kw are one-dimensional and less complex in these reviewed models. CE-QUAL-W2 is the most significant complex model with the laterally averaged equations of fluid mechanics. Applying to different water bodies, AQUATOX, WASP, CE-QUAL-W2, and MIKE-11 apply to all freshwater resources like rivers, estuaries, lakes, and reservoirs. At the same time, EPD-RIV1, QUAL2Kw, and HEC-RAS are applicable only for waterways. Among these models, AQUATOX predicts the ecological behavior of waterbodies more precisely. Whereas EPD-RIV1 has the most comprehensive water quality algorithm, it does not include sediment diagenesis (Table A1). WASP, QUAL2Kw, and AQUATOX have sediment diagenesis. QUAL2Kw, WASP, and AQUATOX require a large number of data; furthermore, QUAL2Kw has the advantage of easy accessibility, frequent upgrades, and flexibility to simulate a higher number of chemical reactions in the hyporheic zone, auto-calibration process, and inclusion of uncertainty analysis. Additionally, QUAL2Kw can predict SOD and hyporheic metabolism, whereas, among these models, WASP and AQUATOX can simulate toxicants and metals. Among the reviewed models, except MIKE-11, reviewed models are obtainable in the public domain. AQUATOX and QUAL2Kw require low training. All of the models are either steady or dynamic conditions. Table A1 describes the potentialities of models, and Table A2 compares the model system, capabilities, limitations, modeling approaches, and availability. All the models reviewed are mathematical, and QUAL2Kw, WASP, and AQUATOX include uncertainty tools. Currently, several water quality models are present to restore water bodies. These models have mainly incorporated different conditions and pollutants. The selection of a model is a complex task as it needs to evaluate its validity, accessibility of necessary data, and apprehensiveness regarding assumptions and capabilities. Models require hydrodynamic, meteorological, and water quality data. The frequency of these data depends on the model type, pollutant type, waterbody type, and solution method type. Moreover, these models require comprehensive data and proper monitoring of the systems. However, water bodies are highly complex systems whose geomorphological conditions change continuously. Therefore, no model is reasonably sufficient to support a natural phenomenon. Each model has some limitations, although based on the reviews, it is possible to select the most comprehensive water quality model that best fits the concerned system.

2.4 Literature review on water quality model QUAL2Kw

After reviewing water quality models, the QUAl2Kw model has been selected for this study as it can simulate shallow-depth rivers with anoxic conditions. With low data availability, this model can predict the fate of the water quality parameters of streams with unequal-spaced points and diffused sources of pollutants. Model summaries are shown in Tables A1 and A2. After reviewing the above models, the model QUAL2Kw has been selected to simulate the urban river reach of Delhi and develop water quality management approaches.

2.4.1 Literature Review of QUAl2Kw Model

For TMDL studies, QUAL2Kw is one of the leading modeling frameworks in the Washington States for the temperature and nutrients of rivers (Carroll & O’Neal, 2006). QUAL2Kw has also been adopted in states other than Washington (Turner et al., 2009) to support the TMDL programs. The latest version of QUAL2Kw can simulate steady and unsteady flow (Cope, 2019) with variable spacing segmentations.

However, multiple loading and abstractions can be added at any reach. It simulates two carbonaceous biochemical oxygen demands (CBOD)-slow CBOD and fast CBOD. This model accomplished anoxia by reducing oxidation reactions to nil at low oxygen levels, modulating denitrification. Sediment water fluxes, bottom algae, light extinction, pH, and pathogens are simulated. Hyporheic exchange, sediment pore and water quality are simulated, including an optional simulation of the metabolism of heterotrophic bacteria in the hyporheic zone. The QUAL2Kw is a simple river water quality model that can simulate temperature, carbonaceous biological oxygen demand, dissolved oxygen, phytoplankton, and several forms of nutrients such as phosphorus and nitrogen. It also simulates pH, alkalinity, inorganic suspended solids, pathogenic bacteria, and bottom algae and can predict conventional (i.e., non-toxic) pollutants. The framework represents the river as a one-dimensional channel with a nonuniform, steady flow and simulates the impact of both point and nonpoint pollutant loadings (Pelletier et al., 2006). In particular, the model affects pH, alkalinity, inorganic suspended solids, pathogenic bacteria, and bottom algae. Q2Kw is framed within the Microsoft Windows framework and is programmed in the Windows macro language. Visual Basic for Applications (VBA) and Excel are used as graphical user interfaces. This paper describes the QUAL2Kw model development, conceptualization, process, capabilities, applications, and limitations. It also reviews the work done by this model and summarizes the capabilities and future aspects of the model. QUAL2Kw version 5 is a model with one-dimensional, steady-uniform hydraulics and heat budget, water kinetics, point and nonpoint sources, and abstractions are included for simulation. The newest version, 6, included a nonuniform unsteady flow system (Cope,2019). QUAL2kw also accommodates features like software interface, unequally spaced reaches instead of equally spaced reaches with multiple loading and abstractions at any point, anoxia by reducing oxygen sediment oxygen demand, nutrient fluxes, bottom algae, pathogenic bacteria, suspended solids, light extinction, pH, alkalinity, total inorganic carbon, hyporheic exchange, and sediment pore water are simulated automatically by using genetic algorithm (Hobson et al., 2015). This model studies the interaction of dissolved oxygen, detritus plants, carbonaceous biochemical oxygen demand, and denitrification. This model included hyporheic and surface transient storage for each reach (Pelletier and Chapra, 2008). The model can also use kinematic wave flow routing. Calibration is a challenging task in modeling, but QUAL2Kw has an autocalibration facility utilizing a genetic algorithm known as PIKALA and calibrates kinetic rate parameters automatically (Pelletier et al. 2006) within user-defined ranges.

Dynamic water quality kinetics with diurnal variables allow more accurate simulations for the biochemical process (Turner et al., 2009). In eutrophic systems, bottom-attached algae(periphyton) and free-floating algae (phytoplankton) are both essential to define water quality criteria, and QUAL2Kw can simulate both the organism (Turner et al., 2009). The model has the capabilities for Monte Carlo uncertainty and sensitivity analysis by adding software YASAlw or Oracle Crystal ball. Models the output program is in Visual Basic Application (VBA). The QUAL2Kw model is widely used worldwide, especially in the USA, China, Iran, India, Portugal, Nepal, Italy, Malaysia, and Indonesia. In the USA, this model is used to develop TMDLs or numeric nutrient criteria and is produced chiefly in the western states of California, Montana, Oregon, Utah, and Washington (Cope, 2019). It is one of Washington state's main tools for TMDL of nutrients and temperature (Carroll & O'Neal, 2006). The Green River basin drains about 529 km^2 of the land area of Washington States, U.S.A, with 105 km length with QUAL2Kw, a temperature TMDL was developed to understand the factors contributing to elevated temperatures in the system (C. and Lee, 2011). Required heat load reduction targets were developed to meet the water quality standards throughout the system. The model was applied by assuming constant flow for a given condition, such as a seven-day or one-day period. Still, critical variables such as water quality, streamflow, and meteorological data pH, conductivity, dissolved oxygen, temperature, relative humidity, flow, periphyton biomass, and riparian shade are allowed to vary with time over a day. Cristea & Burges, (2010) established temperature model for the Wenatchee River and its two major tributaries, Icicle and Nason creeks. Wenatchee River drains the watershed of 3437 km^2 and flows southeast to meet the Columbia River at the city of Wenatchee, Washington. The QUAL2Kw model coupled with the shade model to simulate water temperature; riparian vegetation cover cooling effects are observed, and the absence of vegetation temperature could increase by 1-1.2°C. The Importance of riparian vegetation is suggested for preserving aquatic species and climate changes. Turner et al., 2009, simulated South Umpqua River, Oregon, and concluded that the QUAL2Kw model shows the impacts of nutrients and biomass on pH and DO. QUAL2Kw model with the hyporheic process, shade model, auto-calibration, and sediment diagenesis can be used for periphyton-dominated river systems with limited data. Kannel et al. (2007) applied QUAL2Kw as a framework of water quality modeling to examine the impact of loads on the Bagmati River, Nepal, and to determine the total maximum pollution loads that can ensure the targeted water quality criteria for DO, CBOD, TN, TP, pH, and water (Kannel et al., 2007). The Cértima River, Portugal, is a small river with 45 km length and 535 km^2 basin area. The study of Cértima River evaluated the water quality parameter for a small watershed by a simple tool QUAL2Kw (Oliveira et al., 2012).

In recent years, the Yamuna River of Delhi segment with a 22 km length of the river from Wazirabad barrage to Okhla barrage, Delhi, was studied and developed reaeration equation by multivariate statistical regression technique and QUAL2Kw is used to validate the equation (Arora & Keshari, 2021). A different reaeration model was analyzed for the study area and adjusted for validation. (Zare Farjoudi et al., 2021b) studied the Zarjub River in the north of Iran, a part of the Siahrud River (24km long), and passed from the suburbs and inside the city and, after flowing into the Anzali Lagoon, ends in the Caspian Sea. The QUAL2Kw model integrated with a non-dominated sorting genetic algorithm and decided the reduction of treatment cost and BOD load allocation. Study leads to minimizing the treatment cost and helps to manage the water quality; also, inflow uncertainty can vary the dissolved oxygen concentration. The Pracana River (Albuquerque et al., 2019) and the

Tagus River watershed were simulated for DO, CBOD, and microbiological parameters, and the QUAL2Kw model showed consistent results during the simulation. This model can be used in small and large watersheds and showed satisfactory physical, chemical, and biological results. The Yeongsan River (Cho & Lee, 2019), southwestern Korea, with a drainage area of 533 km^2, is a heavily polluted and targeted river for the TMDL program. As manual calibration is time-consuming and requires specialization, the QUAL2Kw model with an autocalibration system is applied to determine the TMDL of the river. Gharehsou River (Hoseini & Hoseini, 2018), Iran, assimilative capacity was determined for NO, BOD, DO, and pH. Simulation data was used for January and July. It was found that simulation results for July are more sensitive than data for January.

QUAL2Kw is the renewal model developed from QUAL2E and QUAL2K. The model's strengths and limitations were reviewed from the published work to date. QUAL2E is a simple model to simulate dissolved oxygen, and biochemical oxygen demand does not include bottom algae and sediment oxygen demand. Still, these are the numeric nutrient criteria for a system. In contrast, QUAL2K added more features, including extensive computation structures with more water quality parameters, river segments, and elements. Including the features in QUAL2K, more development is done in QUAL2Kw, such as the autocalibration system and capability of the Monte Carlo simulation technique for sensitivity analysis incorporating YASAIw and Oracle (Pelletier & Chapra, 2008). The model QUAL2Kw is a quasi-dynamic and one-dimensional river water quality model used in Jordan River, Utah (Neilson et al., 2013); Wenatchee River, Washington State (Carroll, & O'Neal, 2006); Silver Creek, Utah (Neilson et al., 2013); Silver Bow Creek, Montana (Theses & Potts, 2014); South Umpqua River, Oregon (Turner et al., 2009); Green River (C. and Lee, 2011); Bagmati River Nepal (Kannel, 2007), Dez River, Iran (Ghorbani et al., 2020), Yamuna River, Delhi (Arora & Keshari, 2021), Musi River, Indonesia (Lestari et al., 2019) and predicted the required water quality variables, and calibrated and validated the required pollutant with the limited data available. The model is applicable for one-dimensional steady flow but allows nonuniform flow. Also, it can be used for unsteady flow systems (Cope, 2019), whereas no application is found for an unsteady flow system. The model assumed that flow conditions do not change vertically and laterally, so this model may not apply to the river with high depth where vertical and lateral mixing is possible. However, manually calibrating and adjusting the kinetic constants makes using them for the deep river possible. A critical strength of the model is that it is used in Microsoft Excel Interface and doesn't require any special software. The programming language is Visual Basic for Application (VBA) and is also executable in FORTRAN, which is faster than VBA. Hence, by using the FORTRAN execution system, calibration time is saved. Additionally, the model can predict associative biological effects of nutrients since photosynthesis, bottom algae, respiration, sediment diagenesis, and phytoplankton death are incorporated within the model (Neilson et al., 2013).

The QUAL2Kw model can use diel or constant data throughout the 24 hours to understand the daily maximum and minimum water quality concentrations. It requires an hourly weather pattern, but responses are shown in a diel pattern (Pelletier

& Chapra, 2008). This model assumes a thoroughly mixed system within the modeling period, consistent boundary conditions within the diel period, constant distributed sources, consistent point sources over the diel period, or constant throughout, and weather conditions changing with a diel pattern. Whereas points and distributed flow with variable loading are impossible to simulate, different loading patterns can be calibrated. This model can determine waste load allocation by varying the flow pattern and scenario. The model can simulate unequal spacing of segments only for the main stem of the river. The model assumes branches and tributaries as point sources and abstractions (Pelletier & Chapra, 2008). Whether unequal short segment is analyzed but for branches and tributaries, this model may be incorporated with other models, or different branches and tributaries can be taken as the main river. This model applies only to the river. It must be coupled with WASP or EFDC for lakes, estuaries, and reservoirs. Also, this model cannot simulate toxic metals established by coupling with other models like EFDC, WASP, and AQUATOX. The QUAL2Kw requires data for upstream boundary conditions, inflow and abstraction for point and distributed sources, hydraulics of each monitoring station, meteorological data for each segment, and water quality data for point sources and distributed sources (Hobson et al., 2015). The information depends on the monitoring station's location. Moreover, the modeling period needs a representative data value for the reach, each point source (inflow or abstractions), and diffused flow. The reach sheet of the model requires input data on the geomorphological conditions of the river to calculate slope, elevation, and travel time. So, the geographic coordinate system, upstream and downstream elevation, and the river segment's length must specify the location. These data can easily be accessible in GIS. So, these geospatial data can be integrated into this model through the ArcGIS tool, and it is possible to get output water quality parameters more representatively (Potts, 2014). In QUAL2Kw, N and P are associated only with dissolved and detritus substances, and live algae are excluded (Pelletier and Chapra, 2008) and can only contribute to the carbon cycle within the system among all nutrients (Neilson et al., 2013). QUAL2Kw can simulate one phytoplankton group (Pelletier & Chapra, 2008), whereas other models like HEC-RAS and CE-QUAL- W2 can simulate multiple phytoplankton groups (Camacho et al., 2019). This model simulates carbonaceous biochemical oxygen demand (CBOD) as a state variable and converts $CBOD_5$ into ultimate $CBOD_s$ and $CBOD_f$. However, other models can predict dissolved organic carbon, particulate organic carbon, and CBOD as state variables (Camacho et al., 2019). Although QUAL2Kw is a model with autocalibration by a genetic algorithm within the model environment, manual calibration is required to set the model parameters (Hobson et al., 2015). During calibration, flow balance is checked by comparing predicted and observed values and differences may be due to groundwater exchange (Hobson et al., 2015). Also, from the measurement of specific conductance, it is possible to identify unknown source locations (Neilson et al., 2013), and hence, unknown flow can be measured at the site. Hydraulic properties can be determined using a rating curve or Manning's equation. For Manning's equation, manning's roughness coefficient for the channel is adjusted through manual calibration and trial and error. Constants can be determined using hydraulic models (HEC-RAC) or gauging stations (Hobson et al., 2015). For the reaeration constants, manual calibration requires using different reaeration formulas, and the appropriate value is set by the lowest root mean square error from observed and predicted values (Arora & Keshari, 2021a). QUAL2Kw is a modeling system including the SHADE and receiving water temperature models (Pelletier & Chapra, 2008). The SHADE model can predict the effect of light on a longitudinally and hourly basis by designating topographical locations and inclinations. The temperature model uses the heat balance equation and indicates the temperature requirement of riparian vegetation and shade (Cristea & Burges, 2010). Although these models are quite capable, QUAL2Kw uses inflow load as constant, whereas the highly variable waste load flow may occur. Also, due to the limited method of determining groundwater interference and temperature (Cristea & Burges, 2010), the uncertainty of temperature and required shade cover is found (Neilson et al., 2013). Also, this model does not account for growth limitations for high temperatures (Camacho et al., 2019). However, other models, such as EFDC and CE-QUAL- ICM, have formulations of temperature growth using the Gaussian model within the system.

Similarly, uncertainty for bottom algae stimulation occurs. In shallow rivers, where data is collected from some stations and modeling is completed for the whole reach, uncertainty occurs for the fewest data. These filamentous algae and macrophytes should be incorporated more efficiently in this model (Hobson et al., 2015). However, the water temperatures in the tributaries are very sensitive to shade and temperature models (Cristea & Burges, 2010). Although the data collection procedure is expensive and needs expert personnel, spacing between stations and collecting more data can be incorporated to manage this uncertainty. Another significant uncertainty in this model is the determining Sediment Oxygen Demand (SOD). QUAL2Kw predicts SOD using the sediment diagenesis algorithm (Toro et al., 1981), whereas this value is less than the SOD present in the system. As it is, a continuous process and association of organic substances flow increased the SOD within the system. However, direct measurement of SOD, which is acceptable within the range of QUAL2Kw, can be minimized this uncertainty (Neilson et al., 2013). However, this type of data is less available due to higher costs. Instead, EFDC, a three-dimensional model with sediment containment, is more suitable. Dissolved Oxygen, a crucial water quality parameter required for aquatic biota's biological and metabolic activity, is primarily a simulated parameter with this model. The dissolved oxygen model includes impacts of nitrification, respiration, sediment oxygen demand and primary production of phytoplankton, biochemical oxygen demand, and also incorporating production and respiration of algae and periphyton (Camacho et al., 2015). The QUAL2Kw model is a simple water quality model with less critical data and an integrated tool for sustainable management and protection of a river system. Although a complex model can represent the waterbody more accurately, these models may be reserved for large and deep rivers and require much data. For a large amount of data, data collection and monitoring systems imply high cost and highly expertise systems. The model framework can reasonably be applied to small and large basins to evaluate effects and required modifications in the system. It is a good framework with less precise data as it has accumulated default values. Again, it has an auto-calibration system that calibrates the reaction constants quickly.

Table 2.1 Some applications of QUAL2Kw

Reference	**Study area**	**Watershed Description**	**Remarks**
(Arora & Keshari, 2021a)	Yamuna River, Delhi stretch	The22 km urban river reaches Yamuna	A reaeration equation is developed using a multivariate statistical regression technique, and this model is used for verification.
(Zare Farjoudi et al., 2021a)	Zarjub River in the north of Iran	Part of the 24km Siaharud river, which passes through suburbs and ends in the Caspian Sea	QUAL2Kw model is used with a non-dominating aborting genetic algorithm to minimize the treatment cost and waste load allocation for BOD.
(Ghorbani et al., 2020)	Dez River, Iran	Distance of 150 km of river length	Discharge, BOD, conductivity, and temperature were stimulated with the model QUAL2Lw, and 95% compatibility was found between observed and predicted values.
(Shepur, 2020)	Tungabhadra River	40 km length of the river flowing through the Davangree district in the Karnataka state of India	Simulations have been done for BOD, DO, and Total nitrogen by the model QUAL2Kw.
(Lestari et al., 2019)	Mousi River, south Sumatra	7.1 km length Pulokarto to PT Badja BURO	Determine required segmentation to reduce pollution loads for improving the river conditions.

Reference	Study area	Watershed Description	Remarks
(Albuquerque et al., 2019)	The Pracana River (Central Portugal)	The river is in central Portugal and the Tagus River watershed	DO, CBOD, and microbiological parameters are simulated, and the required treatment is suggested with the help of the model QUAL2Kw.
(Cho & Lee, 2019b)	The Yeongsan River, Southwestern Korea	533 km^2 of the drainage area	TMDL target point is decided with the help of QUAL2Kw
(Cho & Lee, 2019)	Yeongsan River, southwestern Korea	533 km^{2}drainage area	Auto calibration was done by QUAL2Kw for CBOD
(Saadatpour et al., 2019)	Gheshlagh River, Iran	In the Sirvan watershed, Kordestan province in the west of Iran	QUAL2Kw coupling with AMOSA algorithm
(Darajati Setiawan et al., 2018)	Bedog River, Indonesia	2.24 km length of Bedog River, which is a part of Progo Watershed, Indonesia	Pollutant load and load-carrying capacity are determined by simulating BOD and COD with the help of the model QUAL2Kw.
(Hoseini & Hoseini, 2018)	Gharehsou River, Iran	Gharehsou River, Iran	Assimilation capacity was done for BOD, dissolved oxygen, pH
(Barmaki & Nadoushan, 2018)	Zayandehrood River, Isfahan, Iran	From Zardkouh mountain to Sanandaj-Sirjan area	QUAL2Kw can predict BOD and Dissolved oxygen
(Sharma et al., 2017)	Yamuna River, India	39.4 km Delhi stretch with 1483 km^2 drainage area	The simulation was done for water quality parameters BOD, DO, and total nitrogen with the QUAL2Kw model.
(Nikoo et al., 2016)	Zarjub River, Iran	Zarjub River, Iran	Multiple-based waste load allocation management systems were developed by integrating QUAL2Kw.

Reference	**Study area**	**Watershed Description**	**Remarks**
(Flynn et al., 2015)	Yellowstone River in the Northwestern the U.S.A	1091 km length of the river in the USA	It simulated nutrients and the effect of light on algal bloom
(Hobson et al., 2015b)	Silver Creek, Utah	2 km length and 103 km^2 watershed, and the river is a small tributary of Weber River, Utah, USA	The minimum data required for waste load allocation was established by the QUAL2Kw model
(Sarda & Sadgir, 2015b)	Godavari River, India	163 km long reach from Pategaon to Yelli in south Indis	Determined the required reduction of pollutants to mountain minimum dissolved oxygen
(Fang et al., 2014)	The Qiantang River, located in Zhejiang Province, China	With a drainage area of 41700 km^{2}and total length of the river of 524 km, China	This model determines the assimilative capacity of the river
(Hossain et al., 2014)	The Tunggak River, Malaysia	7.51 km length of the river in Malaysia	DO, BOD, and cod were simulated by the QUAL2Kw model
(Gikas, 2014)	Canals, North Greece	Two main canals at Chryssoupolis, north Greece	Return flow from irrigation land containing high nutrients was simulated as nonpoint sources, and water flow was maintained to the canal and. also, the temperature model was determined.
(von Stackelberg & Neilson, 2014)	Jordan River, Utah	83 km long urban reach of Jordan River flowing from Utah Lake to the Great Salt Lake	HEC-RAS model collaborated with QUAL2Kw and determined the rate constants and groundwater effects on DO

Reference	**Study area**	**Watershed Description**	**Remarks**
(Neilson et al., 2013)	Jordan River, Utah, USA	83 km long urban reach of Jordan River flowing from Utah Lake to the Great Salt Lake	Four seasonal data were used to simulate the DO of the river by the QUAL2Kw model
(Kori et al., 2013)	Karanja River. India	122 km long tributary, Godavari River, Andhra Pradesh, India	QUAl2Kw model was used for environmental attribution of different seasonal flow characteristics to ensure minimum oxygen level by QUAL2Kq
(Gupta et al., 2013)	Kshipra River India	19.79 km river stretch	QUAL2Kw stimulated waste load reduction and water quality parameters
(Santos et al., 2013)	Minho River	300 km length of Minho River from Spain to Portugal	In low flow conditions, pathogens are high, and automatic calibration of QUAL2Kw determines the kinetic constants.
(Oliveira et al., 2012)	Cértima River, Portugal	535 km^2basin area and 45 km long reach of Portugal	With a river stretch with high nutrient concentration and river water quality, data is calibrated and validated by QUAL2Kw
(Cristea & Burges, 2010)	The Wenatchee River with two tributaries, USA	3437km^2 watershed and river flowing towards the southeast and meets the Colombia River at Washington, USA	QUAL2Kw does temperature modeling and determines the required shade increasing to reduce the temperature,
(Turner et al., 2009)	South Umpqua River, Oregon	South Umpqua River, Oregon, USA	Waste load allocation was done for both point and nonpoint sources for the river stretch with QUAL2Kw.

Reference	Study area	Watershed Description	Remarks
(Kannel, Lee, Kanel, & Ahn, 2007)	Bagmati River, Nepal	20 km length of Bagmati River lies in Kathmandu Valley, Nepal	QUAL2Kwmodel is used to restore the river stretch and suggested that modeling is necessary to restore a waterbody
(Jim Carroll, Sarah O'Neal, 2006)	Wenatchee River, Washington State, USA	It originates from Lake Wenatchee, drainage of 1371 square miles, and meets at Colombia River at the city of Wenatchee.	Nutrients, BOD, and inorganic phosphates are simulated, and loading capacities are prescribed by the model QUAL2Kw.

2.5 Literature Review on Assimilation Capacity

Water is a crucial element of nature, and all civilizations have advanced near rivers. Due to higher development activities and massive population growth, the quality and quantity of water have become a sensitive issue, and freshwater will be scanty after a while (Pinto & Maheshwari, 2011). Progressively worsening water quality results from rapid industrialization and urban sprawling, degrading the environment. Wastewater from the municipality and industry creates rivers' quality degradation and crucial global issues (González et al., 2014). The aquatic systems play an essential role in carrying out the pollutants accountable for water contamination (Shrestha & Kazama, 2007). These contaminants stabilize with the system's physical, chemical, and biological processes. The pollution level rises when rivers' assimilation capacity is lower than the pollutants added to the water. The self-assimilation of aquatic systems is a complex phenomenon, including physiochemical and biological reactions. This phenomenon helps these systems regain water quality after flowing for a while if the water flow has sufficient substances to stabilize the waste input. Hence, self-purification and water quality enhancements are the primary criteria for natural water systems to sustain aquatic species (Wei et al., 2009). Self-purification is a way to partially or fully repair an aquatic system and make it cleaner after introducing foreign substances, causing sufficient modification of water properties (Benoit, 1971). The process is the recycling of substances with the assistance of physical, chemical, and biological processes. Dilution, adsorption, sedimentation, volatilization, acid-base reactions, precipitation reactions, coagulation, flocculation, bacterial degradation, and assimilation of materials by organisms (Vagnetti et al., 2003) are included in this process. When rivers flow, oxygen increases due to reaeration, and microorganisms present in sewage oxidize organic substances to inorganic materials and purify rivers (González et al., 2014). Thus, assimilation restores the conditions of the aquatic system before receiving wastewater (Ostroumov,2005). Nowadays, researchers focus on the self-assimilation of the contaminated river stretch as the water quality pattern is accountable and effortlessly modified with the environmental transformation (Wei et al., 2009). Rivers can be managed by improving the assimilation capacity. This capacity can be enhanced by decreasing contaminants and increasing the freshwater flow. In the waterbodies, Dissolved Oxygen (DO) is depleted due to organic pollutants from wastewater. DO and Biochemical Oxygen Demand (BOD) indicates the presence of organic substances (Basant et al., 2010). The oxygen-demanding contaminants' natural purification depends on the required oxygen to be concentrated, the oxygen necessary to secure the ecosystem qualities fit for species with designated standards, and the aquatic system's BOD purifying extent, which is assessed by reduction and replenishment of Oxygen (Chapra et al., 2021). The term "BOD" typically refers to Biochemical Oxygen Demand, a key parameter in water quality testing that measures the amount of oxygen consumed by microorganisms in decomposing organic matter in water. If the sample is unfiltered, BOD will reflect the oxidation of both dissolved and particulate organic carbon, and phytoplankton present as particulate BOD can complicate the test through photosynthetic oxygen generation. An increment of CBOD was found for unfiltered samples due to increased algal growth was found in the pool behind the dam of the Upper Mississippi River (Lung, 2022). Earlier, it was assumed that in untreated sewage or partially treated sewage, where DO concentrations are very low, the oxygen consumption is due to the decomposition of carbonaceous substances; hence, BOD_5 can be taken as $CBOD_5$ (Lung, 2022). However, recent studies have shown that NBOD occurred 8 days before the upper Mississippi River and Danshui River (Lung, 2023). In wastewater also, nitrification can be started before five days in favorable conditions (Hall and Foxen 1983). The well-treated wastewater has oxygen and BOD5 values, including carbonaceous BOD and nitrogenous BOD, as oxygen is consumed by nitrifying bacteria (Lung, 2022). Therefore, long-time BOD tests may be required to differentiate CBOD and NBOD (Lung, 2022). The variations of time may be recorded for different samples to completely break down carbon (Lung, 2022). In QUAL2Kw modeling, the filtered sample with nitrification inhibition is required to reflect the CBOD, and $CBOD_5$ is converted to $CBOD_u$ (QUAL2Kw theory, 2008). The nitrification can be inhibited by adding a chemical inhibiting agent such as TCMP (2-chloro-6-(trichloro methyl) pyridine. The measurement then truly reflects CBOD (Pelletier and Chapra, 2008). The QUAL2Kw model is based on the ultimate CBOD, and two possible approaches are measuring a long-time BOD that determines the ultimate BOD and 5-day BOD determination and extrapolating the result to the ultimate by using the following equation $\mathrm{CBODFNU} = \frac{\mathrm{CBODFN5}}{1 - e^{-k_1 5}}$, where CBODFNU = the ultimate dissolved carbonaceous BOD [mgO_2/L], CBODFN5 = the 5-day dissolved carbonaceous BOD [mgO_2/L], and k_1 = the CBOD decomposition rate in the bottle [/d]. Here, FNU stands for Filtration and Nitrification inhibition for Ultimate. Lung(2022) suggested that the $CBOD_u/CBOD_5$ ratio must be determined by a long-term effluent BOD test. $CBOD_u/CBOD_5$ ratio is dependent on treatment levels of wastewater with the variability of effluent characteristics (Leo et al., 1984). $CBOD_u/CBOD_5$ ratio can be removed the effect of nitrification and differentiate the attenuation of carbon and nitrogen in the modeling (Lung, 2022). For the marginally treated wastewater, $CBOD_u/CBOD_5$ and k_1 values are close to 1.0 and o.5 day^{-1}, and these values are dependent on the treatment facilities (Lung, 2022). Chapra (1997) assumed that the bottle rates for sewage-derived organic carbon vary from 0.05 to 0.3/d, and much of the readily oxidizable CBOD will be exerted in about 20 to 30 days. Pelletier and Chapra, 2008 also suggested that long-term CBOD tests should consider 30°C temperature rather than 20°C provisional temperature to speed up the process. The saprophytic bacteria that break down non-living organic carbon in natural waters and sewage thrive best at temperatures from 20°C to 40°C. Thus, a temperature of 30°C is not high enough for the bacterial assemblage to shift to thermophilic organisms that are atypical of natural waters and sewage. The benefit should be higher oxidation rates which would result in shorter analysis times for CBOD measurements (Pelletier and Chapra, 2008). For the limited data, as the Yamuna River, Delhi, where only 5-day BOD data are available to represent the organic carbon, BOD_5 is approximately equivalent to CBODFN5 (Pelletier and Chapra, 2008). The BOD decay rate constant is assumed to be a typical value of about -0.23 day^{-1} (Brown and Barnwell, 1985), and the fast CBOD can be approximated as about 1.46 X BOD_5 (Pelletier and Chapra, 2008). Chapra(1997) stated that the occurrence of nitrification depends on the presence of ammonium, adequate numbers of nitrifying bacteria, alkaline pH, and sufficient oxygen. The Yamuna River, Delhi's reach becomes anoxic after outfalling the Najafgarh drains, and only the degradation of organic carbon happens. Lung 2022 also stated that the low DO levels are not able to oxidize the ammonia of this river reach, and improvement of DO concentrations can be able to denitrification. The increment of ammonia levels downstream is observed in different studies (Verma et al., 2023; Lung, 2022). Dilution with flow augmentation and lowering the organic carbon load can speed up the nitrification process. However, the timing of the initiation of nitrification may be a great uncertainty.

Lung (2022) concluded that the Yamuna River Delhi after Wazirabad showed poor water quality during the May and June pre-monsoon periods due to the lack of dilution and waste input through the Najafgarh drain and sharp COD and BOD increment. The Najafgarh Drain, carrying wastewater inputs from the supplementary drain, drove the DO at Wazirabad to zero immediate outfalling, resulting in this urban reach to anoxic conditions. A high COD level indicates a substantial amount of non-biodegradable carbon present in the wastewater. The Najafgarh drain inputs the highest amount of BOD/COD pollutants into the river reach. At Nizamuddin, after 15 km downstream of the outfalling of Najafgarh drain, BOD and COD levels are reduced due to the attenuation in the river reach. The ratio of COD/BOD_5 is 3, indicating two-thirds of COD is caused by inorganic carbon and ammonia. Meanwhile, BOD_5 is not included in the NBOD, as low DO inhibits nitrification. Assuming the $CBOD_u$ deoxygenation rate as 0.22 day^{-1}, the ratio of $CBOD_u/CBOD_5$ is 1.5, and 50% of COD is inorganic substances from non-domestic wastewater. Analysis of wastewater from main drains also showed that $CBOD_u/CBOD_5$ is 3.0. The minimum value of k_1 was also found $0.22d^{-1,}$ and a higher value is close to 2.0 d^{-1}. Higher values of k_1 imply the rapid assimilation of organic carbon with significant deoxygenation of the Yamuna River Delhi. The BOD_5 results would not include ammonia, as nitrification does not take place in the first five days of the test because the river receives primarily untreated and partially treated wastewater. In addition, the low DO levels could not provide the oxygen needed to oxidize ammonia in the river. Hence, the oxygen budget is dependent on CBOD deoxygenation, and the improvement of DO should be focused on BOD load reduction for the present time. Improvement of DO can also lower the ammonia concentration by speeding up the nitrification process.

The river reach becomes anoxic after the outfalling of the Najafgarh drain. In such conditions, when the water column of a river reaches no oxygen, the decay of BOD occurs by atmospheric oxygen (Gundelach and Castillo, 1976). A lower oxygen consumption rate slows down the decay of BOD, and hence, the deoxygenation rate cannot be normal until the oxygen levels recover (Lung, 2022). Thomann and Mueller (1987) suggested a relationship $k_dL = k_aD$, where k_d is BOD deoxygenation rate (day−1), L is BOD in mg/L, k_a is reaeration rate (day−1), and D is oxygen deficit in mg/L. From this equation, it can be observed that the deoxygenation rate is dependent on the oxygenation conditions of the reach. In the DO deficit condition, the deoxygenation rate will be zero. The k_d value will be resumed after oxygen recovery (Lung, 2022).

Rivers have their assimilation capacity, and it is necessary to acquire knowledge about the pollutant loads disposed of from diverse sources that rivers could receive without retrogression of their indigenous state (Oliveira et al., 2012). Mathematical modeling can validate waste load in a water body by establishing the cause-effect relationship between contaminant load and water quality. Hence, assimilation capacity could be evaluated by several simulation models (González et al., 2014). These frameworks are used as decision-making tools for wastewater management policies (McIntyre & Wheater, 2004). The simulation models correlate the water quality after disposing of wastewater into a water body (Cox, 2003). Water quality models can also predict the reciprocation of the aquatic system with different scenarios. The modeling outcomes are effective managing tools for assisting the river quality administrator in evaluating realistic water body conservation strategies and aspects of pollutant loading uncertainty. The present study aspires to assess the assimilation capacity of a severely polluted river stretch, Yamuna River, Delhi. The model QUAl2Kw predicts the river quality and assesses the assimilating efficiency of the pollutant load. QUAL2Kw was used to simulate the load-carrying ability of the Kali Surabaya River, and it found that the pollutant load for BOD and COD was larger than the purification capacity of the river (Aliffia & Karnaningroem, 2019). The seasonal variation of assimilation capacity for the Karun River, Tehran, has been determined using this model and stated that the different scenarios adopted for modeling, which were reducing wastewater flow, wastewater concentrations, and increasing the flow, enhanced the river characteristics (Nezad et al., 2018). Although there are several models to predict the pollutants' fate, due to easy accessibility, the ability to simulate maximum contaminants, and the availability of uncertainty analysis, QUAL2Kw is the most suitable tool for the calculation of the load-carrying ability of a water body (Darji et al., 2022). Hence, this study has used this framework to predict the assimilative capacity of the Yamuna River, Delhi, and water quality management of the severely polluted stretch of Yamuna, Delhi, by flow augmentation and reducing the BOD and Chemical Oxygen Demand (COD) pollutant load. The urban reach of Delhi is one of the most contaminated river stretches in India, and Delhi contributes 79% of the pollutant load (Joshi et al., 2022). This segment carries wastewater from different industries and municipal sewerage in Delhi (Parmar & Singh, 2015). This segment of the Yamuna River is getting polluted by disposing of 22 outfalling drains within the 22 km from Wazirabad to Okhla (CPCB, 2006). After entering Delhi, due to discharging a massive BOD load and lack of fresh water, the river segment becomes a sewerage line (Upadhyay et al., 2011). Hence, it is the most crucial task to maintain the ecological health of this reach. The wastewater with little or no treatment has deteriorated the river reach (CPCB, 2006). Uninterrupted wastewater input with excessive organic pollutants from different sources decreases river quality. The DO concentration becomes low when the river maintains low flow and receives huge wastewater flow (Gain & Giupponi, 2015). Hence, flow augmentation is required to manage the water quality and increase the DO of such a polluted reach. The DO concentration of this river reaches a sharp decline to zero or is undetectable after discharging wastewater from the Nazafgarh drain, which is the prime contributor to waste load (Parmar & Singh, 2015). Several studies have appraised this segment's river quality (Kumar et al., 2019). However, little work has been done on the pollution-carrying capacity of this reach. The assimilation capacity of the Delhi reach of Yamuna River was done by the Central Pollution Control Board of India (CPCB, 82) for COD and chloride, and four major contributing drains have been considered. Although the study was related to the discharging pollutant load from the point sources. Paliwal & Sharma, 2007, used QUL2E to assess the pollutant load carrying capacity and suggested maintaining ten cumecs of water flow to maintain the river water quality and only considered the BOD load. Verma et al., 2022, suggested that this river reach required a combination of management options, including load reduction, flow augmentation, and external aeration.

2.6 Literature Review on TMDL approaches

Civilization started near rivers, so rivers are mainly located in an environment with dense populations and industries (Othman et al., 2012). Meanwhile, the river water becomes polluted by numerous human activities and natural processes, and water quality deteriorates (Teknologi et al., 2015). These processes include the discharge of domestic and industrial sewage, agricultural runoff, erosion and weathering, decomposition of leaves, and algal growth (Azhar et al., 2015). The river is contaminated with point and nonpoint sources of pollution. Point sources can be identified as disposal locations in surface water bodies. The sewer outfalling drains, industrial wastewater, municipal wastewater, runoff from mines, and overflow from storm and sewer lines are noted as point sources. The sources spread over an extensive area are not considered specific (EPA, 2012) and are known as diffused sources. These include flow from rainfall, surface runoff, and atmospheric deposition (León et al., 2001). Diffused sources are hard to control compared to fixed sources. River water characteristics have become a key concern for the global as all liveliness requires water, and rivers are the most crucial water source. River contamination affects the overall health of the environment. Around 1.8 million infants die from waterborne diseases per year, as reported by WHO (Parween et al., 2017). The contaminants from different industrial areas, municipal areas, runoff from farmland, and urban areas deteriorate surface water sources and make a substantial environmental footprint (Osmi, 2016). To control the deterioration of the water qualities of various waterbodies, USEPA implemented total maximum daily load approaches (TMDL) in the USA (Santhi et al., 2006), specifying the total quantity of stressors responsible for damaging those. The TMDL program defines the load that should be entered from different fixed and diffused sources into a waterbody and repairs the health of the waterbody (Osmi, 2016). Besides the United States, TMDL has been developed in Korea (Lee et al., 2013), Thailand, Taiwan (Chen et al., 2007) and China (Wang et al., 2014). India is the most populated country with an urge for high development and massive urbanization with industrialization. The big cities mainly emerged near the rivers like Ganga Yamuna, Krishna, Kaveri, Satluj, Narmada, etc. In 2015, out of 390 monitored rivers, 275 were polluted (Polluted River stretch, CPCB-2022). Not all rivers are polluted throughout their length, and some stretches are polluted. According to CPCB, 2022, 351 river stretches were identified in 2018, divided into five categories depending on the BOD concentrations. The Yamuna River, Delhi, is the most contaminated stretch in India, observing a maximum BOD of 83mg/l and posing a priority one category (Polluted River Stretch, CPCB-2022). This river stretch is the lifeline of the capital of India, and 70% of Delhi's water requirement is fulfilled by this River (Jaiswal et al., 2019). TMDL is the most considerable quantity of a pollutant that a river can purify to maintain the desired water qualities (USEPA). However, many countries introduced TMDLs for river management. There was no study in India regarding implementing a maximum daily load. This chapter includes a comprehensive literature review on developing the TMDL approach in the USA and other countries such as China, South Korea, Thailand, and Malaysia. The overview of TMDL approaches in these regions will give a better picture of the TMDL implementation plan in India. To develop a TMDL plan, a few steps need to be adopted, as shown in Fig. 2.7. The water quality assessment and modeling have been discussed in the previous chapters. This study used QUAL2Kw, a water quality model, as the TMDL planning tool. Water quality models are the most valuable tools for determining TMDL and can predict the transformation of aquatic bodies, including physiochemical and biological parameters and the interaction between the pollutants and the reduction of the contaminants mathematically (Song & Kim, 2009). The model QUAl2Kw is an appropriate tool to determine the TMDLs of this reach.

2.6.1 TMDL approach in the USA

The USPEA introduced and implemented TMDL in the USA to identify the aquatic bodies that do not fulfill the required water quality standard assigned under section 303d of the Clean Water Act (Camacho et al., 2019). It describes the maximum amount of a pollutant a water body can carry by maintaining the required water quality criteria and pollutant load allocation among point and nonpoint sources (Petersen et al., 2008). TMDL can also be evaluated as quantifying a river's assimilative capacity that does not exceed the allocated load (Wang et al., 2015). To develop a TMDL, identification of the waterbody with geographical location, pollutant, target water quality standard, required pollutant load to meet the water quality standard, waste load allocation, load allocation, margin of safety, seasonal variation, future growth allocation, and lastly implemented plan are necessary (Wang & Bi, 2016). All of these elements are required to be satisfied during the development of a TMDL. The steps needed for developing the TMDL plan are shown in Fig 2.7. Fakhraei et al. (2014) studied the Adirondack region of New York, using a biogeochemical model to relate atmospheric sulfur and nitrogen deposition in the lake water. The authors indicate that controlling sulfur load is more effective than controlling nitrogen, and a 60% decrease in sulfur can improve the lake's acidic conditions. Dors & Tsatsaros. (2012) determined the margin of safety (MOS) for TMDLs. They divided MOS into two categories: implicit and explicit. Implicit components are the conservative estimative parameters, and explicit components include data variability, equipment error, model accuracy, etc. Fig. 2.8 shows the TMDL load distribution for explicit components such as BOD, which has been taken as the target pollutant for this study.

The standard TMDL program starts with identifying the impaired waterbodies. Impairment is defined as a waterbody not supporting designated uses such as fisheries, recreational purposes, agricultural purposes, or public uses (Wagner et al., 2007). The evolution of TMDL has enhanced the water quality restoration capability of the rivers. In the USA, the TMDL program was designed and conducted by the authorities of particular regions, and many TMDLs have been developed. Based on these management approaches, guidelines can be taken to create TMDL plans in India. Wagner et al. (2007) investigated the required load reduction for the biologically impaired river Stroubles Creek, Virginia, using land use data, a water quality model, and reference watersheds. The study's main objective was to bring back a healthy benthic assemblage to the waterbodies into Virginia water quality criteria. They concluded that the biota of a river plays a vital role in TMDL development. Zou et al. (2006) studied a TMDL management plan using an integrated water quality model EFDC and WASP for Wissahickon Creek, Pennsylvania, to determine the level of nutrients causing high biological activities and impairing DO concentration. Integrated modeling approaches show that 99% of Phosphorous reduction can reduce the periphyton growth and increment of DO and suggest that a water quality model-based TMDL implementation plan can improve the water quality. The WASP model has been used to develop a TMDL plan for the Santa Fe River in New Mexico. Bowen et al.

(2003) used the CE-QUAL-W2 model to determine the TMDL of the Neuse Estuary of North Carolina, which faced low dissolved oxygen and high chlorophyll-a concentrations. These caused high mortality of fish. Two extreme nitrogen and three chlorophyll-a conditions were considered. The scenarios were constructed to reduce nutrient loading, and it was observed that nitrogen loading reduction lowers the Chlorophyll-a concentration. A reduction of 30% in nitrogen loading could reduce the Chlorophyll to a concentration of 3 μg/l. In 2011, a post-evaluation study was conducted on the TMDL implementation plan for Neuse River. With the help of the Bayesian model, a 32% reduction of nitrogen in the point sources was achieved to control the water quality. The TMDL implementation plan successfully reduced the pollutants concentrations (Alameddine et al., 2011). For Green River (C.& Lee, 2011), the QUAl2Kw model was used to calculate the heat budget components and simulate water temperature. Modeling and monitoring demonstrated that the lower reaches' temperature sometimes exceeded the lethal temperature, causing health effects of salmonoids, including blocking and delaying migration. Furthermore, high temperature causes a decrease in dissolved oxygen. Increasing and improving riparian zones is required to suggest a water temperature below 16 degrees Celsius for fish survival. TMDL programs are divided into ten regions in the USA, and regional authorities are responsible for TMDL management. Impaired rivers are listed in the CWA 303(d) list. TMDL reports are submitted to the EPA for review. The list of TMDL-implemented areas is shown in Table 2.1. According to EPA, 2018c, about 29.1% of all rivers were assessed, and 51.4% were impaired. Reasons for impaired rivers were mainly high levels of pathogens, sediment, nutrients, and organic substances. These studies show that a suitable water quality model can determine the target load to meet the required quality criteria.

2.6.2 TMDL in Asia

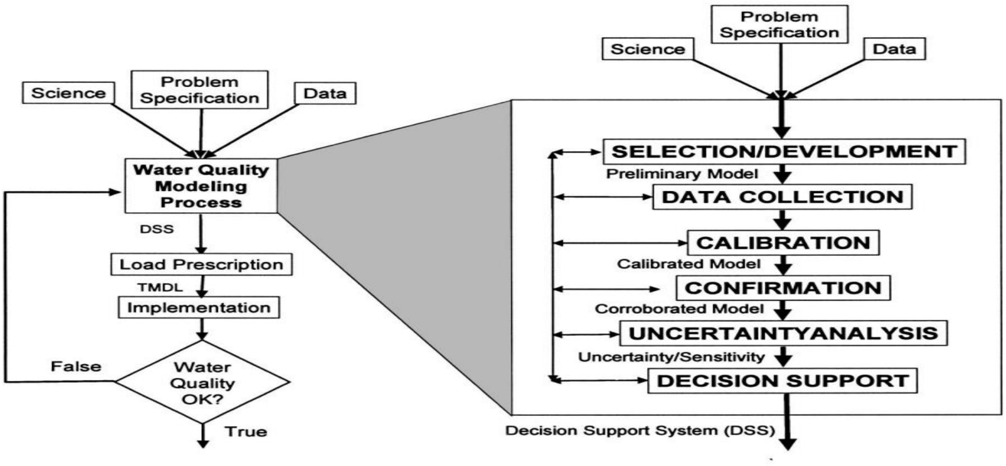
TMDL management approaches have been studied in a few Asian countries, such as China, Taiwan, Thailand, and South Korea. Implementing TMDLs is necessary to repair the impaired waterbodies in these countries. In 2012, a study using the EFDC model for managing the water quality of the Fuxian Lake was conducted, and a TMDL approach was developed by Zhao et al. (2012). Two scenarios were generated to maintain the lake water as a class I category. In the first scenario, TN, TP, and COD loads were required to be reduced by 66%, 68%, and 57%, respectively. Furthermore, the second scenario suggested that only average flow could maintain the required standard without reducing the load. In the future, more pollutant loads could be assimilated without impairing the water quality. Wang et al. (2014) developed TMDL approaches for Dianchi Lake, China, which was not improved after 20 years of undertaking a restoration plan. Therefore, the TMDL was created with a water quality model, EFDC, constructing scenarios to evaluate the loading and eutrophication conditions. The authors observed that 80% of load reduction is required to maintain the class III water utility category. Another study done by Wang et al. (2015) used the WASP model and developed TMDL to control nitrogen and phosphorous for the Zhushan Bay watershed (Wang et al., 2015). The four steps of the process involve the TMDL steps: Data collection, watershed load calculation, numerical modeling, and management scenarios. Modeling results show that to achieve the water quality criteria, approximately 25-35% of CBOD, 50-55% of NH4-N, 50-55% of TP, and 70-75% of TP should be reduced. The authors recommend monitoring and updating the TMDL calculations at 5-year intervals. Wang & Bi. (2016) developed nutrient TMDL for Taihu Lake using flow and temporally variable load expressions. They concluded that the maximum load reduction for BOD, NH4-N, and total nitrogen was in spring, and for phosphorous, it was in winter. Since 2002, the TMDL management system has been regulated in South Korea for four significant rivers, which are the Nakdong River, Geum River, Yeongsan River, and Han River (Poo., 2007). During the first stage of TMDL implementation (2002-2010), the BOD parameter was focused in Korea, and in the second stage (2011-2015), total nitrogen and total phosphorous were also started to be considered (Lee et al., 2013).

Table 2.2 TMDL coverage areas in the USA

Region	Area
Region 1	Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, Vermont, and 10 Tribal Nations
Region2	New York, New Jersey, Puerto Rico, and the U.S. Virgin Islands
Region3	Pennsylvania, Maryland, Delaware, Virginia, and the District of Columbia
Region4	Alabama, Florida, Georgia, Kentucky, Mississippi, North Carolina, South Carolina, Tennessee and 6 Tribes
Region5	Great lakes and upper Midwest states, Illinois, Indiana, Michigan, Minnesota, Ohio, and Wisconsin, and 35 Tribes
Region6	Arkansas, Louisiana, New Mexico, Oklahoma, Texas, and 66 Tribes
Region7	Iowa, Kansas, Missouri, Nebraska, and Nine Tribal Nations
Region8	The states of Colorado, Montana, North Dakota, South Dakota, Utah, and Wyoming, 27 Tribes
Region 9	Arizona, California, Hawaii, Nevada, Pacific Islands, 148 Tribal Nations,
Region10	Alaska, Idaho, Oregon, Washington, and 271 Native Tribes

Source: Osmi, 2019

The authors studied the TMDL management approach using the available data for the Nakdong River basin, Korea, and the TANK model. For TMDL management, the river has been divided into four parts. Load distribution curves were drawn, and water quality targets were settled for the TMDL system. Cho & Lee. (2019) used the QUAL2Kw model for TMDL determination of the heavily polluted Yeongsan and Whangyonggang Rivers in South Korea. This river is under the Korean TMDL program and already set a target BOD and TP values. GA and autocalibration were performed for calibration. The model performance was good, and a TMDL for BOD and TP was established for the target points and the entire river. Results show that target points are not a concern; using the NSE performance criterion as the objective function for auto-calibration is more appropriate. Kim et al. (2016) assessed the TMDL implementation plan for the water quality of the Geum River in South Korea from the pre-TMDL study period and analyzed the effect of TMDL on water quality. The Authors concluded that during the TMDL implementation, the discharge load was reduced, and water quality improved. Meanwhile, they concluded that the TMDL implementation plan has improved water quality, and strict regulatory methods are needed to maintain the mainstream water quality.



(*a*) The TMDL Process (*b*) Water Quality Modeling Process

Figure 2.7 TMDL approaches using a water quality model a) The TMDL Process and B) Water quality Modeling process (Chapra, 2003)

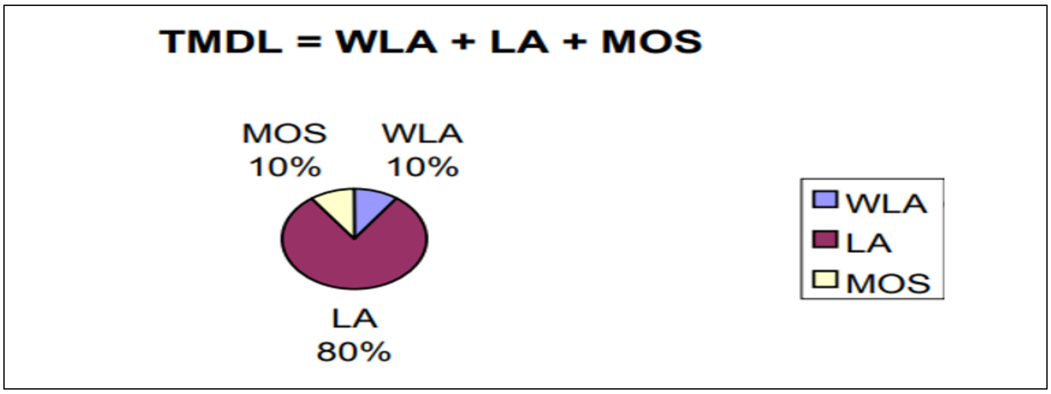


Figure 2.8 LA, WLA, and MOS for TMDLS for BOD as an Explicit component (Dors & Tsatsaros, 2012)

In Thailand, Singkran2010 used the MIKE II model to develop the BOD TMDL of the River Thachin (Singkran, 2010). The author stated that the BOD load from different fixed and diffused sources needs to be reduced to maintain the water quality standard. As the load reduction amount is high, achieving the implementation plan is very difficult due to the lack of regulations, improper wastewater treatment plan, and low wastewater collection and treatment systems. In Taiwan, the Fei-Tsui reservoir, one of the significant drinking water sources, is polluted by diffused sources

(Hsieh & Yang, 2006). The basin model was used to evaluate diffused sources, and the Vollenweider model was used to assess TP. This study will help to develop a management scenario for the proposed TMDL of this reservoir. In another study, Osmi et al. (2016) stated that the TMDL approach is the best management plan in Malaysia and studied a TMDL development strategy for Malacca River, Malaysia, using the EFDC model. The modeling process can used by the decision makers for target load calculations. 11 scenarios have been developed for COD load reduction, and scenario ten was selected for the TMDL plan, which reduces 70% of COD load from all primary point sources and 30% reduction from the tributaries. Treatment plants need to be constructed to minimize COD load from point sources. MBR, SBR, A2O, and Microbubble systems can be adopted for wastewater treatment. For nonpoint sources, wetlands with riparian zones are suggested for controlling strategy. 55% TP should be required to reduce the eutrophication of the reservoir.

Further, it has been observed that the CBOD deoxygenation rate varies with the inclusion of advanced treatment facilities in the wastewater treatment plants (Lung, 2022). Lung (2022) concluded that the CBOD deoxygenation rate varied on the Mississippi River in the USA when wastewater treatment plants adopted secondary treatment and nitrification of the waste water.

2.7 Literature Review on Water Quality Management

Lung (2023) discussed technology-based water quality control and water quality-based control. In the USA, the water quality of the streams was maintained by improving the wastewater treatment plants and, known as the technology-based water pollution control approach. Wastewater treatment plants were upgraded and the technology-based effluents improved the water quality. This approach reduced water pollution, but in some cases, this was not suitable. Water quality models were used for those cases, and water quality could be improved. EPA dropped the technology-based approach and adopted water quality-based approaches. Water quality-based approaches use water quality models as a decision tool to maintain the water quality of the rivers and streams. For the Yamuna River, Delhi must develop a water quality model that may be used as a decision-making tool to improve the water quality of this polluted river reach.

The rapid population growth is putting tremendous pressure on the water resources of developing countries like Western and Southern Africa and South Asia (Turan et al., 2018). Anthropogenic activities release harmful contaminants into the aquatic environment and threaten living organisms (Abbas et al., 2022). These contaminants lead to the destruction of the aquatic ecosystem. High oxygen-demanding pollutants discharged from agriculture, municipal, and industrial activities decrease the dissolved oxygen concentration below the extreme level in the receiving water. The aquatic ecosystem of the river becomes unbalanced, causing the mortality of fish and other organisms, producing odors, and becoming unaesthetic (Cox, 2003). The wastewater coming from municipal sewage contains organic and inorganic substances, including toxic household chemicals including insecticides, pesticides, detergents, personal care products, and other nonbiodegradable substances that cause harmful effects to human health when agricultural lands are irrigated with the water from receiving water resources (Khalil et al., 2022). Agricultural runoff contains residual synthetic fertilizer, and pesticides contain micronutrients (Tauqeer et al., 2022). These microcontaminants also accumulate in the aquatic ecosystem and pose a threat to living organisms (Abbas et al., 2022). Industrial wastewater contains inorganic and toxic substances demanding oxygen. Therefore, the water quality of the waterbodies requires sustainable management. Water quality management approaches involve a highly multi-disciplinary decision related to the parameter's data input, response, and control (McIntyre, 2004). Water quality models can assess the water quality of rivers as these models predict the highly complex relationship between the wastewater and the system’s response (Deksissa et al., 2004). These models are able to predict the water quality after wastewater discharges into the river and, therefore, can decide the degree of treatment required for wastewater for the designated use. Indian significant cities and towns are situated on the riverside, and those cities face severe water scarcity in quantity and quality. A vast amount of municipal and industrial wastewater is generated due to high population growth, non-systematic urbanization, fast industrialization, and irrigation projects. With uncontrolled and accelerated development, wastewater discharged into the river negatively impacts water quality (Singh et al., 2007). Hence, surface water bodies urgently require a sustainable management system. Water quality management aims to reduce pollution's environmental impact (Ghosh & Mujumdar, 2010). The Yamuna River, Delhi segment is the most polluted water reach in India, and partially treated and untreated sewage disposal from different drains causes almost no dissolved oxygen (DO) and high biochemical oxygen demand throughout the year (Sharma, 2013; Sharma et al., 2009; Yamuna et al., 2020). The water quality model QUAL2Kw was used to find a managerial approach for maintaining the water quality of the Yamuna River Delhi reach. The present research intends to develop some management options using this model QUAL2Kw. This model is suitable for the study reach as this segment is almost anoxic after joining the Nazafgarh drain (D1). This model can reduce the oxidation reaction to zero when oxygen availability is deficient (Pelletier & Chapra, 2008). Lung (2022) stated that the CBOD and DO of the Yamuna River are dependent on the deoxygenation rate of CBOD as well as the DO concentration of the Najafgarh Drain.

Butt and Evans. (1983) explained that channel dams, which are also known as low-head dams or weirs, have dramatic effects on the water quality of a stream. The weirs generate a water pool, affecting the free-flowing water's DO level. Reaeration in a stream water is related to water depth and velocity. If velocity is high, reaeration is high, and depth is high, reaeration is low. Also, it was explained that high temperature causes lower DO in water and vice versa. The factors affecting aeration are water levels, air and water temperature, height of the weir, depth of water above the weir, structural design of the weir, flow rate, and water depth at the foot of the weir. DO reduces up to 60% by adding sewage or tap water. DO concentration depends on the quality of water (Butts & Evans, 1983). Harbay et al. (1983), a river water quality management (WQM) was explained with the varying flow and wastewater control with the help of a water quality model (Herbay & MEERS, 1983) and a treatment facility was established to reduce the overall cost of treatment plants. Cubillo et al. (1992) used a revised QUAL2E for the major rivers of Madrid to attain a treatment plan and user interface developed for the river quality managers (Cubillo et al., 1992). Gabriel et al. (2000) used a combination of water allocation (MODSIM) and QUAL2E UNCAS model for Integrated WQM and established six WQM scenarios by varying the level of wastewater treatment for the Piracicaba River basin in Paulo, Brazil (Gabriel et al., 2000). The outcomes from the modeling approach suggested that constructing a new reservoir and diversifying to San Paulo to increase the downstream flow can maintain the water quality. Drolc and Konca (1996) stated that DO decreases in river water due to the disposal of organic and degradable sewage, and DO can increase by atmospheric reaeration and photosynthesis. They evaluated the water quality by QUAL2E for the River Sava Slovenia. The author suggested that wastewater from the Zalog station is required to treat and improve the water quality (Drolc & Konca, 1996). Dai and Labacie. (2001) applied MODSIM and QUAL2E models as integrated WQM programs for the lower Arkansas river basin of Colorado, and various management scenarios were established to maintain the quality and quantity of the water demands. They concluded that conjunctive uses of surface and groundwater can satisfy the demand for watery enhancing salinization (Dai & Labadie, 2001). Campolo et al. (2002) studied water quality control for the Arno River by changing the flow rate and local oxygenation and modifying the waste load using the transport model QUAL2E. With the increasing flow rate by reservoir management, DO decreases in the upper part, and at the downstream, with the reduction of BOD, DO increases. Dam management can be controlled water quality. External reaeration was done using local oxygenators at two places, and it was observed that two oxygenators could increase the DO level above 4 mg/l, although it was expensive. Therefore, weirs were evaluated as less expensive. Four weirs have been considered along the course as flow over the weir is able to entrap air and increase oxygenation. Oxygen quantity entering the stream can be estimated using empirical relation, which may be related to oxygen deficit, geometrical characteristics of the weir, fraction of flow over the weir, and height of the weir. Reduction of BOD concentration of wastewater can also increase the DO. Kannel et al. (2007) simulated the Bagmati River water quality using the QUAL2Kw model and developed a management approach. They have developed several scenarios by modifying pollutant loads, increasing upstream flow, and local oxygenation at critical points. After suggesting the possible flow augmentation and load modification, it was observed that the DO concentration could not be above 4 mg/l in some places. Hence, they have evaluated the effects of local oxygenators with a series of weirs at the critical points. Three critical points were found at 12.5 km, 13,5 km and 14.5 km and the selected height of the weirs were 1.35 m at 12.5 km and each 0.75 m at 13.5 km and 14.5 km. The DO profile met the required standard, and a reduction of DO concentration was observed at 12.25 km, 13.25 km, and 14.25 km due to increasing water depth and decreasing aeration coefficients behind the dams. Meanwhile, in another study, Kannel et al. (2007) stated that to control this river quality, the required load modification was achieved with 30 mg/l of BOD, 5 mg/l TN, 0.25 mg/l TP for the fixed sources, 1 m3/s of upstream flow, and local oxygenation at three critical points at 17, 18 and 19 km required 1 km height weirs. Ahn et al. (2017) studied the combined effects of weirs and reservoirs on the water quality of the Geum River using three models, including QUAL2E, during drought conditions. Sixteen weirs were constructed under the four river restoration projects, and river water quality improved. However, downstream water was dependent on the upstream water flow, including tributaries' water qualities. Jo et al. (2022) studied the effects of the Nakdong River water quality after constructing eight multi-functional weirs. After the construction of the weir, BOD concentration has been controlled. However, COD and TOC could not be controlled due to increasing water retention time and algal bloom. DO concentration was also improved. The study used multivariate statistics to conclude the critical reasons for changing the water environment.

CHAPTER 3

STUDY AREA AND RESEARCH METHODOLOGY

3.1 Study area

The present research develops a management approach for the urban river reach of Yamuna. Delhi is located in northern India between the latitudes of 28°24’17” and 28°53’00” North and longitudes of 76°50’24” and 77°20’37” East. Delhi spreads over 1483 km^2 with an elevation of 213m above the mean sea level (Said & Hussain, 2019). Delhi has two geographical components- the terminal part of the Aravali range and the Yamuna River. The Aravali range maintains the environmental conditions, whereas the River Yamuna fulfills about 70% of the city's total water demand (Sharma, 2013). Delhi's population increased tremendously due to migration from the nearby state, as shown in Table 3.1. Fig. 3.1 shows the decadal increment of population. Over the last two decades, growth rates have been falling due to the development of neighboring cities. However, Delhi accounts for about 1.39% of India’s population and is one of the most populated cities in the world (About MPD-2041, 2021). Table 3.2 shows the urban and rural areas of Delhi.

Table 3.1: Decadal growth rate of Delhi’s population

Census	Decadal Growth Rates of Delhi
1951-61	52.44%
1961-71	52.91%
1971-81	52.98%
1981-91	51.45%
1991-01	47.03%
2001-11	21.03%

(MoEF-DDA-Expert, 2014)

Table 3.2 Urban and Rural Areas of Delhi

Sr. No	Classification of area	1991		2001		2011	
		Sq. km	%	Sq.km	%	Sq.km	%
1	Rural	797.66	53.79	558.32	37.65	369.35	24.9
2	Urban	685.34	46.21	924.68	62.35	1113.65	75.1
3	Total	1483.00	100.00	1483.00	100.00	1483.00	100.00

Demographic profile Delhi Source:(Economic Survey of Delhi, 2018-19)

3.1.1 Delhi: Yamuna River basin

Yamuna River (Fig. 3.2), the largest tributary of the River Ganga, emerges from an elevation of about 6387 m above mean sea level. Yamunotri glacier near Bander Punch h (38°59'N 78°27'E) in the Mussourie range of the lower Himalayas, in the district of Uttarkashi (Uttarakhand). Before reaching Delhi at Palla, the river crosses some of the states of Uttaranchal, Uttar Pradesh, Himachal, Haryana, Madhya Pradesh, and the entire state of Delhi (CPCB, 2009). The river enters Delhi in Palla Village and, traversing 26 km, reaches Wazirabad (MoEF, 2014). The river enters Delhi in Palla Village and, traversing 26 km, reaches Wazirabad (Joshi et al., 2022). After reaching Wazirabad, around 23 km upstream (Joshi et al., 2022), most indigenous water withdraws and supplies to Delhi, and the perennial river remains little or no fresh water. From Wazirabad to Okhla, the river feeds 16 main drains containing around 3000 MLD of wastewater with 265 TPD of BOD load (DPCC, 2020). National Green Tribunal, 2014 also reported that the national capital of India leads to pollution of the Yamuna River Delhi stretch by drains containing domestic and industrial sewage. Due to the disposal of untreated and partially treated wastewater from different sewage treatment plants through these drains, the river stretch becomes mostly anoxic after the Wazirabad barrage. It contains high oxygen-demanding substances, microorganisms, and nutrients. The study includes Delhi’s 22 km urban river reach between the Wazirabad barrage to the Okhla barrage and sixteen outfalling drains. Downstream of Wazirabad (around 25 km), the river again diverted to Agra Canal for irrigation water supply and tapped at Okhla barrage (Sharma, 2013). Subsequently, little or no flow is allowed during the dry season. Downstream of Okhla Barrage, the river again acquired wastewater from the Shadra drain, which collects wastewater from Shaibabaad, East Delhi, and Noida.

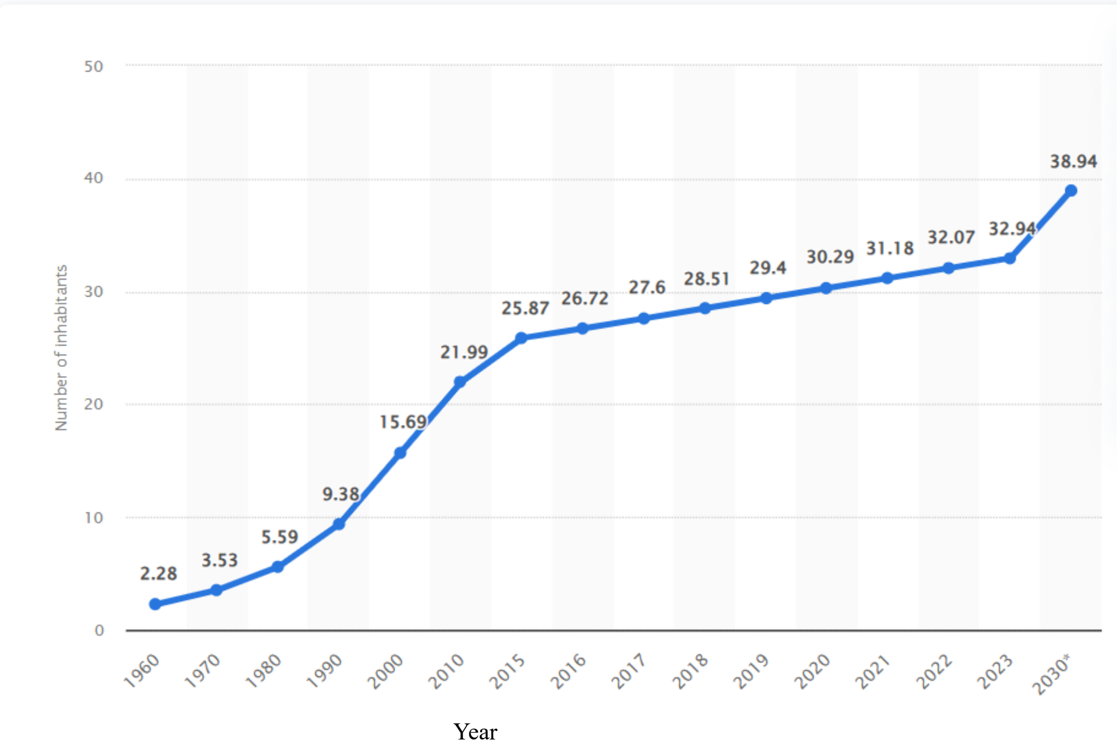
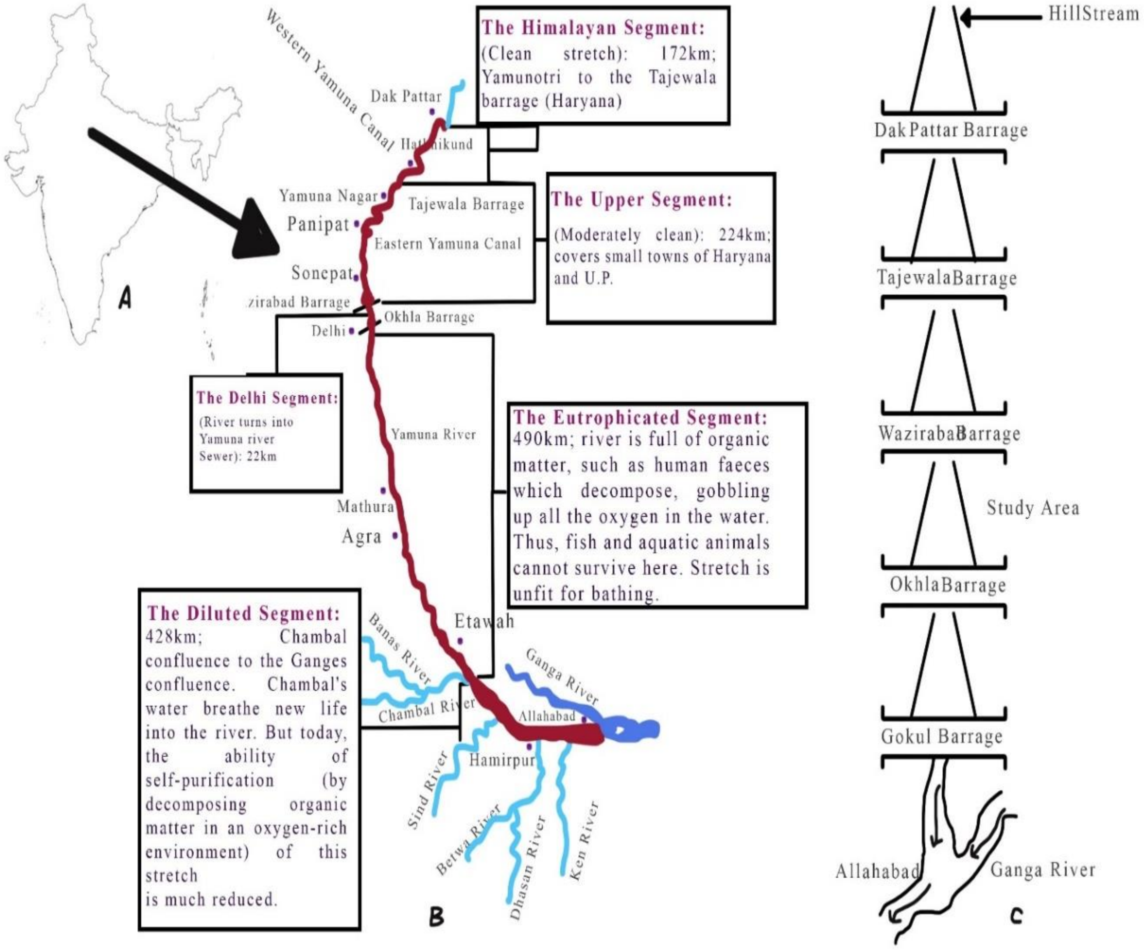


Figure 3.1 Population of Delhi metropolitan area in India from 1960 to 2023, with estimates for 2030(in millions) (www.statistica.com accessed 3/01/2024)



The Himalayan Segment: (Clean stretch): 172km; Yamunotri to the Tajewala barrage (Haryana)

The Upper Segment: (Moderately clean): 224km; covers small towns of Haryana and U.P.

The Delhi Segment: (River turns into Yamuna river Sewer): 22km

The Eutrophicated Segment: 490km; river is full of organic matter, such as human faeces which decompose, gobbling up all the oxygen in the water. Thus, fish and aquatic animals cannot survive here. Stretch is unfit for bathing.

The Diluted Segment: 428km; Chambal confluence to the Ganges confluence. Chambal's water breathe new life into the river. But today, the ability of self-purification (by decomposing organic matter in an oxygen-rich environment) of this stretch is much reduced.

Figure 3.2 River Yamuna (A) Basin Map (B) Classification of the river concerning pollution (c) Barrage locations (CPCB, 2006)

Fig. 3.3 shows the Yamuna River basin area, 366,223 km^2 (141,399 sq mi), 40.2% of the entire Ganges Basin. After Okhla Barrage, the river receives water from its tributaries like Chambal, Sindh, Betwa, and Ken and joins the River Ganga along with an underground River Saraswati at Prayag (Allahabad) after traveling approximately 1370 km (CPCB, 2006). The basin covers 10.7% of the country's area. Five barrages in the river result in highly variable flow conditions throughout the year. From October to June, the river remains "dry" or observes very little flow in many stretches, whereas it is "flooded" during the monsoon period (July to September). The river water irrigates about 6 million hectares of land in the entire basin. The river water is used for both abstractive and in-stream uses, including irrigation, domestic and industrial consumption, etc. The stretch between the Wazirabad barrage and the Chambal River confluence (580km) is critically polluted due to the addition of partially or untreated effluent from 28 wastewater drains (CPCB, 2006). It has been observed that both point and non-point sources contribute to the river's pollution, with

Delhi being the major contributor, followed by Agra and Mathura. The climatic condition of this area varies between hot in summer and cold in winter. The average summer temperature is 32°C, with a maximum temperature of 45°C. At the same time, the average temperature in winter is 12-13°C, and the lowest temperature is around 2°C (Arora & Keshari, 2021b). The monsoon period starts from late June to September, and the highest average rainfall was approximately 515mm in August (Joshi et al., 2022). During this time, wastewater dilutes with rainwater and improves river quality. Hence, variation in water quality was observed during the monsoon period. Delhi has collected water from surface water as well as groundwater. Fig. 3.4 shows the water cycle in Delhi. It has been seen that Yamuna River water has been used for different purposes, including domestic, agricultural, and industrial. Wastewater generated from these sections finds its way to STPs and CEPTs via wastewater drains. Fig. 3.5 shows the STP location in the study area.

Table 3.3 Locations of the monitoring stations (DPCC Domain)

Monitoring sites	Coordinates
S1	28°42'47.27"N, 77°13'54.95"E
S2	28°40'16.87"N, 77°14'1.72"E
S3	28°37'42.34"N, 77°15'12.59"E
S4	28°35'29.62"N, 77°16'17.52"E
S5	28°32'40"N, 77°18'49"E

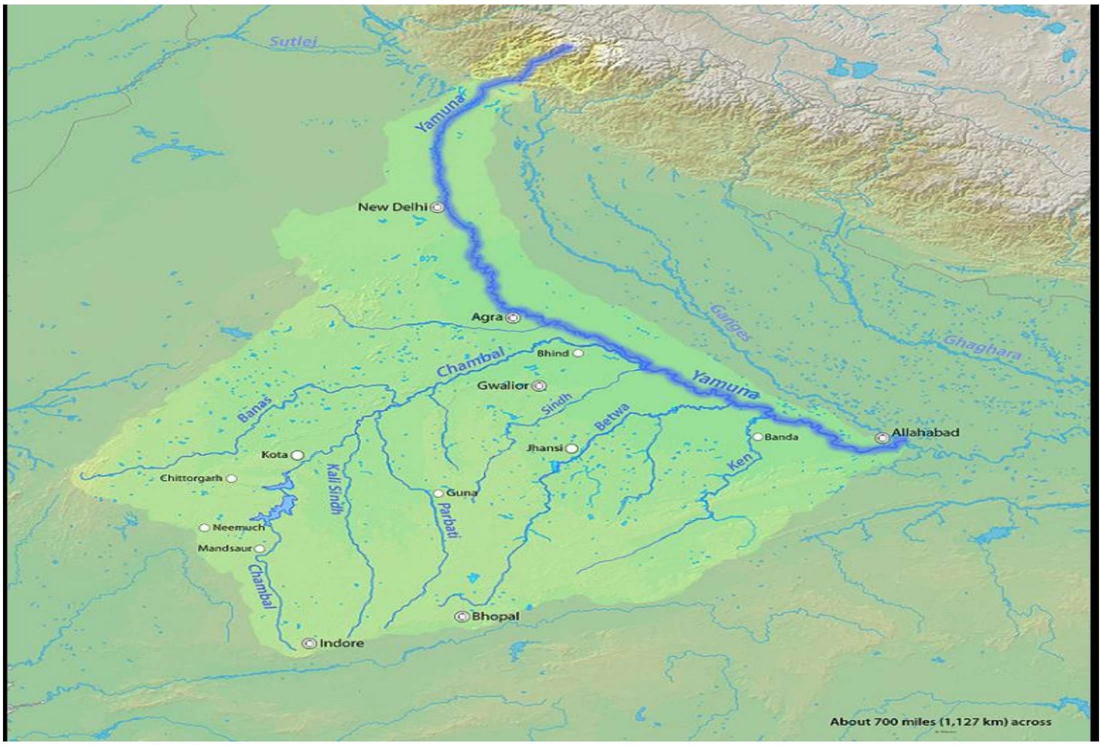


Figure 3.3 Yamuna River Basin with its tributaries (Source: https://en.m.wikipedia.org/wiki/Yamuna)

3.2 Research Methodology

This research aims to develop a methodological framework that includes the application of water quality models in formulating a river management plan. Fig. 3.7 shows a description of the framework of the research methodology. For evaluating the water quality management approaches, the water quality data of the study area was gathered from five monitoring stations, as shown in Table 3.3. Moreover, spatiotemporal variations of the water quality assessment have been done for upstream and downstream stations to determine whether the water quality criteria have been achieved. If not, then studying past and existing projects is necessary. Subsequently, new water quality management approaches are required to be developed. To establish water quality management approaches, it is essential to identify an appropriate water quality model to predict the fate of the pollutants. This includes finding an existing validated WQM for the study region. If one exists, then the model can be used for scenario generation. Otherwise, water quality models were reviewed and screened based on their strengths and limitations. After that, the screened model was applied and evaluated using past data. The selected model(s) are calibrated, validated, and statistically tested using the observed and predicted water-quality values, and the best-fit model (in case of more than one model) was selected based on the statistical analysis. Then, the selected model is used to conduct intervention analysis and scenario generation to identify the assimilation capacity and maximum allowable pollutant load and develop an appropriate water quality management plan.

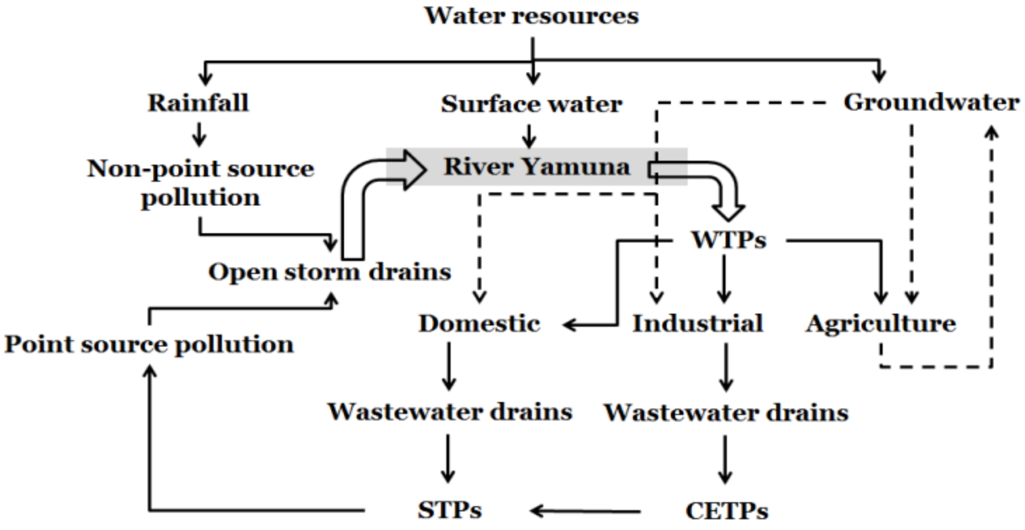
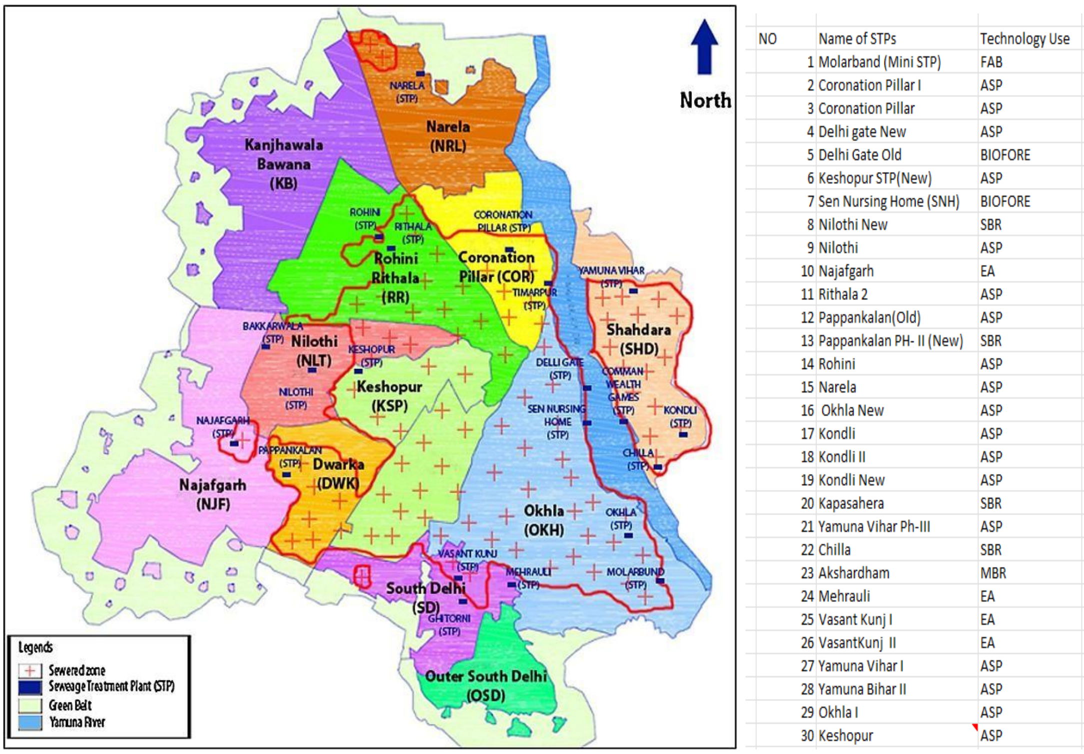


Figure 3.4 Water cycles of Delhi. Source:(Sharma, 2013)



NO	Name of STPs	Technology Use
1	Molarband (Mini STP)	FAB
2	Coronation Pillar I	ASP
3	Coronation Pillar	ASP
4	Delhi gate New	ASP
5	Delhi Gate Old	BIOFORE
6	Keshopur STP(New)	ASP
7	Sen Nursing Home (SNH)	BIOFORE
8	Nilothi New	SBR
9	Nilothi	ASP
10	Najafgarh	EA
11	Rithala 2	ASP
12	Pappankalan(Old)	ASP
13	Pappankalan PH- II (New)	SBR
14	Rohini	ASP
15	Narela	ASP
16	Okhla New	ASP
17	Kondli	ASP
18	Kondli II	ASP
19	Kondli New	ASP
20	Kapasahera	SBR
21	Yamuna Vihar Ph-III	ASP
22	Chilla	SBR
23	Akshardham	MBR
24	Mehrauli	EA
25	Vasant Kunj I	EA
26	VasantKunj II	EA
27	Yamuna Vihar I	ASP
28	Yamuna Bihar II	ASP
29	Okhla I	ASP
30	Keshopur	ASP

Figure 3.5 STPs location with no and drainage area in Delhi (Source: Wastewater-treatment-plants-and-drainage-zones-in-NCT-of- Delhi-DJB-2014-modified)

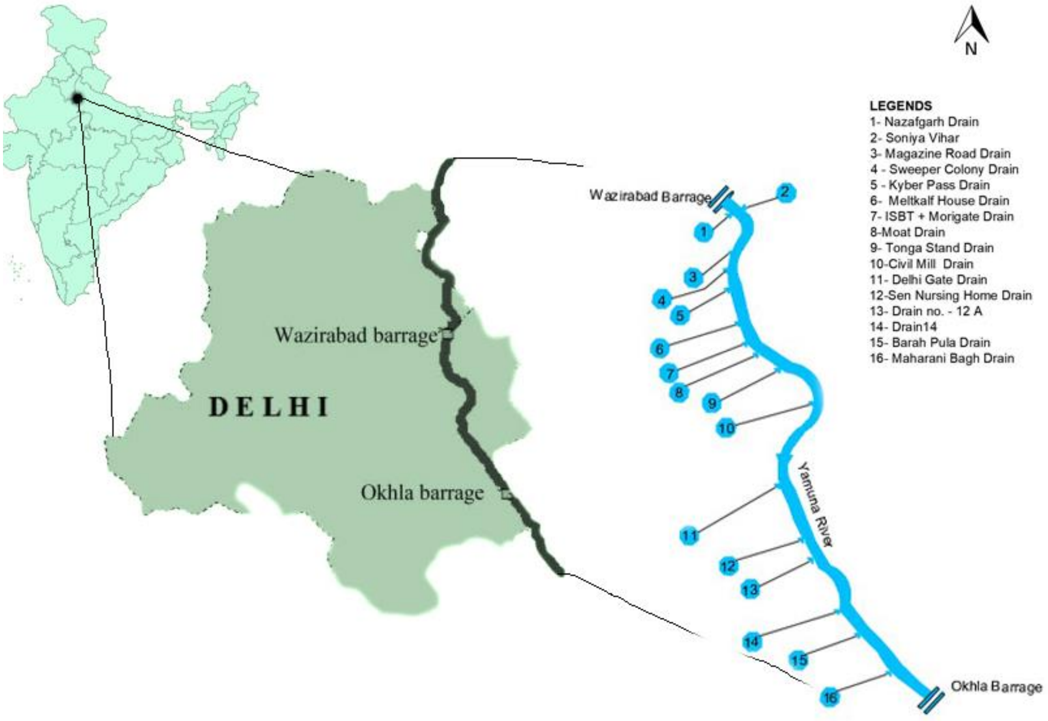


Figure 3.6 (a) Study area with point sources (DPCC 2020)

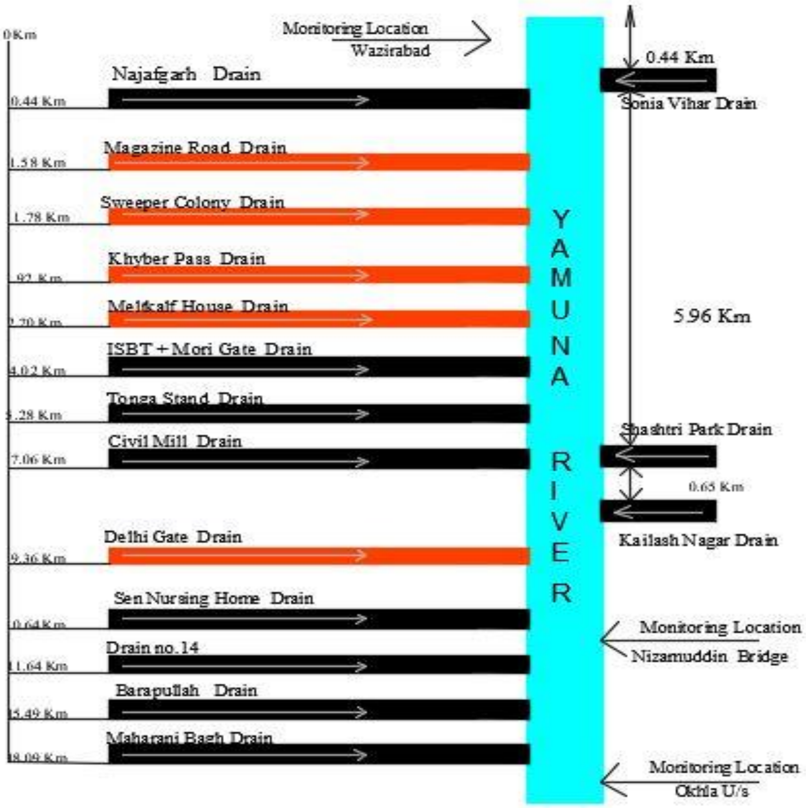


Figure 3.6 (b) Study area with distances of point sources (DPCC, 2020)

3.2.1 Water quality assessment

The present study collected data from the real-time water quality monitoring stations at ST1 (6085 hourly observations) and ST5 (25540 no observations at 15-minute intervals). The observation period was March 2021 to February 2022. The parameters analyzed were DO, conductivity, BOD, COD, pH, water temperature, turbidity, NH4 nitrogen, NO3 nitrogen, TSS, and TOC. Hourly data was used for multivariate analysis, and valuable information was extracted. Hourly data are subdivided monthly to evaluate the average monthly water quality variations by Box Whisker plots. For PCA/FA, complex datasets were divided into four subdivisions – Summer, monsoon, post-monsoon, and winter. Box-whisker plots were used to interpret the temporal and spatial variation in 11 parameters. Significant parameters have introduced a classification for further assessment. The data sets were subdivided monthly, and Box whisker plots were drawn for each parameter and both stations to interpret the spatiotemporal variations of parameters. Principal component analysis is a data-minimizing method (Singh et al., 2020). It gives details of the most crucial constituents, explaining the variability of data sets (Singh et al., 2004). PCA reshapes the Indigenous variables into a lower set(Vega et al., 1998) and can be expressed as (Bu et al., 2010)

$$z_{ij} = a_{i1}x_{1j} + a_{i2} + a_{im}x_{mj} \tag{3.1}$$

Where z and a are component score and loading, respectively, x=observed variables quantity. I= constituent no, j=sample no, m= total no of variables. FA was computed using varimax rotation generating factors. PCA is included in FA, and FA is the dominating tool to lower the dimensionality of the data matrix with a high no of related variables (Singh et al., 2004). The PCs are extracted from the cross-product data matrix and help to explain the disintegration of multiple parameters by obtaining eigenvalues and eigenvectors. Varifactors or factors obtained after rotating Varimax rotation distributes PCs loading by maximizing the dispersion and minimizing the number of co-efficient. This tool extracts latent information and discriminates parameters with a large load. The PCs are used for varimax rotation and generate varifactors (VFs), including hypothetical, latent, and unobservable values, to gather the details(Helena et al., 2000). FA simplifies the data structure coming from PCs and decreases the contribution of low-significant observations (Bu et al., 2010).

$$z_{ij} = a_{f1}f_{i1} + a_{f2}f_{i2} + \cdots + +e_{fi} \dots\dots\dots\dots\dots\dots\dots\dots \tag{3.2}$$

where z= observed variables, a and e are factor loading and score, e= residual term associated with error and other variations, i = sample no, m= no of factor. For PCA/FA, water quality datasets were arranged into four main seasons: Summer, monsoon, post-monsoon, and winter. The data were standardized to classify correctly for the higher difference in data dimensionality(Liu et al., 2003). The PCs are extracted from the cross-product data matrix and help explain multiple parameters' disintegration by obtaining eigenvalues and eigenvectors. Varifactors or factors obtained after rotating Varimax rotation distributes PCs loading by maximizing the dispersion and minimizing the number of co-efficient. Standardization makes variables dimensionless to enhance their influence with different variances by eliminating the different measurement units(Singh et al., 2004). PCA was applied, and the variance, covariance, loading, and score were calculated. All the computations were performed using Excle2019, SPSS 20.0, and Origin Pro (2022).

3.2.2 Water Quality Trend Analysis

Ten years of data for the River Yamuna Delhi has been collected from DPCC for the five stations for water quality trend analysis. The water quality parameters analyzed were DO, BOD, COD, and pH. Box Whisker plots were drawn for the data from 2013-2022 (Table A6). Time series trend analysis for DO, BOD, and COD has been done with ORIGIN PRO 2023. A simple time series was done with single exponential smoothing varying Alpha constants. The square root of mean deviation, mean absolute deviation, and mean squared deviation (Table A7) were determined and smoothed, and predicted plots were drawn.

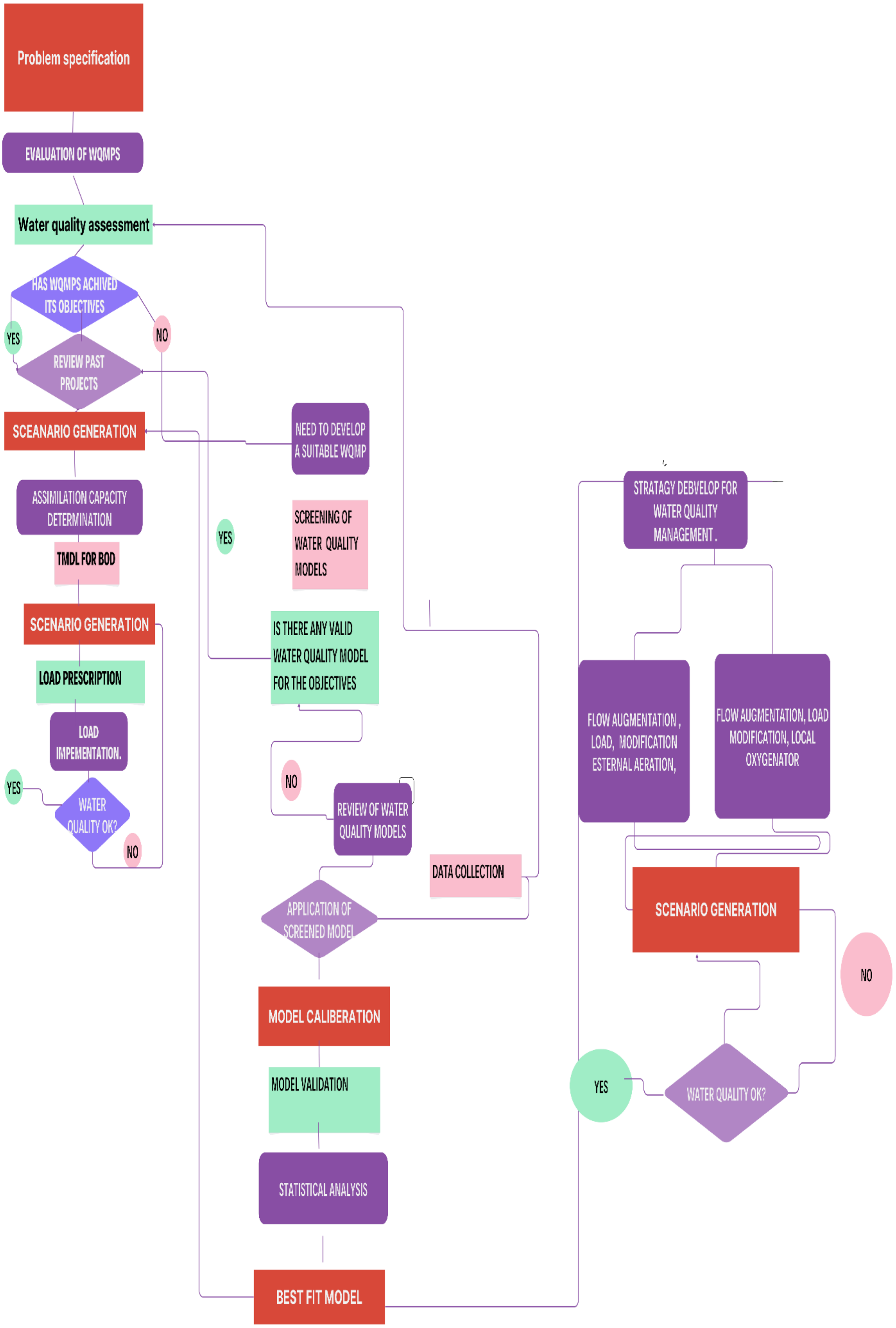


Figure 3.7 Research Methodology

3.2.3 Point and non-point sources inventory

Point source data were collected from DPCC for July 2019-November 2023(Table A9). BOD and COD data were collected, and Box whisker plots were drawn for sixteen drains. Frequencies for different BOD and COD counts have been drawn. Trend analysis of BOD and COD for sixteen drains was also drawn by ORIGIN PRO 2023. For non-point sources evaluation, land use patterns and land cover pattern data have been collected from the National Natural Management System, ISRO, and rainfall data has been collected from IARI.in. Sewage Treatment Plant data from 38 STPs (DPCC Domain) has been collected from Nov2020-Nov2022, as shown in Tables A16 and A17.

3.3 QUAL2Kw Model Development

The QUAL2Kw model is a simple water quality model with less critical data and an integrated tool for the sustainable management and protection of a river system. Although a complex model can represent the waterbody more accurately, these models may be reserved for large and deep rivers and require much data. For a large amount of data, data collection and monitoring systems imply high cost and highly expertise systems. The model framework can reasonably be applied to small and large basins to evaluate effects and required modifications in the system. It is a good framework with less precise data as it has accumulated default values. Again, it has an auto-calibration system, so it calibrates the reaction constants very fast. Equations 3.3-3.88 are the governing equations used in the formulation of the model, and equation 3.9 has been used for auto-calibration. For QUAL2Kw, the general mass balance for a substance present in the water column of a reach i is (Pelletier and Chapra, 2008)

$$\frac{dc_i}{dt} = \frac{Q_{i-1}}{V_i} c_{i-1} - \frac{Q_i}{V_i} c_i - \frac{Q_{ab,i}}{V_i} c_i + \frac{E'_{i-1}}{V_i}\left(c_{i-1} - c_i\right) + \frac{E'_i}{V_i}\left(c_{i+1} - c_i\right) + \frac{W_i}{V_i} + S_i + \frac{E'_{hyp,i}}{V_i}\left(c_{2,i} - c_i\right) \quad (3.3)$$

The general mass balance equation for a constituent concentration in the hyporheic sediment zone of a reach ($c_{2,i}$) is written as

$$\frac{dc_{2,i}}{dt} = S_{2,i} + \frac{E'_{hyp,i}}{V_{2,i}}\left(c_i - c_{2,i}\right) \quad (3.4)$$

The input load is calculated as

$$W_i = \sum_{j=1}^{psi} Q_{ps,i,j} c_{psi,j} + \sum_{j=1}^{npsi} Q_{nps,i,j} c_{npsi,j} \quad (3.5)$$

Flow balance equation

$$Q_i = Q_{i-1} + Q_{in,i} - Q_{ab,i} \quad (3.6)$$

$$Q_{in,i} = \sum_{j=1}^{psi} Q_{ps,i,j} + \sum_{j=1}^{npsi} Q_{nps,i,j} \quad (3.7)$$

$$Q_{ab,i} = \sum_{j=1}^{pai} Q_{pa,i,j} + \sum_{j=1}^{npai} Q_{npa,i,j} \quad (3.8)$$

where Q_i = from reach I outflow into the downstream reach (i + 1) in m^3/d Q_{i-1} = inflow, upstream reach (i – 1) i[m^3/d], $Q_{in,i}$ i= the total inflow from point and nonpoint sources int[m^3/d], and $Q_{ab,i}$= total outflow from point and nonpoint abstractions [m^3/d] to the reach, psi = the total number of point sources to reach i, $Q_{nps,i,j}$ non-point source inflow to reach i [m^3/d] from jth point, and $npsi$ = total non-point source inflows to reach i. p_{ai} = total number of point abstractions from reach i, W_i = the external loading to reach i [mg/d], S_i = sources and sinks of the constituents $Q_{npa,i,j}$ is the jth non-point abstraction outflow from reach i [m^3/d], v_a = phytoplankton settling velocity [m/d], Auto calibration for fitness

$$f(x) = \left[\sum_{i=1}^{q} W_i\right]\left[\sum_{i=1}^{q} \frac{1}{W_i}\left[\frac{1}{m}\sum_{j=1}^{m} O_{i.j} \Big/ \left[1/m \sum_{j=1}^{m}(P_{i,j} - Q_{i,j})^2\right]^{1/2}\right]\right] \tag{3.9}$$

3.3.1 Model set up

The QUAl2Kw model has been used in this study to simulate BOD, COD, DO, and pH. This framework divided the reach into unequal, properly mixed segments of the same hydrological and water quality conditions (Kang et al., 2020). The 22 km river reach has been divided into fourteen segments depending on the confluence of drains as point sources. The model’s capabilities and descriptions are found in the user manual of QUAL2Kw. The framework is suitable for the river to reach with more or less constant pollutant loads and flow (Oliveira et al., 2012). The input data comprised headwater flow and water quality data, 16 outfalling drains wastewater flow, and quality data as point sources. These point sources carry domestic and industrial wastewater and discharge from sewage treatment plants. Delhi receives deficient rainfall; hence, surface runoff is very low. Besides this, some diffused sources of pollutant loads are used for cattle bathing, washing clothes, and bathing people. The model was calibrated using low flow and dry period data for March 2021. Geometrics and hydraulics data are shown in Table 2. Calibration was done repeatedly until the predicted values came closer to actual conditions. The Manning constant and river slope have been taken as 0.05 and 0.0002, respectively (Ghosh & Singh, 2001). Manning’s equation was used for limited data availability. The BOD values were taken as CBODf and COD as generic constituents. The constituents included in the model are flow, temperature, BOD, DO, COD, pH, conductivity, and alkalinity. Due to data constraints, nutrient data was not included in this study. There are data constraints for the modeling of DO/BOD of the Yamuna River, Delhi. The model QUAl2Kw can be simulated with limited data conditions. If only BOD_5 data is available and it can be used as $CBOD_5$, and CBODu could be approximated as 1.46 * BOD_5, assuming the typical values of BOD decay rate as 0.23 day^{-1} (Palletier and Chapra, 2008). The present water quality monitoring of this river reach is based on BOD, COD, and DO. Lung (2022) stated that no data is available to determine the instream deoxygenation rate K_d, and this should be addressed for future conditions and concluded that k_d values ranged from 0.1-o.4 day^{-1}.

For the slow-moving river with shallow depth, the O'Conner-Dobbins equation has been used to calculate reaeration constants (Paliwal et al., 2007). The BOD and DO deal with the mechanism of sedimentation and settling, but due to low oxygen availability, 25% settleable BOD (CPCB, 82) decomposes in anoxic conditions and hence no trade of DO (Paliwal et al., 2007). Again, product methane rises upward, and due to buoyant forces, settled substances resuspend (Kazmi & Hansen, 1997). Due to high turbidity, sunlight is obstructed (Kazmi,2000), and hence phytoplankton activities are negligible. The variation in dissolved oxygen due to photosynthesis and respiration is insignificant for this reach (Parmar & Keshari, 2014). An exponential model was chosen for oxygen inhabitation for CBOD, and the calculation step was set to 2.8125 for model stabilization. Except for the monsoon period, flow conditions are almost the same throughout the year (CPCB, 2000). The non-monsoon flow prevails most of the year, and critical flow is essential to determine the assimilation capacity. For calibration and validation, 1m^3/s flow is assumed at the upstream point (Parmar & Keshari, 2014). The Yamuna River, Delhi, is polluted with loads from different nonpoint sources. Although groundwater recharge is negligible for this area, pollution from nearby slum areas, cattle bathing, and agricultural runoff should be considered (Kazmi & Hansen, 1997). In this study, 1 mg/l of distributed BOD load has been adjusted after a 5 km distance. The model was run until simulated values agreed with observed values. The model was auto-calibrated for a population size of 100 and 50 generations, and simulation was done with new datasets for April 2022 for confirmation. The root means squared error was calculated to verify the calibration result with validation results. Air temperature has been collected from Indian Meteorological Department (maximum and minimum). The dew point temperature has been calculated. Wind speed and cloud cover data have been collected from worldweather.com and AccuWeather. Global values for rate parameters have been used. The rate parameters used for these studies were slow CBOD, fast CBOD, and genetic constituents. The post-monsoon period model was calibrated from October to December 1999-2005 and validated for the same months from 2006-2008. The rate sheets used for calibration and validation are shown in Table A12. Tables A13, A14, and A15 show the reparation constraints, climatic conditions, and light sheets used for calibration and validation.

3.3.2 Assimilation capacity

In this study, data has been obtained from the Delhi Pollution Control Committee (DPCC), which is responsible for collecting data on Delhi's reach and all the drains outfalling between the distances. The monitoring stations included in this study covered five stations of DPCC ST1(Wazirabad downstream), ST2(ISBT), ST3(ITO), ST4(Nizamuddin bridge), and ST5(Okhla Upstream). The DO, BOD, COD, and pH water quality data were collected for March 2021 and April 2022. For the Delhi region, March-May is the low flow period due to negligible rainfall, known as the pre-monsoon period. The sixteen outfalling drains were taken as point sources, and data were collected from DPCC. Due to data constraints, only four parameters were collected and simulated. The model QUAL2Kw was selected for this study, and the average data of March 2021 was used for calibration, and April 2022 was used for confirmation.

3.3.3 Scenario generation for assessment of assimilation capacity

The model developed in this study for the urban river reach of Delhi has been applied to assess the assimilation capacity of this polluted stretch. Hence, four cases were studied, generating 41 scenarios varying the BOD and COD load with flow augmentation. Table 4.10 shows input BOD and COD loads with point source flow. The head water flow has been increased at ten cumecs intervals for different scenarios. The scenarios were generated to achieve the water quality suggested for this river stretch, i.e., Class 'C' by the Central Pollution Control Board (CPCB), India. For this criterion, river water should maintain DO greater than 4 mg/l and BOD less than 3 mg/l. The upstream flow has been increased to keep the requirements by adding different BOD and COD loads. Fig. 3.8 shows the cases generated for different scenarios to assess the assimilation capacity of the urban river reach of Delhi.

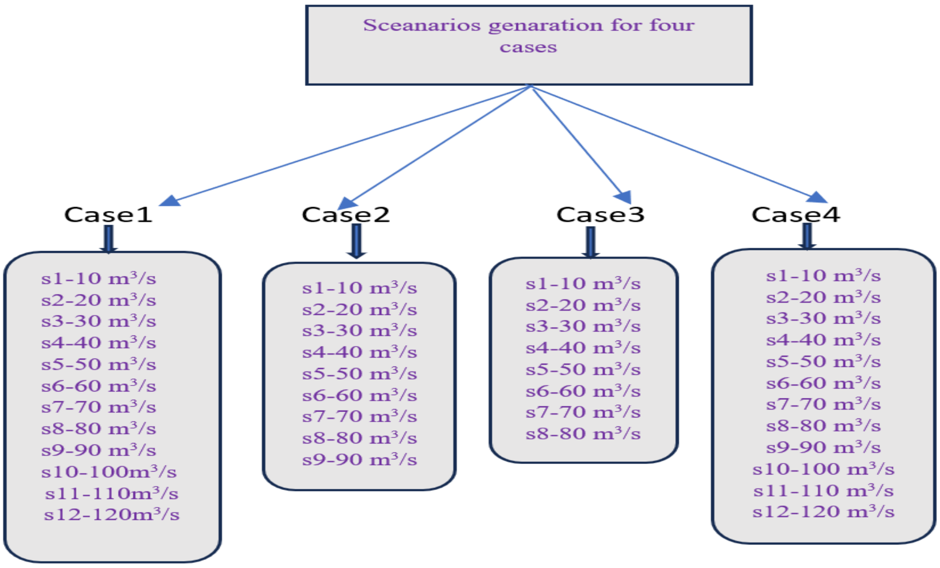


Figure 3.8 Methodology for scenarios of determination of assimilation capacity

Table 3.4 Strategies for assessment of assimilation capacity of the river reach

Sl. No	Description
1 Strategy -1	Without any pollutant load
2 Strategy -2	With existing BOD and COD load
3 Strategy -3	Load modification and flow augmentation

3.4 Methodology for TMDL assessment

TMDL assessment was done for the water quality parameter BOD, keeping the target below 3 mg/l. The developed water quality model in section 3.3 was used to simulate different scenarios. Ten scenarios have been evaluated, including varying BOD load and upstream flow. In the first five simulations (Scenario A), only the BOD load of different point sources was varied, and the upstream flow was kept as 10 cumecs, which are suggested for the minimum flow for this reach. For simulations 6-9 (Scenario B), upstream flow increased up to 50 cumecs with varying BOD inputs. In simulation 10 (Simulation C), the flow was kept at 50 cumecs, and the BOD load decreased more to achieve a better-predicated value. Table 3.5 shows the upstream flow and load modification used for different simulations regarding the TMDL assessment of BOD. Tables 3.6 and 3.7 show the load modification for scenarios A, B and C, respectively.

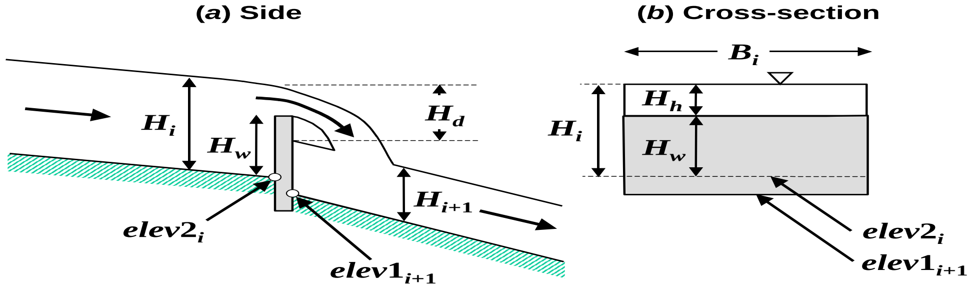
Table 3.5 BOD loading and upstream flow for different scenarios

Scenarios	Simulation No	Descriptions
A	Simulation1	D1-16 BOD load 10 mg/l, Upstream flow 10 cumecs
	Simulation2	D1-16 BOD load 5 mg/l, Upstream flow 10 cumecs
	Simulation3	D1- 2.5 mg/l, D2- D16 5 mg/l of BOD, Upstream flow 10 cumecs
	Simulation4	D1 3 mg/l, D2-16 5 mg/l BOD and upstream flow 10 cumecs
	Simulation5	D1 3 mg/l, D2—D12 5 mg/l, D13-14 2.5 mg/l, D15-16 5 mg/l BOD and upstream flow 10 cumecs
B	Simulation6	D1-D16 with 10 mg/l of BOD and 20 cumecs of upstream flow
	Simulation7	D1-D16 5 mg/l of BOD and upstream flow 30 cumecs
	Simulation8	D1 4 mg/l, D2-D16 5 mg/l of BOD and Upstream flow 40 cumecs
	Simulation9	D1 with 4mg/l, D2-D10 with 5 mg/l, D11-D16 with 15 mg/l BOD load and upstream flow 50 cumecs
C	Simulation10	D1 with 4 mg/l, D2 with 0 mg/l, D3-12 with 30mg/l, D13-14 with 20 mg/l and D15-16 with 15 mg/l, Upstream flow 50 cumecs

*D5 has no flow

3.5 Methodology for Water Quality Management Plan

The developed QUAL2Kw model has been run for different scenarios to achieve suitable management plans to maintain the required water quality criteria for BOD and DO. Two management plans were developed. In the first plan, 23 scenarios were developed with varying upstream flow (Table 3.8 and 3.9): point sources flow, DO, BOD, and COD. Point sources are assumed to be at critical locations, as some small drains can be diverted, and those are showing little or no flow. Six outfalling drains were assumed at locations 0.44, 5, 8, 11, 13, and 15km downwards from Wazirabad. Small drains may be diverted in these drains. In case 1, all point sources except D1 assumed zero flow, and the model has been run with 25 cumecs wastewater input from D1. Headwater flow conditions are shown in Table A11. Case 2 was established assuming all the point sources input 1 cumecs except D1. All the cases for approach 1 have been shown in Table A12. Up to 50 cumecs upstream flow has been varied, and DO and BOD profiles have been studied. The load has been modified for each headwater flow value, and simulation profiles are drawn. Plan 2 was established using weirs at the critical points with sharp oxygen declination. In QUAL2Kw, reach sheets and weir options have been adopted.


(*a*) Side

(*b*) Cross-section

Figure 3.9 (a-b) Weirs for local oxygenation (Peletier & Chapra, 2005)

Table 3.6 Load Modification for Scenario A

Point Source	*Flow, MLD	*Avg BOD	Simulation (BOD in TPD)				
			1	2	3	4	5
D1	1938.8	133.82	19.3838	9.691	4.846	5.861	5.861
D2	114.05	9.12	1.1405	0.570	0.570	0.570	0.570
D3	4.32	0.3	0.0432	0.022	0.022	0.022	0.022
D4	5.4	0.1	0.054	0.027	0.027	0.027	0.027
D6	3.45	0.11	0.0345	0.017	0.017	0.017	0.017
D7	37.94	2.67	0.3794	0.189	0.189	0.189	0.189
D8	4.46	0.59	0.0446	0.022	0.022	0.022	0.022
D9	5.76	0.75	0.0576	0.029	0.029	0.029	0.029
D10	11.14	0.67	0.1114	0.056	0.056	0.056	0.056
D11	9	2.7	0.09	0.045	0.045	0.045	0.045
D12	39.02	3.43	0.3902	0.195	0.195	0.195	0.195
D13	31.53	4.69	0.3153	0.158	0.158	0.158	0.080
D14	6.54	0.07	0.0654	0.033	0.033	0.017	0.009
D15	151.77	10.46	1.5177	0.759	0.759	0.379	0.379
D16	30.16	3.51	0.3016	0.151	0.151	0.151	0.075
Total	2392.92	172.99	23.93	11.96	7.12	7.74	7.58

*Yamuna 2020

Table 3.7 BOD loading Scenario B and C (BOD in TPD)

Point Sources	*Flow(MLD)	Scenario B Simulations				Scenario C Simulation
		6	**7**	8	9	10
D1	1938.38	19.384	9.691	7.752	7.752	7.752
D2	114.05	1.1405	0.570	0.570	0.570	No flow
D3	4.32	0.0432	0.022	0.022	0.022	0.132
D4	5.40	0.0540	0.027	0.027	0.027	0.162
D6	3.45	0.0345	0.017	0.017	0.017	0.104
D7	37.94	0.3794	0.189	0.189	0.189	1.138
D8	4.46	0.0446	0.022	0.022	0.022	0.134
D9	5.76	0.0576	0.029	0.029	0.029	0.173
D10	11.14	0.1114	0.056	0.056	0.056	0.223
D11	9.00	0.0900	0.045	0.045	0.135	0.270
D12	39.02	0.3902	0.195	0.195	0.585	0.781*
D13	31.53	0.3153	0.158	0.158	0.473	0.473*
D14	6.540	0.0654	0.033	0.033	0.098	0.131*
D15	151.77	1.5177	0.759	0.759	2.277	2.277*
D16	30.16	0.3016	0.151	0.151	0.420	0.603*
Total	2392.92	23.93	11.96	10.03	12.67	14.35

*Include 4mg/l of DO

Table 3.8 Headwater conditions for different cases for water quality management plan varying upstream flow and pollutant load modification

Cases	Flow (Cumecs)	DO, BOD and COD (mg/l)
Case 1-2	1	4, 3 and 25
Case 3-4	10	4, 3 and 25
Case 5-7	20	4, 3 and 25
Case 8-9	30	4, 3 and 25
Case 10-17	40	4, 3 and 25
Case 18-23	50	4, 3 and 25

Table 3.9 Point source load for different cases of water quality management with flow augmentation and load modification (Distance in km, Flow in cumecs, BOD in mg/l, COD in mg/l, DO in mg/l)

No	Distance	Flow	DO	BOD	COD	Flow	DO	BOD	COD
Case1						Case 2			
D1	0.44	25	0	10	50	25	4	10	50
D2	5.0	0	0	0	0	1	4	10	50
D3	8.0	0	0	0	0	1	4	10	50
D4	11.0	0	0	0	0	1	4	10	50
D5	13.0	0	0	0	0	1	4	10	50
D6	15.0	0	0	0	0	1	4	10	50

Case 3						Case 4			
No	Distance	Flow	DO	BOD	COD	Flow	DO	BOD	COD
D1	0.44	25	4	10	50	25	4	10	50
D2	5.0	1	4	10	50	1	4	10	50
D3	8.0	1	4	10	50	1	4	10	50
D4	11.0	1	4	10	50	1	4	10	50
D5	13.0	1	4	10	50	1	4	10	50
D6	15.0	1	4	10	50	1	4	10	50
Case 5						Case 6			
D1	0.44	25	4	10	50	25	4	8	50
D2	5.0	1	4	10	50	1	4	10	50
D3	8.0	1	4	10	50	1	4	10	50
D4	11.0	1	4	10	50	1	4	10	50
D5	13.0	1	4	10	50	1	4	10	50
D6	15.0	1	4	10	50	1	4	10	50
Case 7						Case 8			
D1	0.44	25	4	7	50	25	4	10	50
D2	5.0	1	4	10	50	1	4	10	50
D3	8.0	1	4	10	50	1	4	10	50
D4	11.0	1	4	10	50	2	4	10	50
D5	13.0	1	4	10	50	2	4	10	50
D6	15.0	1	4	10	50	2	4	10	50
Case9						Case 10			
D1	0.44	25	4	10	50	25	4	10	50
D2	5.0	1	4	10	50	1	4	10	50
D3	8.0	1	4	10	50	1	4	10	50
D4	11.0	2	4	10	50	2	4	10	50
D5	13.0	2	4	10	50	2	4	10	50
D6	15.0	2	4	10	50	2	4	10	50
Case 11						Case 12			
D1	0.44	25	4	10	50	20	4	7.00	50
D2	5.0	1	4	10	50	1	4	10.0	50
D3	8.0	1	4	10	50	1	4	10.0	50
D4	11.0	2	4	10	50	2	4	13.0	50
D5	13.0	2	4	10	50	2	4	13.0	50
D6	15.0	2	4	10	50	2	4	13.0	50
Case 13						Case 14			
D1	0.44	20	4	7.0	50	20	4	8.00	40
D2	5.0	1	4	10	50	1	4	10.0	50
D3	8.0	1	4	10	50	1	4	10.0	50
D4	11.0	2	4	13	50	2	4	15.0	50
D5	13.0	2	4	13	50	2	4	15.0	50
D6	15.0	2	4	13	50	2	4	15.0	50

Case 15						Case 16			
No	Distance	Flow	DO	BOD	COD	Flow	DO	BOD	COD
D1	0.44	20	6.0	8.00	30.0	20	4	8.0	30.0
D2	5.0	1	6.0	10.0	50.0	1	4	10	50.0
D3	8.0	1	6.0	10.0	50.0	1	4	10	50.0
D4	11.0	2	6.0	20.0	50.0	2	4	25	50.0
D5	13.0	2	8.0	20.0	50.0	2	4	25	50.0
D6	15.0	2	8.0	20.0	50.0	2	4	25	50.0
Case 17						Case 18			
D1	0.44	20	4	7.00	30.0	20	4	10.0	30.0
D2	5.0	1	4	10.0	50.0	2	4	10.0	50.0
D3	8.0	1	4	10.0	50.0	2	4	10.0	50.0
D4	11.0	2	4	25.0	50.0	2	4	25.0	50.0
D5	13.0	2	4	25.0	50.0	2	4	25.0	50.0
D6	15.0	2	4	25.0	50.0	2	4	25.0	50.0
Case 19						Case 20			
D1	0.44	20	4	8.0	30.0	20	4	7.00	30.0
D2	5.0	2	4	10	50.0	2	4	10.0	50.0
D3	8.0	2	4	10	50.0	2	4	10.0	50.0
D4	11.0	2	4	25	50.0	2	4	25.0	50.0
D5	13.0	2	4	25	50.0	2	4	25.0	50.0
D6	15.0	2	4	25	50.0	2	4	25.0	50.0
Case 21						Case 22			
D1	0.44	20	4	6.00	30.0	20	4	5.0	30.0
D2	5.0	2	4	10.0	50.0	2	4	10	50.0
D3	8.0	2	4	10.0	50.0	2	4	10	50.0
D4	11.0	2	4	25.0	50.0	2	4	25	50.0
D5	13.0	2	4	25.0	50.0	2	4	25	50.0
D6	15.0	2	4	25.0	50.0	2	4	25	50.0
Case 23									
D1	0.44	20	4	5.00	25.0				
D2	5.0	2	4	10.0	25.0				
D3	8.0	2	4	10.0	25.0				
D4	11.0	2	4	10.0	25.0				
D5	13.0	2	4	10.0	25.0				
D6	15.0	2	4	10.0	25.0				

Table 3.10 Point sources load using different cases generated by utilizing the weir (Distance in km, flow in cumecs, BOD, COD, and DO in mg/l)

		Scenario 1			Scenario 2			Scenario3		
Distance	Flow	DO	BOD	COD	DO	BOD	COD	DO	BOD	COD
0.44	25	0	10	50	0	30	50	0	25	50
5.000	2	0	10	50	0	30	50	0	30	50
8.000	2	0	10	50	0	30	50	0	30	50
11.000	2	0	10	50	0	30	50	0	30	50
13.000	2	0	10	50	0	30	50	0	25	50
15.000	2	0	10	50	0	30	50	0	30	50
		Scenario 4			Scenario 5-9(case2-3)					
0.440	25	0	20	50	0	30	50			
5.000	2	0	30	50	0	30	50			
8.000	2	0	30	50	0	30	50			
11.000	2	0	30	50	0	30	50			
13.000	2	0	20	50	0	30	50			
15.000	2	0	30	50	0	30	50			

Figure 3.9 shows the weirs represented in QUAL2Kw. Here H_i = the depth of the reach upstream of the weir [m], H_{i+1} = the depth of the reach downstream of the weir [m], $elev2_i$ = the elevation above sea level of the tail end of the upstream reach [m], $elev1_{i+1}$ = the elevation above sea level of the head end of the downstream reach [m], H_w = the height of the weir above elev2_i [m], H_d = the drop between the elevation above sea level of the surface of reach i and reach i+1 [m], H_h = the head above the weir [m], B_i = the width of reach i [m]. For a sharp-crested weir where $H_h/H_w < 0.4$, flow is related to the head (Finnemore & Franzini, 2002)

$$Q_i = 1.83 B_i H_h^{3/2} \tag{3.10}$$

where Q_i is the outflow from the segment upstream of the weir in m^3/s, and B_i and H_h are in m. Equation (9) can be solved for

$$H_h = \left(\frac{Q_i}{1.83 B_i} \right)^{2/3} \tag{3.11}$$

This result can then be used to compute the depth of reach i,

$$H_i = H_w + H_h \tag{3.12}$$

and the drop over the weir

$$H_d = elev2_i + H_i - elev1_{i+1} - H_{i+1} \tag{3.13}$$

The velocity and cross-sectional area of reach i can then be computed as

$$A_{c,i} = B_i H_i \tag{3.14}$$

$$U_i = \frac{Q_i}{A_{c,i}} \tag{3.15}$$

Different scenarios were established, keeping the headwater constant, the suggested environmental flow, and water quality criteria. Crest height and width have been varied using equation 6 trial and error method. Different scenarios were established with varying BOD loads, and flow has been kept constant for all the scenarios. Table 3.10 shows the headwater and point source inputs for different scenarios. In simulations 1-4, weir height and width have been kept constant, and only the BOD of the point sources has been varied. In case 2, crest width has been varied, and simulations 5-7 have been developed. In case 3, the height of the weir has been varied, and simulations 8-9 are generated. Table 3.11 shows the height and width of the weir for simulations 1-9.

Table 3.11 Height and Width of the weir used for simulations

Weir location	Weir Height (m)	Weir width(m)	Flow cumecs
Scenario 1-4(case 1)			
reach 2	0.8	0.05	35
reach 8	0.9	0.05	39
Scenario 5 (case 2)			
reach 2	0.8	0.1	35
reach 8	0.9	0.1	39
Scenario 6			
reach 2	0.8	0.075	35
reach 8	0.9	0.075	39
Scenario 7			
reach 2	0.8	0.04	35
reach 8	0.9	0.04	39
Scenario 8(case 3)			
Weir location	Weir Height	Weir width	Flow cumecs
reach 2	0.7	0.05	35
reach 8	0.8	0.05	39
Scenario 9			
reach 2	0.9	0.05	35
reach 8	1.0	0.05	39

CHAPTER 4

DATA DESCRIPTION

4.1 General

The data has been collected for water quality assessment, point and nonpoint sources inventory, water quality simulations, TMDL assessment, and water quality management plan evaluation. Real-time water quality data for ST1 and ST5 have been collected for 11 parameters. The statistics of the real-time data have been presented in A3 and A4.

4.2 Data for water quality assessment

11 parameters have been collected in real-time for ST1 and ST5, and statistics for these 11 parameters are shown in Tables A3 and A5. Decadal data have been collected from DPCC and used to assess water quality, as shown in Table A5. Table 4.1 shows that the data represents the decadal average for all monitoring stations ST1-ST5.

Table 4.1 Statistics of decadal data (2013-2022) for water quality assessment of the river

DO(mg/l)							
Stations	Total no (observation)	Mean	Standard Deviation	Sum	Min	Median	Max
ST1	111	6.48288	1.60889	719.6	0	6.8	10
ST2	111	0.22162	0.71876	24.6	0	0	3.6
ST3	111	0.29279	0.66095	32.5	0	0	3
ST4	111	0.68108	1.25027	75.6	0	0	6
ST5	111	0.57928	1.29833	64.3	0	0	7.1
BOD(mg/l)							
Stations	Total no (observation)	Mean	Standard Deviation	Sum	Min	Median	Max
ST1	111	4.74324	2.20469	526.5	1	4	10
ST2	111	32.92072	11.9607	3654.2	7.6	31	75
ST3	111	30.1955	11.99691	3351.7	2.2	28	66
ST4	111	29.71171	12.45438	3298	9	27	66
ST5	110	32.1	15.74318	3531	10	28	79

COD							
Stations	Total no (observation)	Mean	Standard Deviation	Sum	Min	Median	Max
ST1	111	26.88288	18.40343	2984	4	20	88
ST2	111	109.5676	45.78321	12162	28	96	280
ST3	111	98.65766	43.5317	10951	28	92	288
ST4	111	100.4865	46.12313	11154	30	88	256
ST5	111	105.8559	57.50239	11750	24	84	274

Table 4.2: Descriptive statistics for BOD of sixteen outfalling drains for the July 2019-November 2023

Drain name	Total no(obs)	Mean	Std. dev	Sum	Min	Med	Max
Najafgarh	51	58.098	19.26889	2963	20	55	100
Meltcalf	17	27.588	14.03593	469	11	26	70
Kyberpass	31	32.161	21.53926	997	6	29	96
Sweeper Colony	40	55.6525	40.07172	2226.1	6	50	160
Magazine	26	77.0192	64.49193	2002.5	15.5	54	305
ISBT	51	54.3921	26.27248	2774	9	52	150
Tonga	38	39.4736	18.16105	1500	8	35.5	90
Civil Mill	46	57.8152	23.56677	2659.5	20	56	130
Power House	51	62.392	23.06433	3182	24	60	142
S. N. H	50	71.26	28.62624	3563	22	65	180
Drain 14	40	33.875	20.55909	1355	6	29.5	90
BaraPulla	51	53.1803	23.57922	2712.2	7.2	52	124
MahaRani Bagh	51	67.5882	34.5949	3447	34	56	193
SoniaVihar	29	66.3103	19.6125	1923	24	67	100
Kailash Nagar	31	59.9032	24.67705	1857	20	58	123
Sastri Park	30	53.9666	21.41782	1619	27	49	97

S.N.H= Sen Nursing Home

4.3 Point sources inventory

For point sources inventory, five years of monthly data have been collected from the DPCC domain from July 2019 to November 2023. The data has been presented in Table A8. BOD and COD data have been gathered. Tables 4.2 and 4.3 show the BOD and COD statistics for different drains used as point sources.

4.4 Nonpoint sources data

For the assessment of nonpoint sources of pollution, land use pattern data has been collected from ISRO and shown in Figures 4.1 and 4.2. Monthly basis rainfall data for the period 2018-2023 has been collected to determine the surface runoff from India Agriculture Research Institute and shown in Table 4.4.

Table 4.3 Descriptive statistics for COD of sixteen outfalling drains

Point Sources	No of total obs.	Mean	Standard Deviation	Sum	Min	Median	Max
Najafgarh	51	238.3726	99.5542	12157	56	256	496
Metcalf	17	98.11765	71.27577	1668	40	80	348
Khyberpass	31	119.0968	79.45622	3692	24	96	336
Sweeper Colony	40	204.6	156.5226	8184	20	180	728
Magazine Road	26	245.3846	171.4305	6380	68	186	900
ISBT	51	213.2353	86.71599	10875	44	213	464
Tonga	38	129.079	61.61273	4905	36	120	340
Civil Mill	46	223.2174	81.30762	10268	64	222	400
Power House	51	238.3137	73.70766	12154	80	240	412
Sen Nursing Home	50	280.08	86.53319	14004	92	296	480
Drain 14	40	112.75	70.38165	4510	26	96	368
Barapulla	51	224.0588	80.34063	11427	48	240	364
Maharani Bagh	51	262.7059	80.7716	13398	136	258	476
Sonia Vihar	29	310.2414	93.2277	8997	104	368	426
Kailash Nagar	31	233.129	84.28948	7227	80	192	368
Shastri Park	30	222.6667	67.77719	6680	128	224	368

Source: DPCC domain

4. 5 Data for Assessment of Self-assimilation

The model QUAL2Kw was developed for self-assimilation for Delhi's urban river reach. The 22 km river reach has been segmented into 14 sub-reaches according to the change in the wastewater flow. Table 4.6 shows the river segmentation. Table 4.5 shows the reach geometrics. Tables 4.7 and 4.9 show the headwater input and point sources input for calibration and validation. Table 4.8 shows the headwater input for developing different scenarios for determining the assimilation capacity. Table 4.10 shows the BOD and COD load used to formulate different scenarios.

Table 4.4 Rainfall data for Delhi (mm)

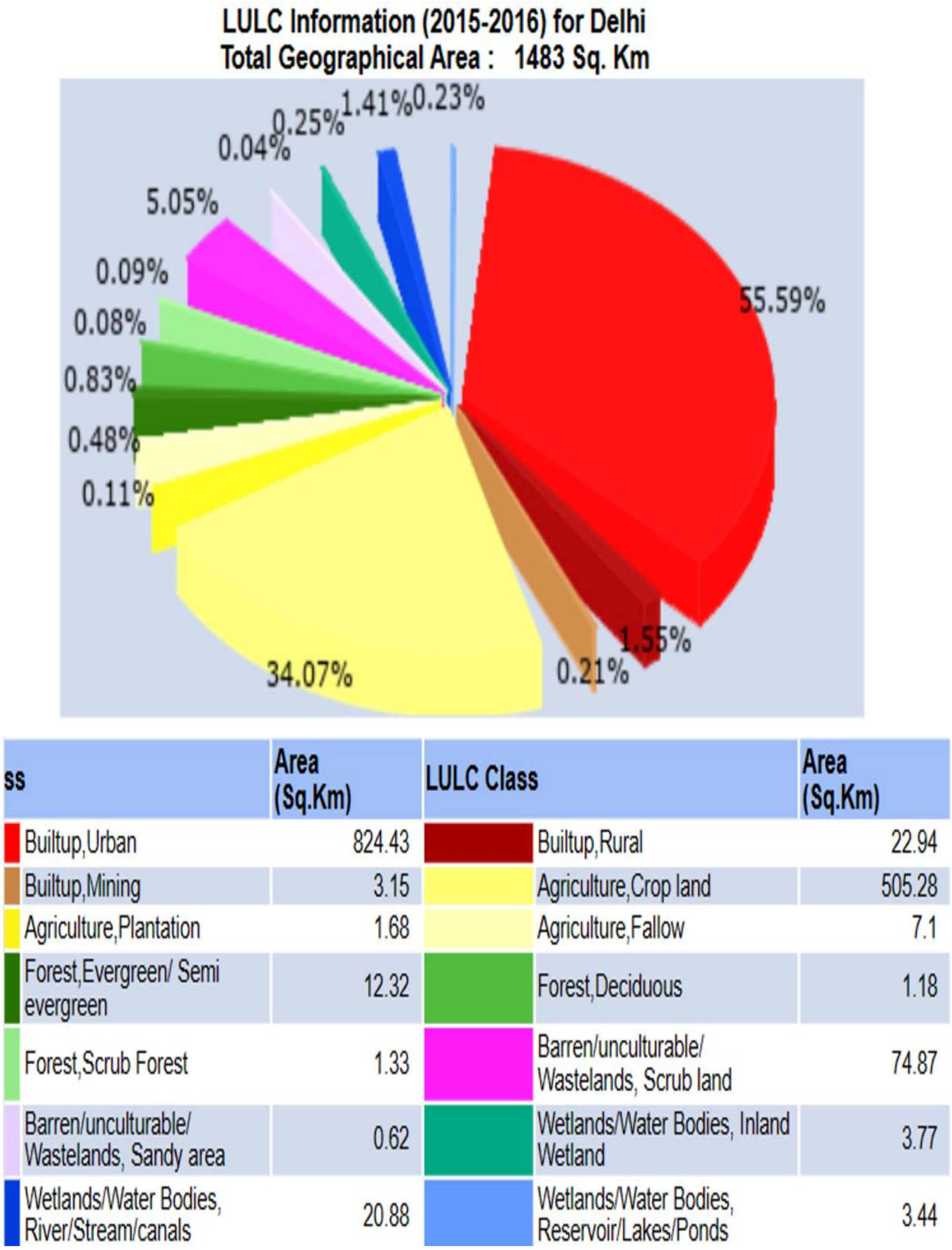
	Year					
Month	2018	2019	2020	2021	2022	2023
Jan	6	52	47.7	56.3	141.9	33.4
Feb	0	70.8	2	7	30	0
Mar	0	10.2	174.6	2	0	105
Apr	26	5.7	8.8	5.2	0	10.9
May	27.2	45.4	37.4	214.6	74.8	118.3
Jun	75	31.2	59.9	50.1	22.8	234.8
Jul	368.4	283.9	270.9	497.1	325.4	366
Aug	247.7	227	334.6	257.4	168.2	181.2
Sep	237.9	17.4	9.8	127.7	134.9	4
Oct	0	41	0	127.7	134.9	4
Nov	4	7.4	3.2	0	0	12.4
Dec	0	66	0	9.6	0	0

Source: iari. res.in

Table 4.5 Reach Geometrics

Reach no	Reach length, km	Width* m	Depth* m	Reach no	Reach length, km	Width* m	Depth* m
0	0	60	0.4	8	1.28	170	1.2
1	0.44	83	1.1	9	1	115	6
2	1.14	110	1.1	10	1.95	120	1.8
3	1.12	110	1.1	11	1.9	130	2.1
4	2.58	130	1.4	12	2.6	130	2.1
5	1.12	120	1.3	13	1.92	272	3
6	0.66	125	1.2	14	1.99	200	2.5
7	2.3	185	1.2				

* (Parmar & Keshari, 2014)



LULC Information (2015-2016) for Delhi
Total Geographical Area : 1483 Sq. Km

	ss	Area (Sq.Km)		LULC Class	Area (Sq.Km)
🟥	Builtup,Urban	824.43	🟥	Builtup,Rural	22.94
🟫	Builtup,Mining	3.15	🟨	Agriculture,Crop land	505.28
🟨	Agriculture,Plantation	1.68	🟨	Agriculture,Fallow	7.1
🟩	Forest,Evergreen/ Semi evergreen	12.32	🟩	Forest,Deciduous	1.18
🟩	Forest,Scrub Forest	1.33	🟪	Barren/unculturable/ Wastelands, Scrub land	74.87
🟪	Barren/unculturable/ Wastelands, Sandy area	0.62	🟩	Wetlands/Water Bodies, Inland Wetland	3.77
🟦	Wetlands/Water Bodies, River/Stream/canals	20.88	🟦	Wetlands/Water Bodies, Reservoir/Lakes/Ponds	3.44

Figure 4.1 Land use pattern of Delhi (source ISRO)

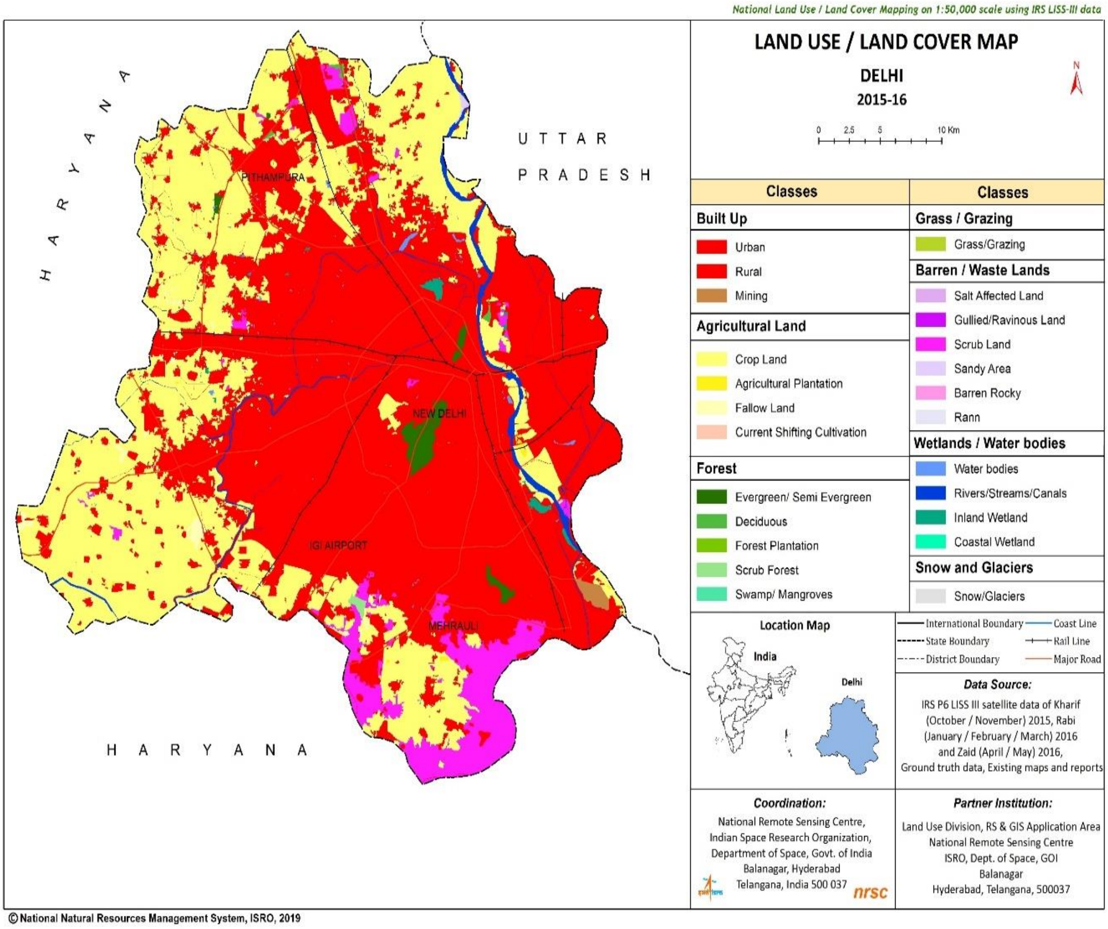


Figure 4.2 Land use map of Delhi region (ISRO)

Table 4.6 River Segmentation

Reach Lebel	Downstream end of reach	Reach No	Reach length (km)
Upstream	Wazirabad	0	
Wazirabad	Najafgarh drain	1	0.440
Najafgarh drain	Khyber Pass drain	2	1.14
Khyber Pass drain	ISBT+ Morigate Drain	3	1.12
ISBT+ Morigate Drain	Tonga Stand Drain	4	2.58
Tonga Stand Drain	Shastri Park Drain	5	1.12
Shastri park Drain	Kailash Nagar drain	6	0.66
Kailash Nagar Drain	Delhi gate Drain	7	2.30
Delhi gate Drain	Sen Nursing Home Drain	8	1.28
Sen Nursing Home Drain	Drain 14	9	1.00
Drain 14	Nizamuddin	10	1.95
Nizamuddin	Barapulla Drain	11	1.90
Barapulla Drain	Maharani Bagh	12	2.60
Maharani Bagh Drain	Old Agra canal	13	1.92
Old Agra canal	Okhla upstream	14	1.99

Table 4.7 Headwater Input

Name of the parameter	For calibration	For validation
Flow	1m^3/s	1m^3/s
DO*	5.3mg/l	5 mg/l
BOD*	8.6 mg/l	9 mg/l
COD*	64 mg/l	72 mg/l
pH*	7.36 s.u.	7.41 s.u

Source: *DPCC domain

Table 4.8 Headwater input for different strategies

Parameters	Quantity
Flow	1m3/s
DO	5.8mg/l
BOD	2.8mg/l
COD	12mg/l
pH	7.4

Table 4.9 Point sources data (BOD and COD are in mg/l)

	For calibration				For validation			
Drain No	Point inflow, m^3/s	BOD mg/l	COD mg/l	pH	Point inflow, m^3/s	BOD, mg/l	COD, mg/l	pH
1	34.38	75	272	7.26	30.33	80	352	7.41
2	1.2	86	368	7.29	1.32	80	400	7.46
3	0	0	0	7	0	0	0	7
4	0.07	135	476	6.31	0	0	0	7.69
5	0.11	60	180	6.43	0.04	0	0	7
6	0	0	0	7	0	0	0	7
7	0.54	80	288	7.38	0.5	68	256	6.96
8	0.7	26	84	6.66	0.62	40	155	7.58
9	0.19	76	224	7.2	0	0	0	7
10	0.08	26	80	6.79	0.07	60	224	7.86
11	0.02	106	320	7.33	0.034	85	368	7.91
12	1.52	68	200	6.6	0.69	75	288	7.59
13	0.46	118	480	6.46	0.45	73	336	7.11
14	0.09	31	86	6.88	0.9	30	136	7.06
15	2.27	63	176	6.88	1.73	56	345	7.62
16	0.31	138	404	7.2	0.3	56	213	6.91

Source: DPCC domain

Table 4.10 BOD and COD load added to the formulation of scenarios of assimilation capacity(BOD, COD and DO in mg/l)

Drain no	Flow, MLD	DO	BOD existing	Case 1		Case2	
				BOD	COD	BOD	COD
D1	1938.48	0.0	69.03	10	50	10	25
D2	114.05	0.0	80	10	50	10	25
D3	4.32	0.0	69.44	10	50	10	25
D4	5.4	0.0	18.51	10	50	10	25
D5	9.5	0.0	40	10	50	10	25
D6	3.45	0.0	31.88	10	50	10	25
D7	37.94	0.0	70.37	10	50	10	25
D8	4.46	0.0	132.2	10	50	10	25
D9	5.76	0.0	130.2	10	50	10	25
D10	11.14	0.0	60.15	10	50	10	25
D11	9	0.0	300	10	50	10	25
D12	39.02	0.0	87.9	10	50	10	25
D13	31.53	0.0	148.7	10	50	10	25
D14	6.54	0.0	10.7	10	50	10	25
D15	151.77	0.0	68.92	10	50	10	25
D16	30.16	0.0	116.3	10	50	10	25

Drain no	Flow, MLD	DO	BOD existing	Case 3		Case4	
				BOD	COD	BOD	COD
D1	1938.48	0.0	69.03	5	25	10	50
D2	114.05	0.0	80	5	25	10	50
D3	4.32	0.0	69.44	5	25	10	50
D4	5.4	0.0	18.51	5	25	10	50
D5	9.5	0.0	40	5	25	10	50
D6	3.45	0.0	31.88	5	25	10	50
D7	37.94	0.0	70.37	5	25	10	50
D8	4.46	0.0	132.2	5	25	10	50
D9	5.76	0.0	130.2	5	25	10	50
D10	11.14	0.0	60.15	5	25	10	50
D11	9	0.0	300	5	25	5	50
D12	39.02	0.0	87.9	5	25	5	50
D13	31.53	0.0	148.7	5	25	10	50
D14	6.54	0.0	10.7	5	25	5	50
D15	151.77	0.0	68.92	5	25	10	50
D16	30.16	0.0	116.3	5	25	10	50

Source:DPCC

CHAPTER 5

ASSESSMENT OF THE EXISTING WATER QUALITY AND WASTE INPUTS THROUGH VARIOUS POINT AND NONPOINT SOURCES

5. 1 Introduction

This chapter includes water quality assessment of the river reach, point, and nonpoint sources assessment, and sewage treatment plants assessment to develop a management approach for this urban river reach. The primary target of the management plan is to quantify the BOD and COD load to meet the water quality standard set for this river reach by the Central Pollution Control Board of India. Bhargava (1985) stated that different anthropogenic activities, such as industrial, commercial, agricultural, and domestic, generate considerable waste that gets into this river's reach and alters the water quality (Bhargava, 1985) and water was usable in winter for fisheries, wildlife, and noncontact recreation, but in the summer, water could not be used for any function. Bhargava (1983) also stated that several outfalls discharged BOD load into the Delhi reach. BOD concentration was raised as much as 60 mg/l in the summer after entering the Najafgarh drain. The present study applied PCA, FA, and box whisker plots to analyze the real-time dataset of the urban reach of Yamuna River, Delhi, India. This stretch has been turned into a sewage drain due to tremendous anthropogenic pressure aggravating the pollution load (Upadhyay et al., 2011b). The river stretch between Wazirabad and Okhla gets massive pollutant input from sixteen major drains comprising domestic sewage and industrial effluent from different clusters of Delhi(CPCB, 2012). Khullar & Singh. (2022) assessed water quality with a deep learning method for the Palla, which is upstream of the Delhi reach (Arora & Keshari, 2021b). A pattern recognition method was used to assess the river stretch using data from the five years 2006-2010 for seven parameters. Sharma and Kansal (2011) evaluated the water quality index for BOD and DO based on the monthly data from 1999 to 2009. This chapter considers the spatiotemporal variations of eleven physiochemical water quality parameters from the large one-year hourly datasets (March 2021-February 2022) for the upstream and downstream of the Yamuna River Delhi stretch. It reveals the hidden factors describing the large data sets and impacts of probable water pollutant sources.

5.2 Water Quality Assessment of the Urban River Reach of Delhi

This section captures the status of the water quality of the Urban River Reach of Delhi. Real-time water quality data was used to determine spatio-temporal water quality variations between two boundary locations of the river reach. Multivariate techniques were used to find the hidden factors causing the deterioration of water quality

5.2.1 Assessment of spatiotemporal variation of water quality parameters

Yamuna River Delhi stretch is a leading source of water for Delhi. The river stretch is a receptacle of urban liquid waste caused by human interference from domestic and industrial fields and leads to the most contaminant reach of the country. The present study used multivariate techniques to represent the spatiotemporal water quality variations and interpreted a large hourly complex dataset (March 2021-February 2022) obtained from two real-time monitoring stations upstream and downstream of this reach. Eleven water quality parameters were assessed, and Box Whisker plots were drawn monthly. The increased concentrations of Conductivity, BOD, COD, TOC, NH4, and low DO downstream indicated the influence of outfalling drains and diffused sources contributing pollutants into the river stretch. A higher BOD, COD, and TOC concentration was observed downstream in monsoon attributed to the organic substance in surface runoff. FA and PCA were implemented in the standardized data set to reveal the correlation between the water parameters. For upstream, Turbidity, TOC, COD, and TSS have strongly positively loaded for factor 1 for all the seasons except monsoon. For downstream, TOC and COD contributed strongly positive load except in winter. The study reveals that the urban river flows with agricultural and surface runoff and industrial and domestic wastewater with organic and inorganic substances.

The water quality data for 11 parameters were collected from March 2021 to February 2022. The summary of the dataset is given in Tables A3 and A4. For ST1, the data set for May was not available. Tables A3 and A4 show the monthly mean values of eleven water quality parameters. Data were analyzed for monthly spatial and temporal variations, and box whisker plots are shown in Figs. 5.1 & 5.2. For ST1, mean DO varied between 4.64 mg/l to 12.8 mg/l. Whereas for ST5, it varied from 1.62 mg/l to 5.43 mg/l. BOD varied from (1.37±1.34) mg/l to (6.65±0.8) mg/l for ST1. A higher value was observed during the monsoon (July). Whereas for ST5, from (7.24±6.75 mg/l) to (25.98±13.9 mg/l). During monsoon season, high BOD might be caused by the decaying of organic substances and vegetation in the river water due to surface runoff (Gadhia et al., 2013). COD observed (8.15±3.5) mg/l in August and (64.09±88.7) mg/l in April at Wazirabad (ST1). At Okhla (ST5), COD fluctuated from (52.13±6.1) mg/l to (158.02±219.9) mg/l. The conductivity varied from (351.35±99.47) to (1181.92±197.48) at ST1, whereas the parameter varied from (548.55±34.7) to (1575.71±234.65) at ST5. The values for pH were found within the range for both stations. For ST1, the mean pH varied from (7.22±0.44) to (7.99±0.5), and for ST2, pH varied from (6.0949±0.3971) to (7.97±0.2926). The median pH is around 7.5 t0 8, describing the river outfalls with wastewater-neutralizing water (Arora & Keshari, 2021b). The mean temperature of river water was from (13.99±1.1) to (33.9±0.58) and (15.23±0.96) to (30.06±1.05) for ST1 and ST5, respectively. A high mean turbidity concentration was observed in monsoon (733.88±489.4 NTU) at ST1 and (239.85±26.43 NTU) in winter at ST5. NH4 varied from 0.02 to 1.2 for ST1, whereas 8.39 mg/l to 59.11 mg/l. Turbidity varied from 10.38 NTU to 733.88 NTU for ST1. PCA/ FA is shown in Figs. 5.3-5.5. Factors and their variances are shown in Table 5.1-5.3. The data assessment observed that DO concentration varied sharply, revealing that substantial oxygen-consuming pollutants were discharged through the sixteen main drains (Fig. 3.5) (Mandal et al., 2010). At ST1, DO concentration was high in December (12.84±2.96). It might be due to the water's low temperature and high inflow water volume, as DO is inversely related to temperature (Water Science School, 2018). At ST5, DO was found high in September (4.98±4.47) due to the integrated effect of high wind speed and freshwater mixing for rainfall (Das et al., 1997). DO is an indicative parameter for the fitness of an aquatic ecosystem, the metabolism, and the respiration of aquatic organisms (Gadhia et al., 2013). At Wazirabad, the minimum DO was adequate to sustain lives. However, at the ST5, the minimum DO was observed as nil for most of the year (Arora & Keshari, 2021b). Maximum COD was found during monsoon season (Fig 5.1). The monsoon brought runoff from agricultural fields, raising the nutrient concentration (Gadhia et al., 2013). The high COD load is caused by surface runoff, indicating organic pollution caused by non-point sources. Joseph & Srivastava. (1993) concluded that higher BOD observed during the monsoon period indicated high demands of oxygen required for life process support. Clark, 1(986) also stated that higher organic load experienced in monsoon caused higher BOD levels. Due to continuous rainfall, soil erosion and surface runoff with non-point pollutants are attributed to additional organic waste load in the river water and increased BOD level (Odokuma & Okpokwasili, 1997). The large value of BOD and COD indicated the presence of organic-inorganic chemicals (Arora & Keshari, 2021b). Furthermore, it clearly stated the presence of high oxygen-demanding pollutants from both fixed and diffused sources. The chemical oxygen demand was high in the monsoon. Since BOD and COD are highly related, the causes for BOD and COD being high during the monsoon accounted for unchanged. Industrial effluents carried high COD, resulting in high values of oxygen-demanding chemicals in river water (Gadhia et al., 2013). The summer season showed a higher conductivity range, which might occur due to the lower flow available in the river during summer (Gadhia et al., 2013). The conductivity value decreased during the monsoon at the station. It might be a high volume of water from the upstream end due to rainfall. In monsoon, river water gets diluted due to the increasing volume of water (Izonfuo & Bariweni, 2010).

TSS includes fine clay, silt, microorganisms like plankton, and organic and inorganic substances. TDS value was high in lean summer flow (76.95±1) and (147.5±138.6) for ST5, respectively. Higher values of ST5 indicated wastewater outfall with substances increasing TDS. During the monsoon, a low TSS value was observed for both points. TSS can be changed by changing the pH, which causes precipitated solutes and affects solubility (Gadhia et al., 2013). pH was observed higher in the summer and low in the rainy season. Variations in pH values are attributed to factors like dilution (Rajasegar, 2003) of water, reduction of temperature, decaying of organic substances, and degradation of CO_2 during photosynthesis through reduction of bicarbonate (Izonfuo & Bariweni, 2010). Higher conductivity, BOD, COD, and low DO express that the outfalling point sources and diffused sources contribute pollutants to the river stretch (Arora & Keshari, 2021a). Two locations did not show significant temperature variation, revealing that the outfalling drains did not contribute to high-temperature wastewater (Arora and Keshari, 2021a) and 22 km distance between the two locations (Singh et al., 2004). Maximum Turbidity was found in the pre-monsoon period (Fig.5.2a). Turbidity in water shows the presence of suspended matter like silts, clay, plankton, other microorganisms, and organic and inorganic substances. NO_3 concentration was high in ST1 during monsoon season and could be due to organic substances discharged from the surroundings (Das et al. 1997). NH_4 level was low during the same period. The cause may be the oxidation of ammonia to nitrite and nitrate (Rajasegar, 2003). Fig.5.2(b) shows that the availability of sufficient flow due to rainfall reduces the ammonia concentration in river water (Arora & Keshari, 2021b). A high variation of ammonia concentration was observed between the two locations, and it concluded that the river gets discharged with a high volume of nutrient-rich wastewater. TOC concentration was low in the monsoon period due to sufficient flow and high in the summer season at Wazirabad. A higher concentration of TOC was observed at Okhla during the monsoon, attributed to the presence of the organic substance in surface runoff.

5.2.2 Principal Component Analysis and Factor Analysis

For PCA/FA, the total dataset has been divided into four seasons for both locations: summer, monsoon, post-monsoon, and winter. The PCA reduces the data dimension, keeping information unchanged and identifying the eigenvector and eigenvalue (Arora & Keshari, 2021b). Scree plots (Fig. 5.3) were used to determine the principal components for each dataset to perceive the data structure (Vega et al., 1998). The PCs were selected from scree plots with eigenvalues of more than one. Loadings of PCs and actual variables are shown in Fig 5.4. The biplot provides correlation and impact of different parameters with PCs, as shown in Fig. 5.5 for multiple locations. A new set of factors were defined by rotating the PC's axis. New factors introduced primarily involved a subset of original variables without overlapping each other and independent groups. FA and PCA were used for the standardized data to correlate the structural designs of the water parameters and identify the parameters that influence factors. Tables 5.1-5.4 show the variances for factor analysis of different seasons.

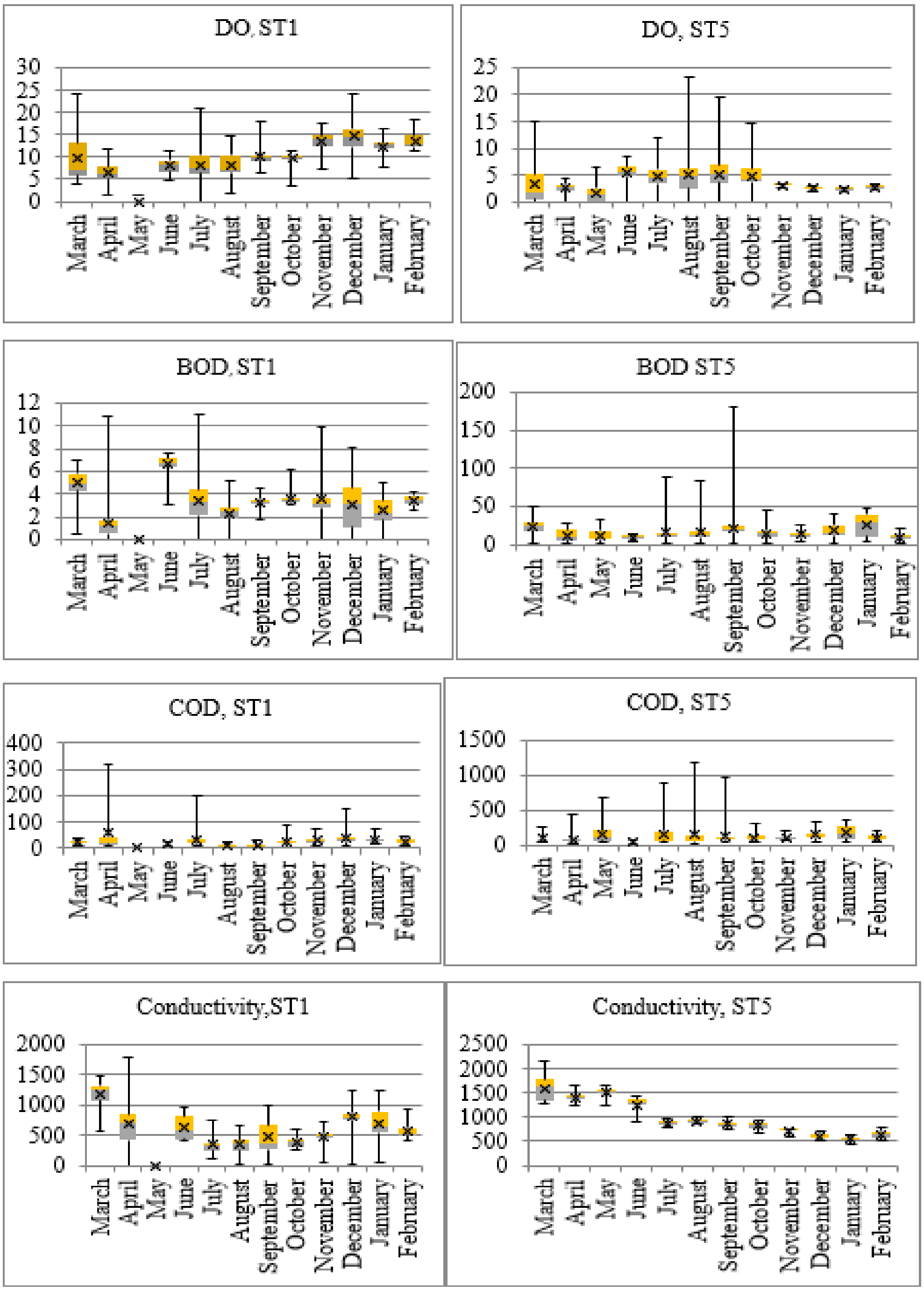


Figure 5.1 Box Whisker plots showing spatiotemporal variations (DO, BOD, COD, and Conductivity) (all parameters are in mg/l except Conductivity (µS/cm)

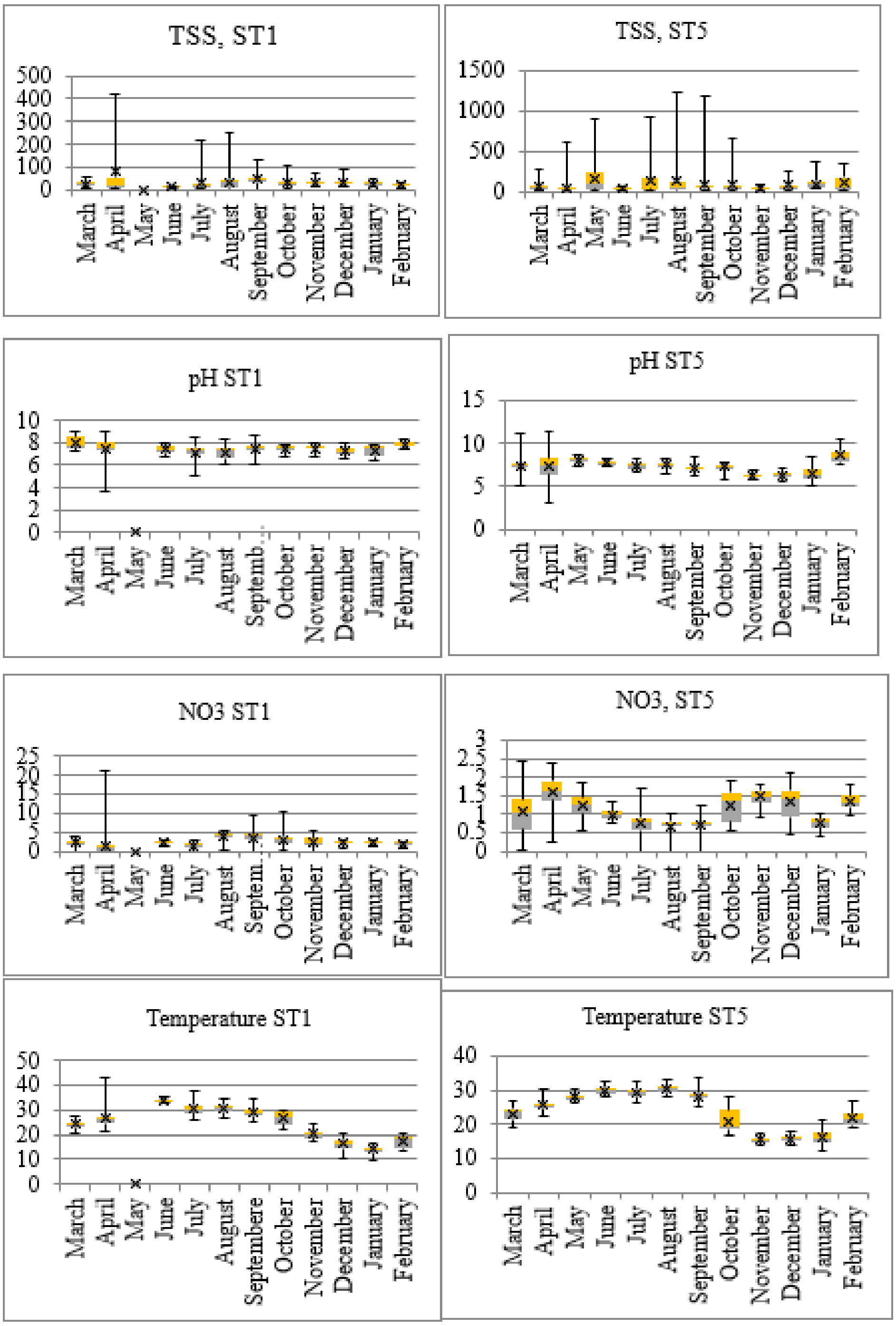


Figure 5.2 (a) Box whisker plots for spatiotemporal variations –TSS(mg/l), pH, NO_3(mg/l), and Temperature(°C) (Verma et al., 2023a)

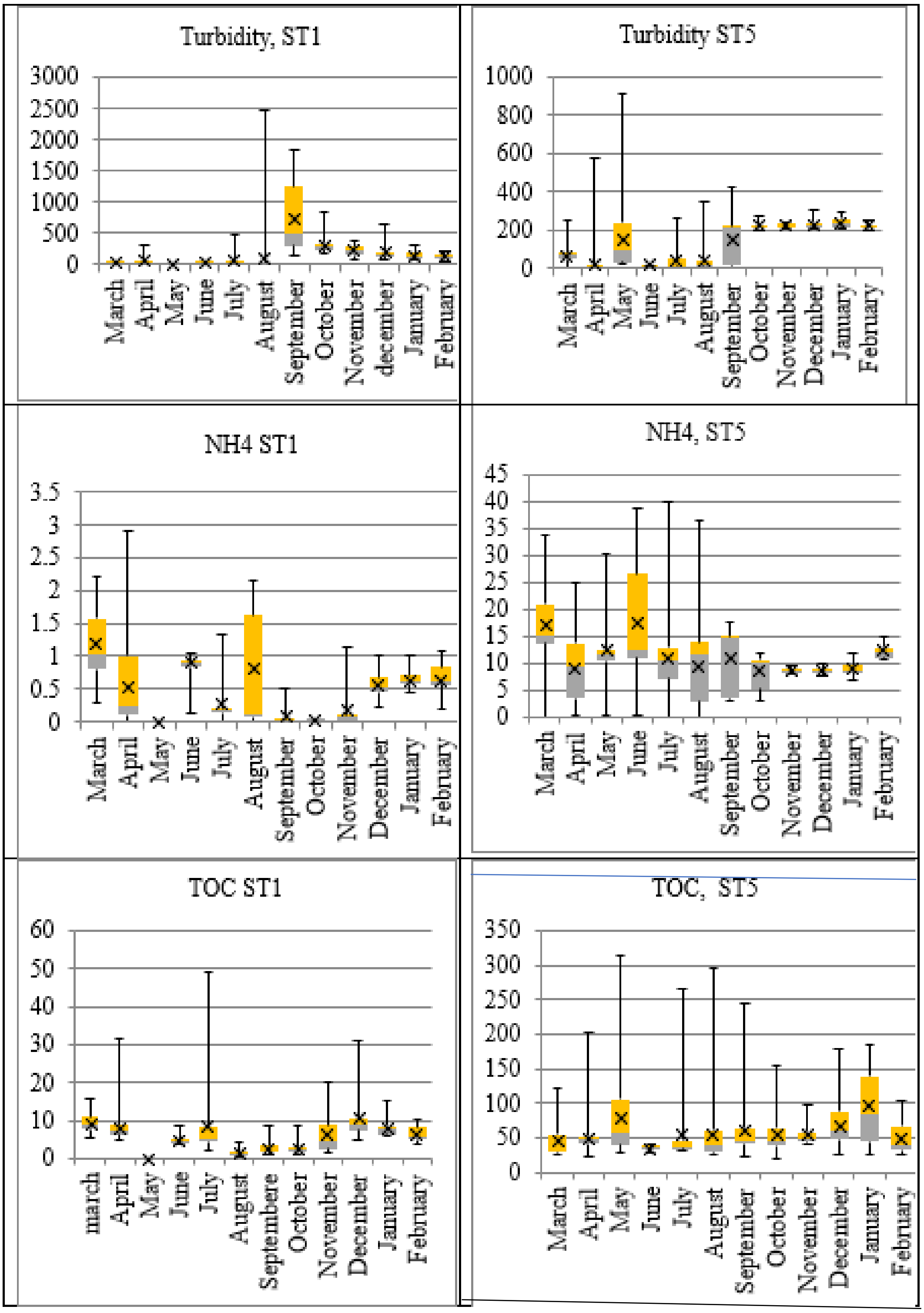


Figure 5.2 (b) Box whisker plots for spatiotemporal variations –Turbidity (NTU), NH_4, and TOC are in mg/l (Verma et al., 2023a)

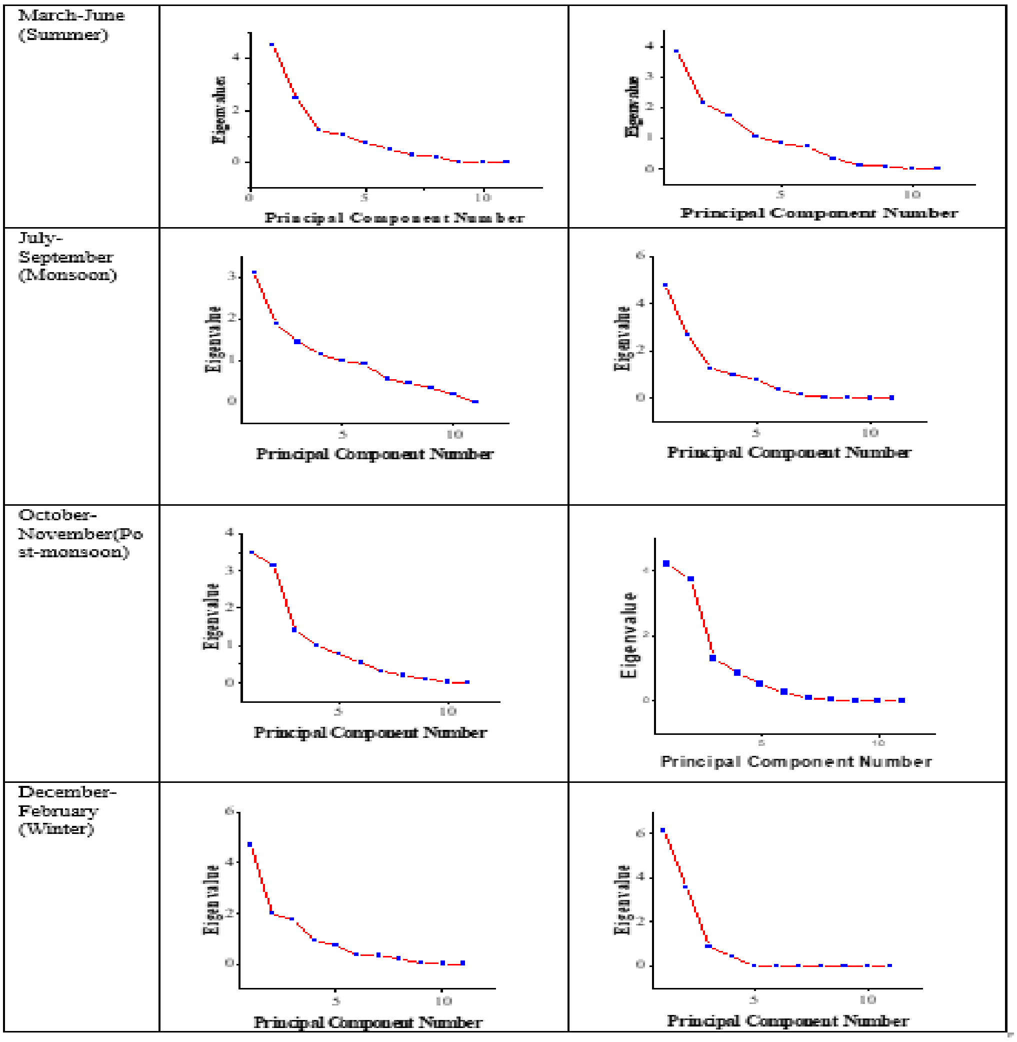


Figure 5.3 Scree plots for determining Principal Components for four seasons (Verma et al., 2023a)

For ST1, four PCs with eigenvalues >1 in summer explain about 84% of the whole variance in the data. The first PC counted 41% of the combined variance and showed positive correspondence with COD, Turbidity, TSS, and TOC. The factor loaded with TSS indicates that the runoff originated from a field of high solids and waste (Singh et al., 2004). The second PC that contained 22.3 % of the aggregated variance and positive loading were conductivity, NO_3, pH, and DO. The scree plot was used to select the no of PCs with an eigenvalue greater than 1 (Vega et al., 1998). FA further examined the values of PCs and identified the factors that participated more clearly. Liu et al. (2003) explained the factor loading as strong (> 0.75), moderate (0.75-0.50), and weak (0.50-0.30), correlating to absolute loading. Four factors identified with 84% of the variance, TOC, Turbidity, COD, and TSS, were strong loading with factor 1. The excessive loading of these parameters might be due to low flow, erosive process, presence of microorganisms, and huge suspended organic and inorganic substances from upstream (Fan et al., 2010). NO_3 and conductivity were correlated with factor 2, and Factor 4 strongly correlated with DO and pH. The strong relationship between NO3 and conductivity might be due to high agricultural runoff (Ogwueleka, 2015).

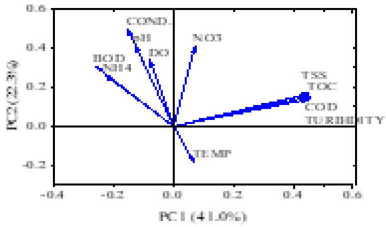
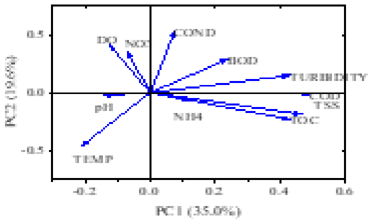
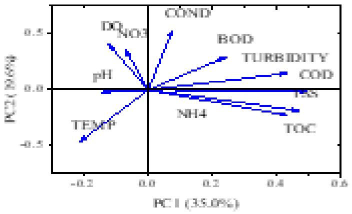
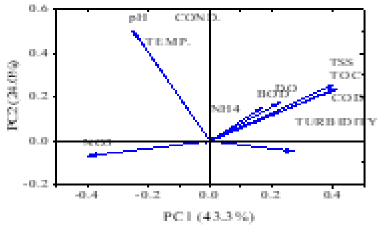
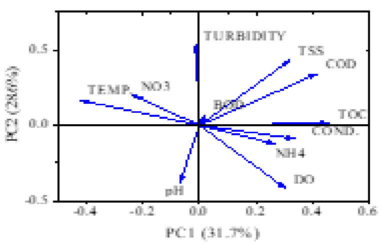
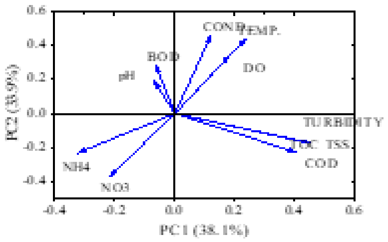
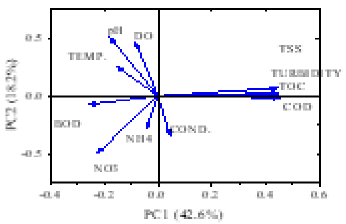
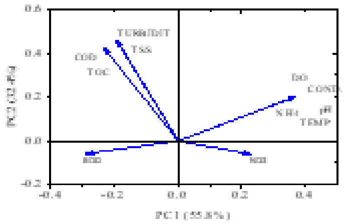
	ST1	ST5
March-June (Summer)		
July-September (Monsoon)		
October-November (Post-monsoon)		
December-February (Winter)		

Figure 5.4 Loading Diagram for Principal Components (PC) (Verma et al., 2023a)

Factor 3 has a strong negative correlation with temperature. BOD has moderate loading in factor 2, indicating excessive dissolved organic matter added from urban runoff carrying nutrients with high oxygen demand (Pati et al., 2014). For ST5, during the summer season, PCs were four, with 80% of the aggregated variance, and PC1 had 35% of the variance. Factors were determined, and factor 1 was strongly correlated with TOC, COD, and TSS. Factor 2, factor 3, and factor 4 were associated with conductivity, NH_4, and NO_3, respectively. Factor 3 was strongly negatively correlated with pH. These factors loading indicated that domestic wastewater, industrial discharges, and agricultural runoff strongly affect the water quality.

For monsoon, PCs were 4 for the ST1 with a variance of 68%. PC1 with a 28.2% variance. TOC, COD, and TSS were strongly correlated with PC1. Factor 1 was strongly loaded with TOC and COD, moderately loaded with TSS, and had very low negative turbidity loading. It revealed that compared to the summer season, in the monsoon season, sufficient water flow is present in the location, which reduces Turbidity and TSS. However, organic and inorganic substances with a high oxygen demand were attributed. Factor 2 and 3 were strongly loaded with NH4 and Turbidity, respectively. Factor 4 was not strongly correlated with any variables, and moderate loading with BOD indicated the presence of moderate oxygen-demanding organic substances. For ST5, 3 PCs were obtained for the monsoon period with 78.8% whole variance. PC1, with 43.3% variability, positively correlated with TSS, TOC, and COD, indicating domestic, industrial, and surface runoff with a high volume of organic and inorganic substances, microorganisms, and fine materials (Akbal et al., 2011). For post-monsoon, ST1 had four PCs with 82% of the total variance. Factor 1 loading revealed low flow conditions with high Turbidity, TSS, and COD. Factor 2 was strongly loaded with conductivity and moderately loaded with NH_4. The reasons could be upstream flow with agricultural runoff with high nutrients, Factor 3 had a strong negative loading of NO_3, and Factor 4 had a strong positive loading of BOD. For ST5, three PCs with 83.9% variance and DO have strongly positive loading in factor 2. For winter, ST1. 76.5% of total variance with 46.2% variance in PC1. For ST5, PCs were two with 86.2% of the total variance, and PC1 had the 55% of the variance. For Factor 1, intense positive loading was Turbidity, TOC, COD, and TSS, indicating 55% total variance with anthropogenic sources of pollution. Factor 2 showed a high positive relation with DO, temperature, and conductivity, explaining the physical characteristics of the river. This element illustrated that DO in water depends on temperature (Bu et al., 2010). However, significant loading of BOD and COD revealed that partially treated and untreated wastewater discharged into the river contained pollutants. In contrast, the strong loading of TKN and NH_4 indicates the transfer of excess nutrients from industrial effluent and agricultural runoff (Singh et al., 2020). Negative loading of pH and DO also indicate contamination with industrial effluents forming anaerobic conditions with high pH and low oxygen. The wastewater carrying industrial effluent and domestic sewage is outfalling the length between ST1 and ST5. The factor analysis of the Yamuna River reveals anthropogenic pollution sources and a high volume of organic and inorganic substances demanding a large amount of oxygen, hence undergoing an anaerobic fermentation process, forming ammonia and other organic acids (Singh et al., 2004).

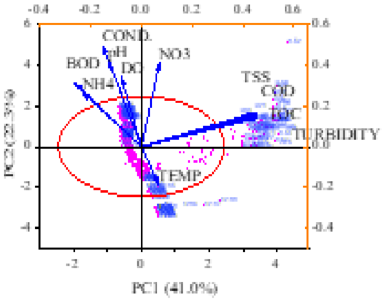
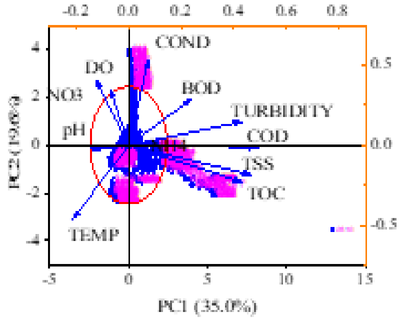
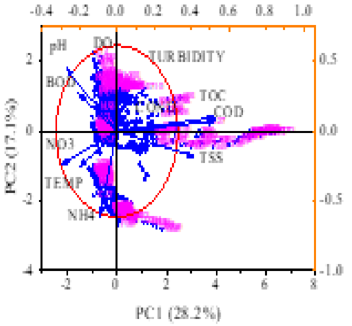
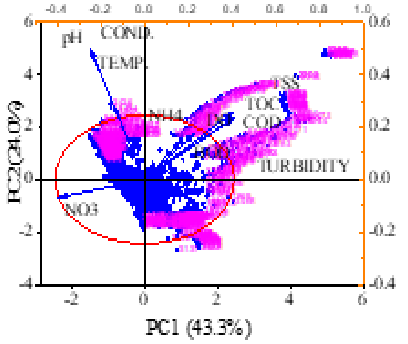
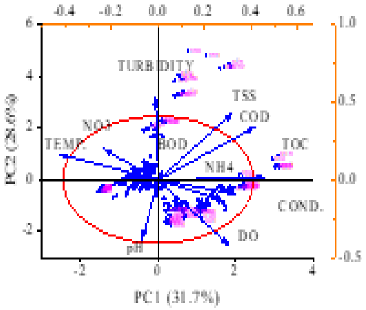
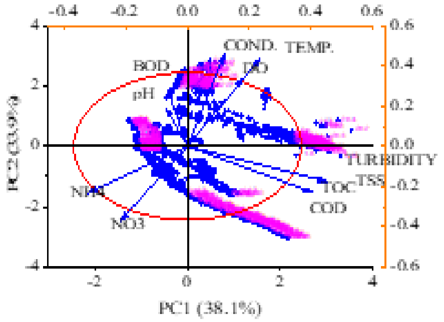
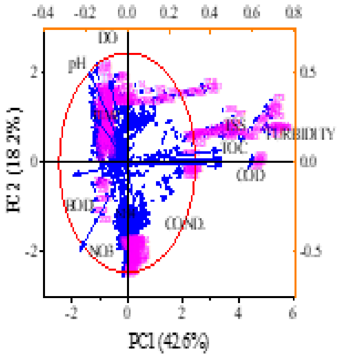
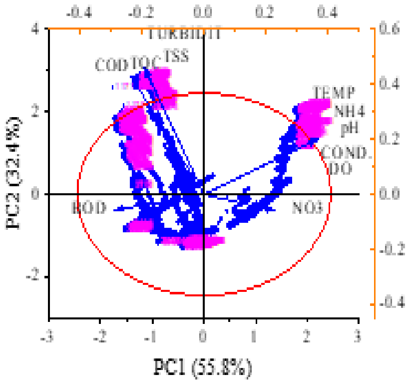
Season	ST1	ST5
March-June Summer		
July-September Monsoon		
October- November Post- monsoon		
December- February Winter		

Figure 5.5 Biplot for Principal Components (PC) (Verma et al., 2023a)

Table 5.1 Factor for water quality parameters at two stations– Summer season (Bold Values show Strong Correlation)

ST1					ST5			
Variables	Factor1	Factor2	Factor3	Factor4	Factor1	Factor2	Factor3	Factor4
DO	-0.03	0.203	-0.172	**0.8932**	-0.341	0.585	-0.09	0.038
Turbidity	**0.988**	-0.038	-0.068	-0.05	0.73	0.485	0.1197	-0.37
TOC	**0.992**	-0.005	-0.07	-0.022	**0.93**	-0.277	0.0737	0.111
NO3	0.302	**0.774**	-0.055	0.0688	-0.103	0.209	0.0681	**0.909**
BOD	-0.42	0.749	0.002	0.1775	0.489	0.433	-0.269	0.212
NH4	-0.311	0.248	0.571	0.2082	0.097	-0.101	**0.9197**	0.162
COD	**0.988**	-0.005	-0.096	-0.037	**0.976**	0.101	0.0829	0.04
pH	-0.036	0.087	0.466	**0.796**	-0.074	-0.135	-0.913	0.092
COND.	-0.072	**0.759**	0.478	0.1635	-0.015	**0.841**	0.0867	0.04
TEMP	-0.02	0.027	**-0.851**	0.0636	-0.326	-0.673	-0.059	0.281
TSS	**0.993**	-0.018	-0.047	-0.014	**0.908**	-0.044	0.1179	-0.32

Table 5.2 Factor for water quality parameters at two stations– Monsoon season (Bold Values show Strong Correlation)

	ST1				ST5		
Variables	Factor1	Factor2	Factor3	Factor4	Factor1	Factor2	Factor3
DO	-0.019	-0.2454	0.4236	0.4848	0.4001	-0.0169	0.7237
Turbidity	-0.004	-0.1918	**0.8903**	-0.043	0.4687	-0.3441	0.1549
TOC	**0.9644**	0.0021	0.0229	-0.014	**0.9746**	-0.0544	0.1144
NO3	-0.627	0.3781	0.4433	-0.018	**-0.888**	0.2755	0.13
BOD	-0.179	-0.3799	-0.0893	0.6289	0.2101	-0.0084	**0.8866**
NH4	-0.26	**0.805**	-0.1565	0.0435	-0.1087	-0.0177	0.2724
COD	**0.963**	0.0419	0.0189	0.0051	**0.9777**	-0.0602	0.1185
pH	-0.402	-0.6727	0.1362	0.0361	-0.1092	**0.9714**	-0.0044
COND.	0.1165	0.0298	0.0152	0.2819	-0.1084	**0.9843**	-0.0232
TEMP	-0.251	0.3781	-0.1271	0.7202	-0.1085	**0.9843**	-0.0234
TSS	0.6285	0.4729	0.4796	-0.163	**0.970**	-0.0231	0.1029

5.3 Trend Analysis of DO, BOD, and COD

For the trend analysis of biochemical oxygen demand (BOD) and dissolved oxygen (DO), and Chemical oxygen demand (COD), 10 years of data for the five stations Wazirabad (ST1), ISBT (ST2), ITO (ST3), Nizamuddin (ST4), and Agra canal, Okhla (ST5) have been collected for 2013-2022. Table A5 shows the 10-year monthly data collected from the DPCC domain. Table 5.5 shows the mean and standard deviation of DO, BOD, and COD for the stations ST1-ST5. At station ST1, DO concentration satisfied the required standard, above 4mg/l, and after entering the outfalling pollution-contributing sources, DO concentrations were depleted. However, it was observed that, for some periods, the DO concentration improved after monitoring station ST3. This might be due to the increase in fresh upstream flow or lower wastewater flow, as well as the increase in assimilation capacity. Furthermore, the water quality could not be improved. Mean BOD concentrations were higher than the desired standard (less than 3mg/l) for ST1-ST5. Joshi et al.(2022) concluded that the Palla station, upstream of rural Delhi reach, contained a higher level of BOD. With increasing distance upstream from Wazirabad (ST1), the concentrations of BOD were getting high. Furthermore, as no standards for COD were prescribed in this reach, high COD concentrations were found throughout the spread, which depleted the DO concentration. Fig. 5.7 shows the Box Whiskers plots of DO, BOD, and COD, respectively.

Table 5.3 Factor for water quality parameters at two stations– post-monsoon season (Bold Values show Strong Correlation)

ST1					ST5		
Variables	Factor1	Factor2	Factor3	Factor4	Factor1	Factor2	Factor3
DO	-0.426	0.5613	0.6057	0.1364	0.0377	**0.7544**	0.0698
Turbidity	**0.8242**	-0.233	-0.396	0.0571	**0.9752**	0.1149	-0.1
TOC	0.3962	0.3312	0.7243	0.3421	**0.9611**	-0.033	-0.029
NO3	0.0526	-0.025	**-0.862**	0.3269	-0.032	-0.87	0.1333
BOD	0.0575	-0.064	-0.091	**0.7544**	-0.358	0.4257	0.1107
NH4	0.0274	0.7428	0.0651	-0.451	-0.282	**-0.77**	0.4656
COD	**0.8752**	0.3417	0.2582	0.1317	**0.9611**	-0.033	-0.029
pH	-0.7	0.0603	0.1203	0.4261	-0.094	0.1281	**0.9688**
COND.	0.1037	**0.8099**	0.0535	-0.039	-0.097	**0.8455**	0.4758
TEMP.	-0.034	-0.738	-0.366	-0.429	0.0752	**0.9568**	0.1938
TSS	**0.9442**	0.1164	0.154	0.1713	**0.972**	0.1167	-0.098

Table 5.4 Factor for water quality parameters at two stations– winter season (Bold Values show Strong Correlation)

ST1				ST5	
Variables	Factor 1	Factor2	Factor3	Factor 1	Factor2
DO	-0.0759	**0.783517**	-0.18294	**0.988745**	-0.06384
Turbidity	**0.976323**	-0.01286	0.05929	-0.0445	**0.990699**
TOC	**0.985584**	-0.01003	0.080926	-0.16006	**0.977882**
NO3	-0.52831	-0.20446	0.692523	0.456462	-0.35217
BOD	-0.53339	0.310666	0.351375	-0.69496	0.221442
NH4	-0.17709	-0.573	0.016162	**0.98873**	-0.0637
COD	**0.977242**	-0.12436	0.042429	-0.16006	**0.977882**
pH	-0.34638	0.388568	-0.67418	**0.988694**	-0.06498
COND.	0.125873	0.207543	**0.859875**	**0.988737**	-0.06371
TEMP.	-0.23439	**0.781761**	0.180959	**0.988739**	-0.06368
TSS	**0.982774**	0.069416	0.05171	-0.03966	**0.990255**

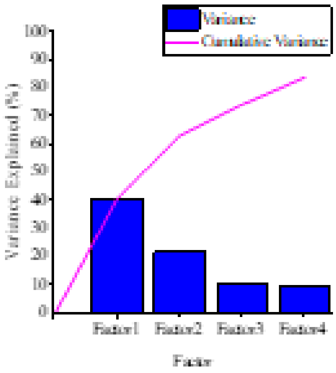
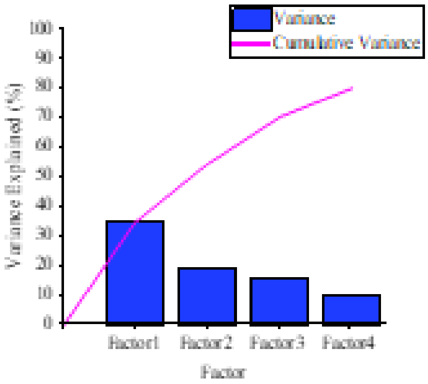
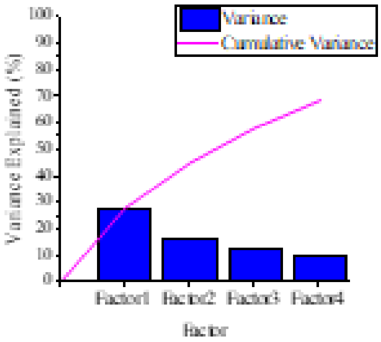
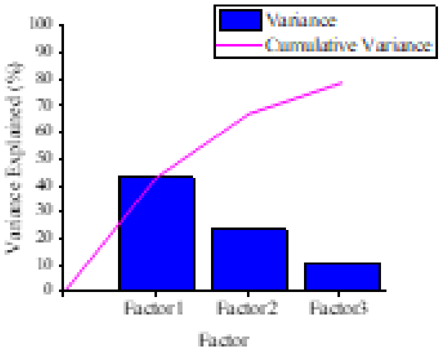
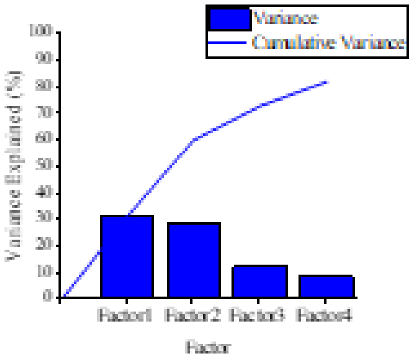
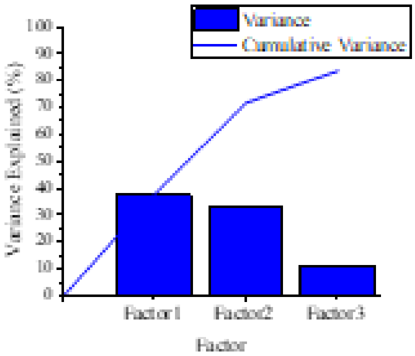
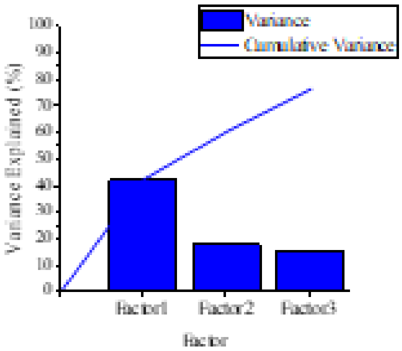
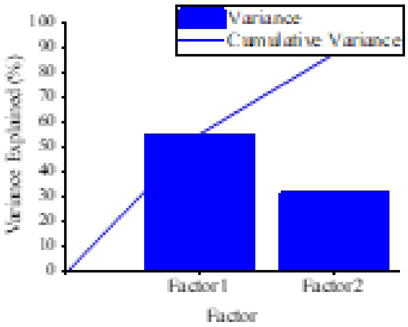
Season	ST1	ST5
March-June (Summer)		
July-September (Monsoon)		
October-November (Post-Monsoon)		
December-February (Winter)		

Figure 5.6 Variances for Factors

Table 5.5 Mean and standard deviation of DO, BOD, and COD for different monitoring stations

Stations	DO, mg/l	BOD, mg/l	COD, mg/l
ST1	6.48 ± 1.61	4.74 ± 2.20	26.88 ± 18.40
ST2	0.22 ± 0.72	32.92 ± 11.96	109.6 ± 45.78
ST3	0.29 ± 0.66	30.2 ± 12.0	98.66 ± 43.53
ST4	0.68 ± 1.25	29.71 ± 12.45	100.49 ± 46.13
ST%	0.57 ± 1.29	32.1 ± 15.74	105.86 ± 57.50

Fig. 5.8 shows the variation of DO for monitoring stations ST1-ST5 and ten years of monthly data from 2013-2022. It has been shown that for ST1, DO values were above the desired values throughout the period except for 4 data, below 4 mg/l. For ST2, the DO values were zero for most periods, signifying a massive amount of oxygen-demanding substances discharged into this reach length. However, a slight improvement was shown at the ST5, which may be due to the high assimilation capacity of BOD in this river reach, as concluded by Kazmi and Hansen(1999). Furthermore, it was observed that upstream DO concentration had a significant role in the variations of downstream concentrations. Table A6 shows the statistics of times series analysis for BOD, COD, and DO. Table A7 shows the times series forecast data for DO, BOD, and COD. 95% LCL and 95% UCL forecasts were shown for five stations. The forecast profiles of DO are shown in Fig. 5.9.

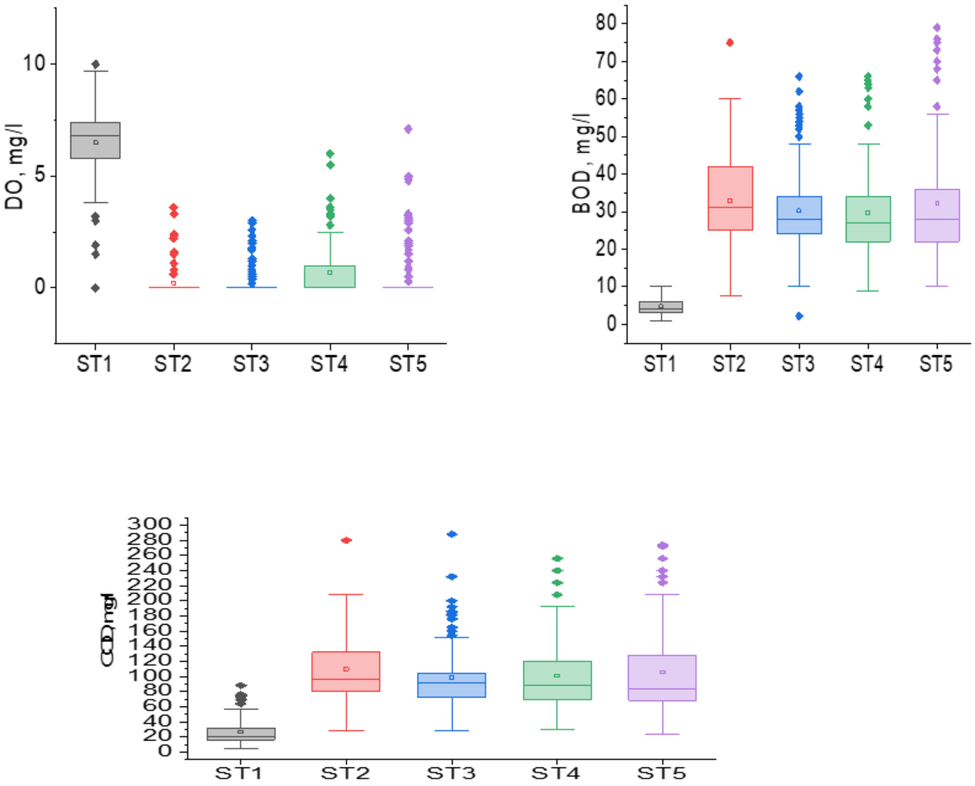


Figure 5.7 Box-Whiskers plot for different monitoring stations' DO, BOD, and COD

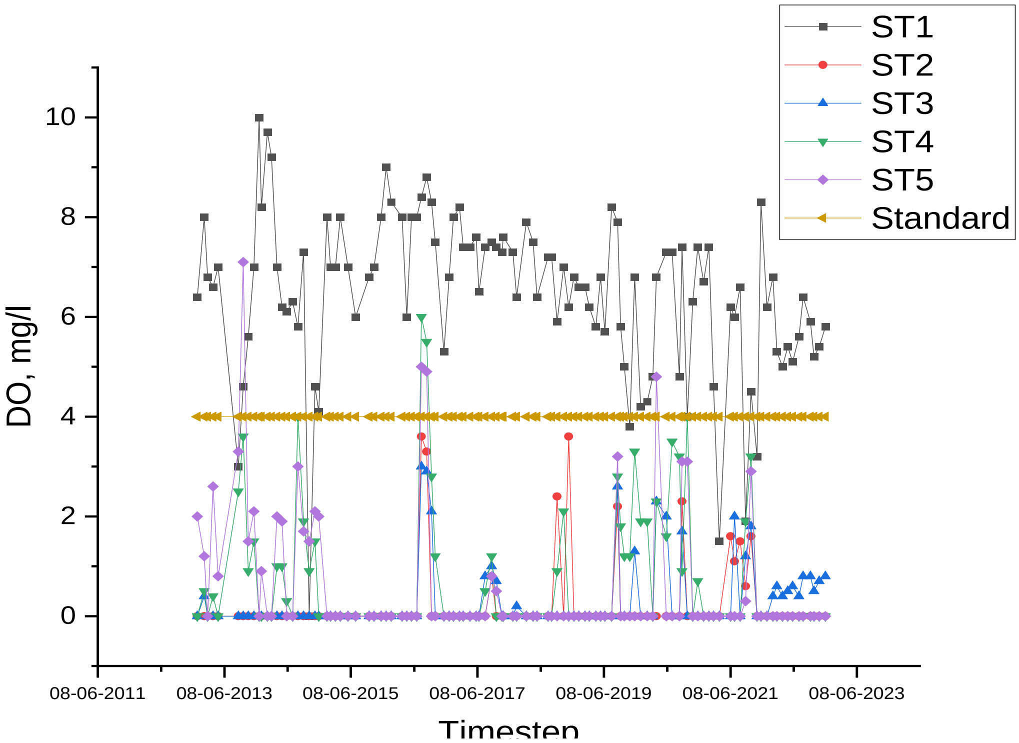


Fig. 5.8 DO profile for different monitoring stations.

Fig. 5.10 shows the BOD profile for the stations ST1-ST5. It has been observed that BOD values for ST1 were higher than the standard permissible values of 3 mg/l, except for a few values. Therefore, it has been seen that the BOD upstream is higher, and after the ST1, the trend of BOD increased with the downstream. BOD concentration also increases with the time spent at all the monitoring stations. So, it can be concluded that wastewater with highly oxygen-demanding substances generates more over time. Fig. 5.11 shows the smoothed and predicted profiles of BOD for five monitoring stations. Fig. 5.12 shows the COD trends for ST1-ST5. Except for ST1, COD values were very high and increasing with time. COD values were observed high in all the monitoring stations within the time period. Fig. 5.13 shows the COD forecast for five stations.

5.4 Point and non-point sources inventory

Table A8 shows the monthly BOD and COD data for the main sixteen drains from July 2019 to November 2023. Tables A9 and A10 show different point sources' BOD and COD counts. Figs. 4.1 and 4.3 show the Delhi region's land use pattern for inventing nonpoint sources.

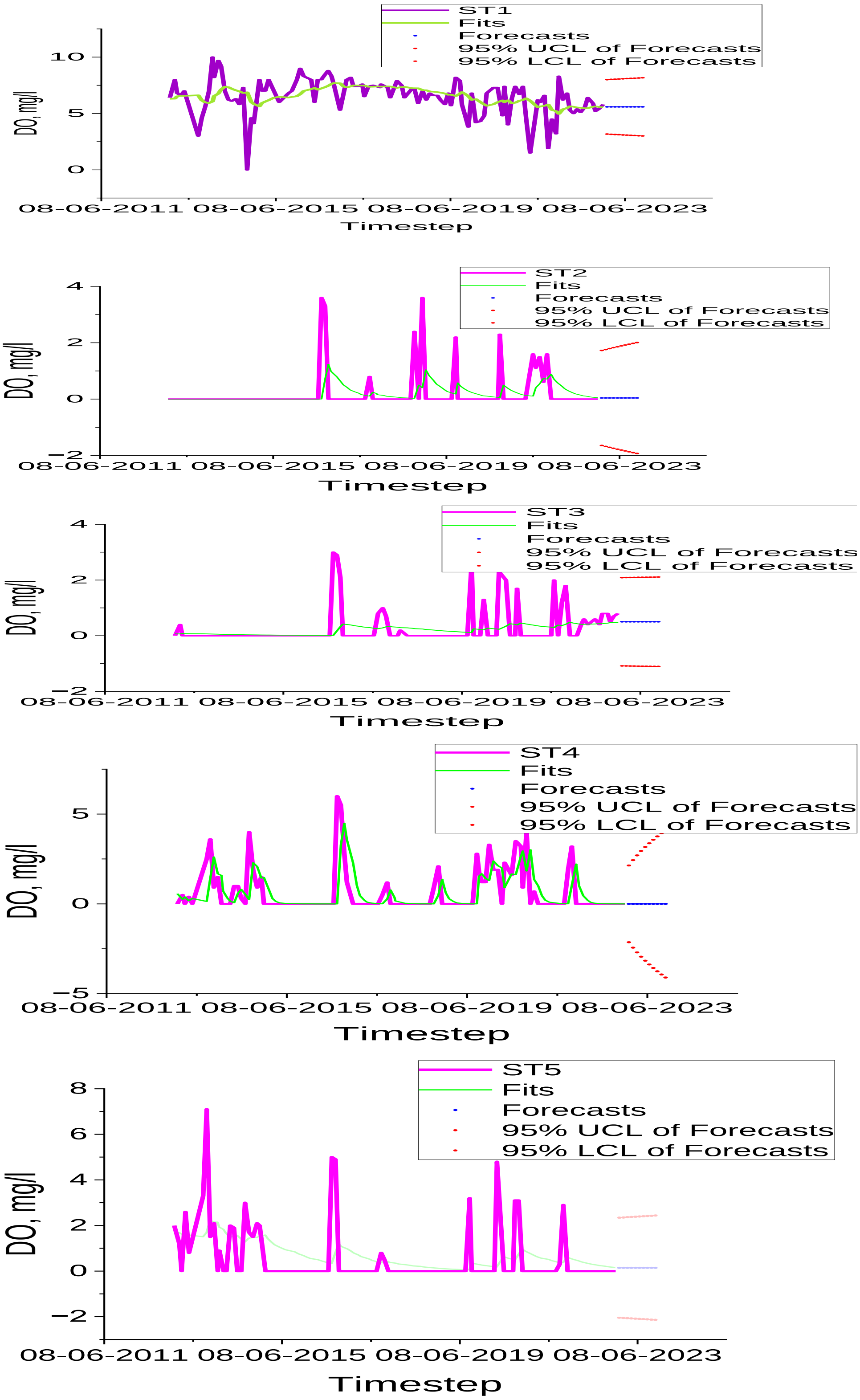


Figure 5.9 DO forecast for different monitoring stations.

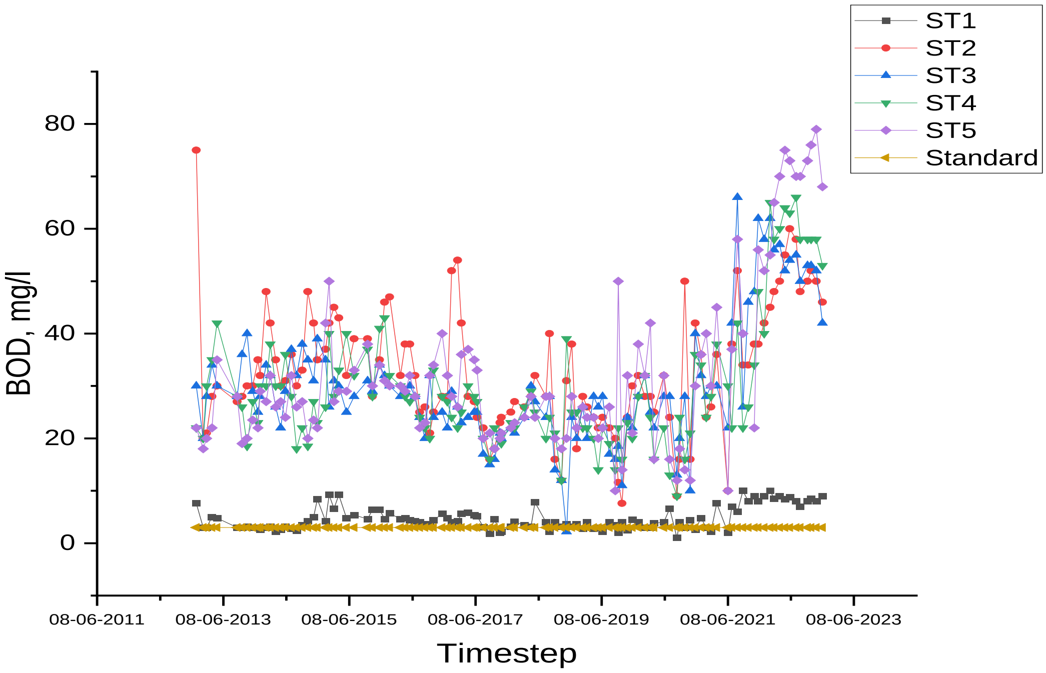


Figure 5.10 BOD profile for different monitoring stations.

5.4.1 Point Sources Assessment

Fig. 5.14 shows the BOD load discharging wastewater through sixteen significant drains into the 22 km long urban river reach of the Yamuna. All these outfalling drains discharge more than 10 mg/l permissible loads of BOD for the river reach (NGT, 2020). Table 5.2 shows that the Najafgarh drain, which contributes to the highest wastewater, contains an average of 58.1 mg/l of BOD for the study period of July 2019-November 2023. Meanwhile, the Magazine Road drain contributes a maximum BOD load of 305 mg/l and a mean value of 77.01 mg/l. However, some drains, including Magazine Road drains, have shown no flow in the recent period (Table A10), which might be due to the tapping of some drains (Rejuvenation of River Yamuna (2018). According to the DPCC's Monthly progress report for August 2023, the Metcalf drain, Khyber Pass Drain, Sweeper Colony drain, Magazine Road drain, Tonga Stand Drain, Drain No. 14, and Civil Mill drain have been tapped, and drains show no discharge in the river reach. However, after tapping these small drains, there is little or no improvement in water quality, and further measures must be taken (Fig. 5,14). Fig. 5.15 shows the Box whisker plots for sixteen-point sources. Figure 5.16 shows the COD variations for point sources. It has been observed that Sonia Vihar drain has the highest mean value of the COD concentration of 310.24 mg/l. However, mean values of COD were found above 250 mg/l for the Najafgarh drain and Sen Nursing home drain (Fig. 5.17).

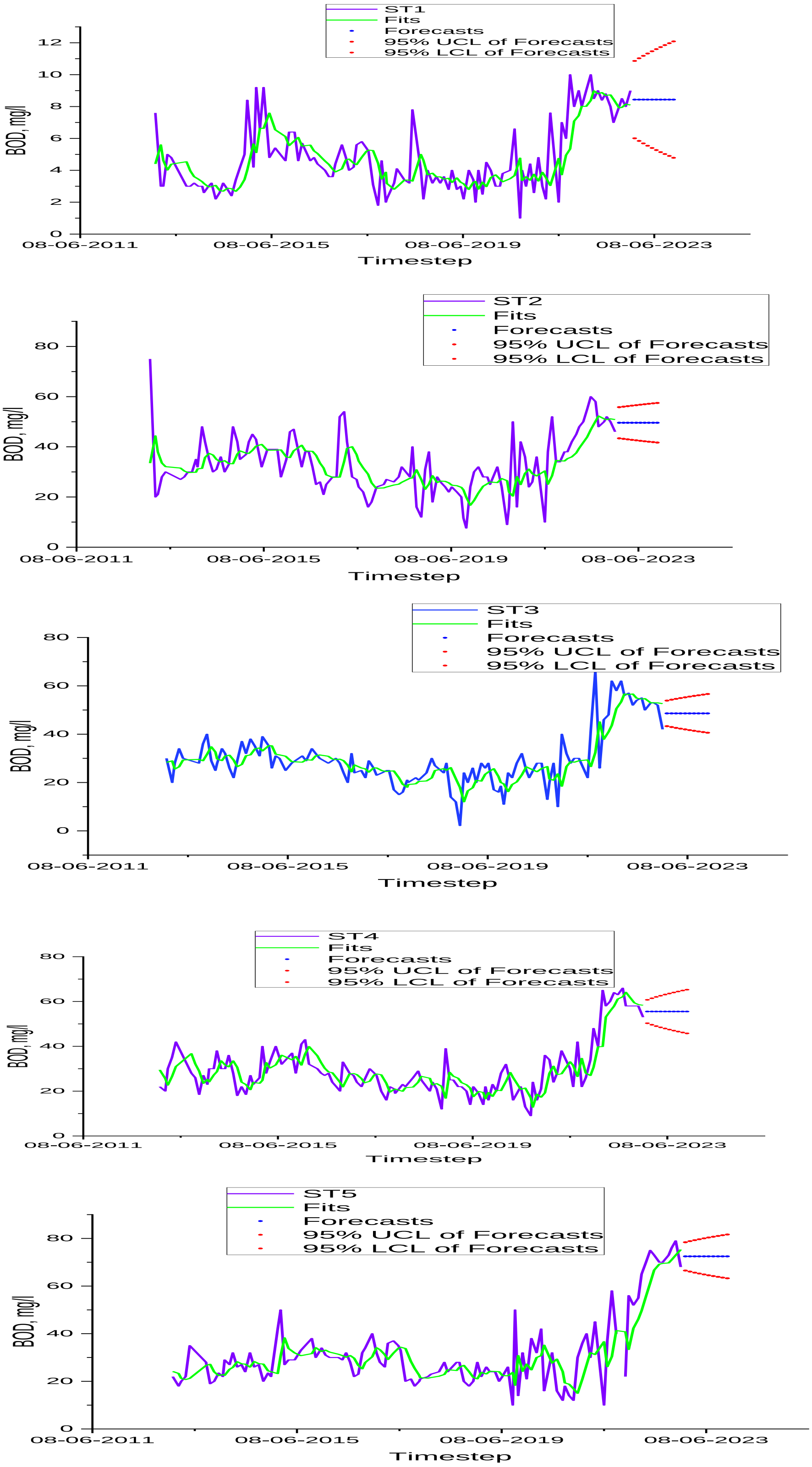


Figure. 5.11 BOD forecast for different monitoring stations

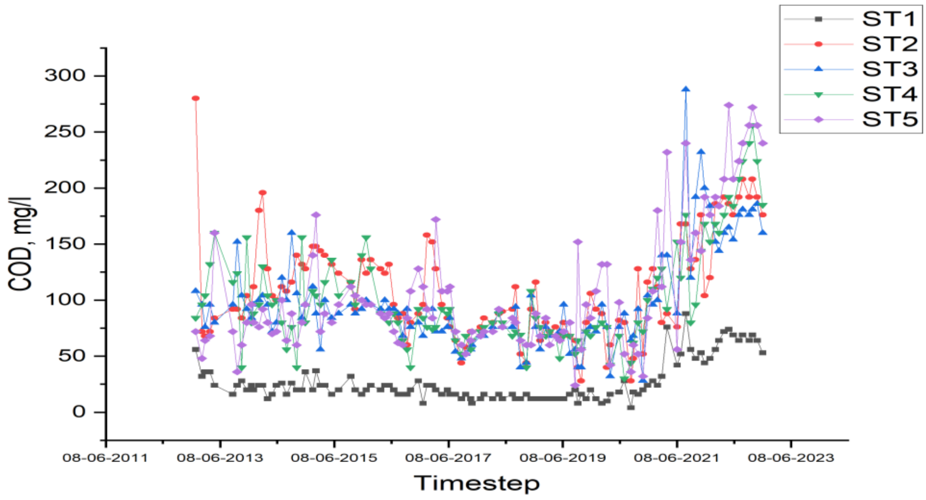


Figure. 5.12 COD profile for different monitoring stations.

5.4.2 Non-point Sources Pollution

The total area included in this study is 1483 sq. km. The land use classification and percentage of land use patterns are shown in Figs. 4.1 and 4.2. Fig. 4.2 shows that a wide area is under the urban build-up area. River Yamuna and other waterbodies comprise 1.43% of the total area. Meanwhile, river reach has an area of 1.07% (Sharma, 2013). Fig. 4.2 shows that the city's center is densely urbanized, with a few scattered green areas. The river bank is surrounded by green areas like Rajghat, Shanti van, etc., and farming by residents. High urbanized built-up area is expected to have very high surface runoff during precipitation. Table 4.4 shows the total rainfall in different months of 2018-2023. It has been observed that there is very little rainfall except during the monsoon period. Much of the runoff water in the catchment area is diverted to different drains and sewerage lines, which are further accounted for as point sources. The runoff from nearby slum areas and rural areas, as well as cattle bathing, washing of clothes, and bathing, are also contributed as point sources. Kazmi (1997) has suggested assuming 10% of the total point load as a diffused load and can be distributed after 2 km apart of the reach (Kazmi & Hansen, 1997).

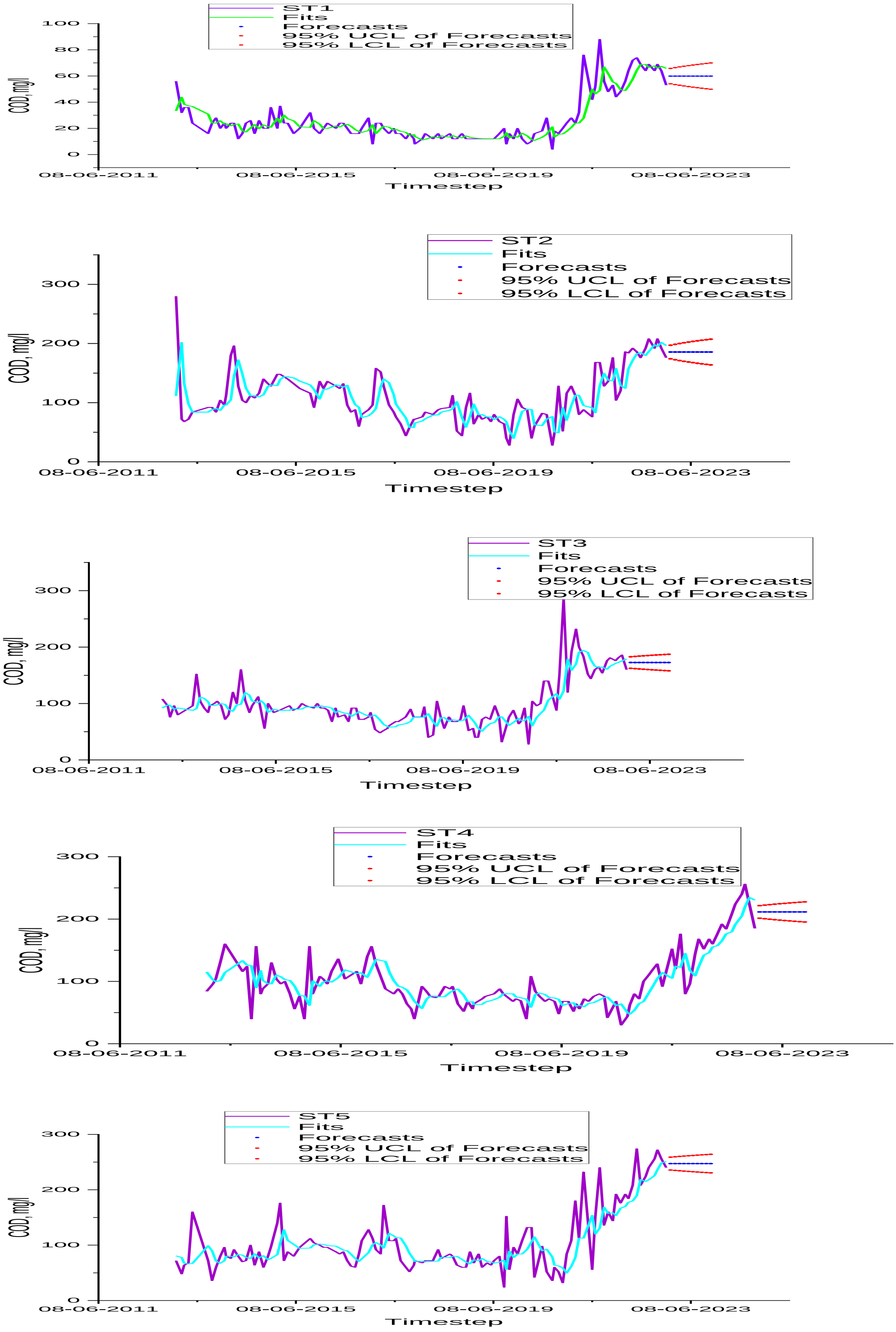


Figure 5.13 COD forecast for different monitoring stations

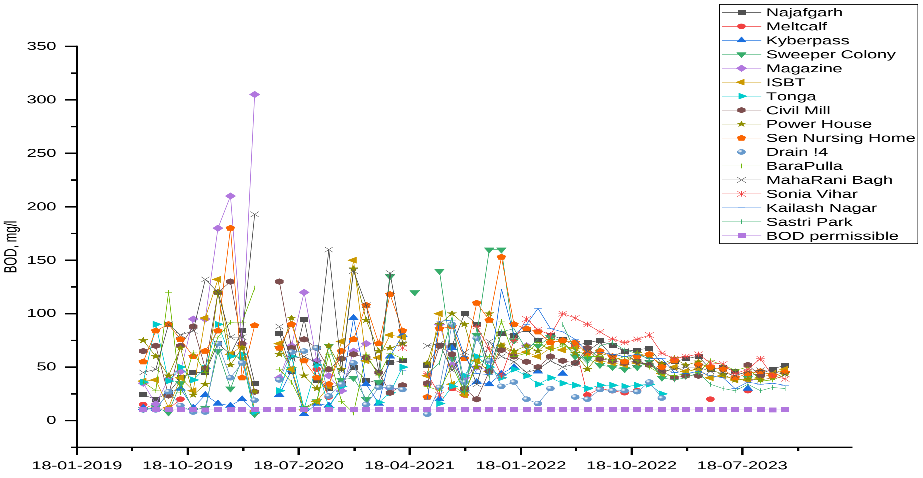


Figure 5.14 BOD variation of outfalling Point sources into the river

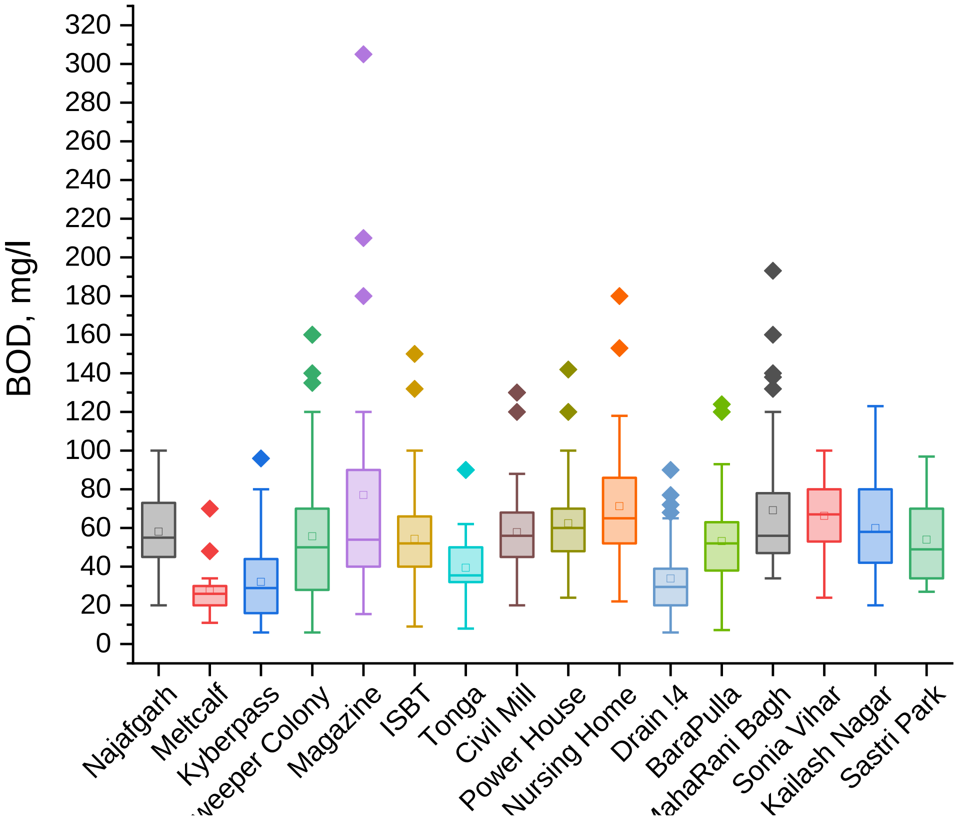


Figure 5.15 Box-Whiskers Plot for BOD of different point sources

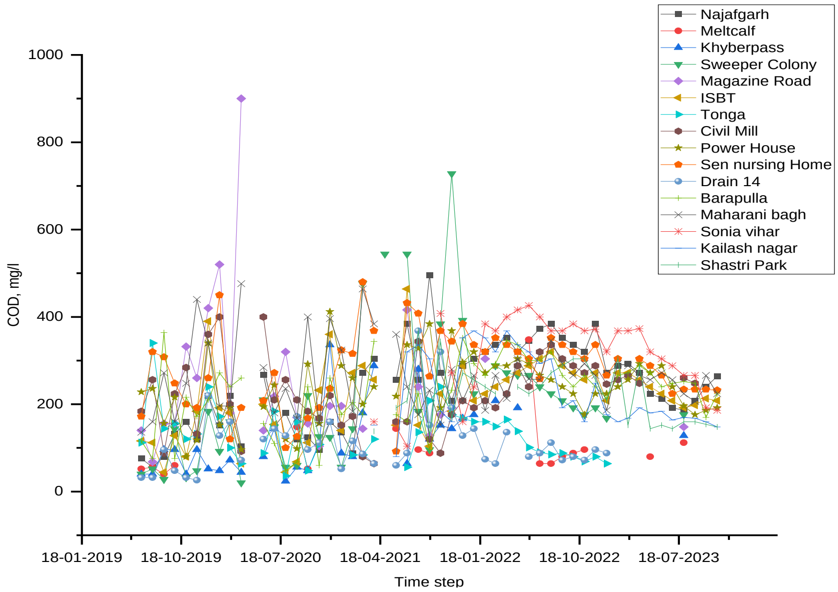


Figure 5.16 COD variation of outfalling Point sources into the river reach

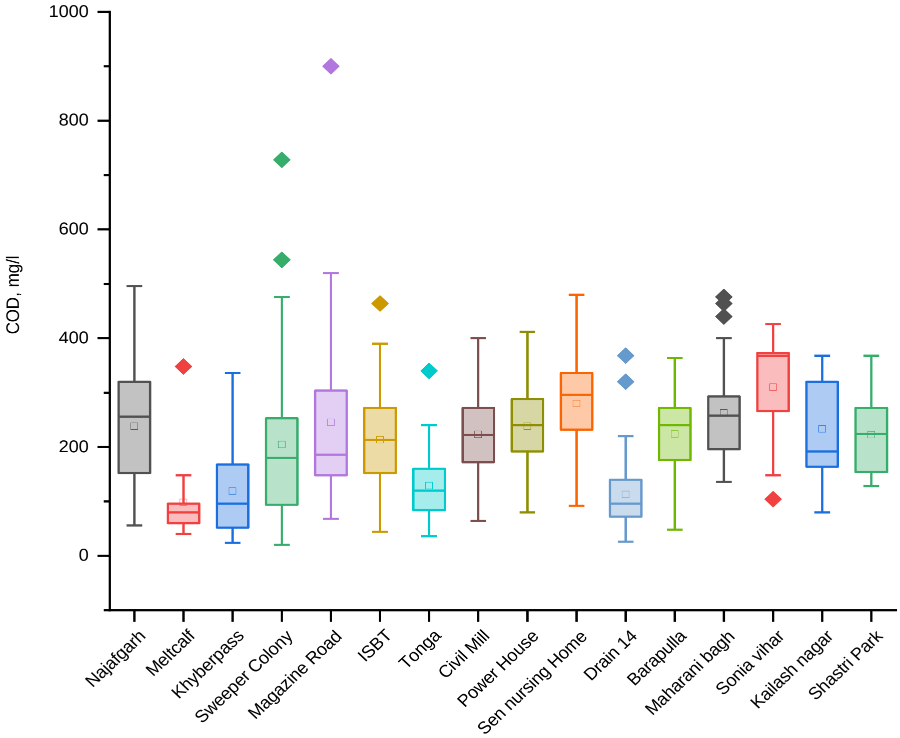


Figure 5.17 Box -Whiskers Plot for COD of different point sources

5.5 Assessment of Wastewater Treatment Plants

Table 5.5 shows the different treatment technologies adopted in the existing 38 STPs in Delhi (Sewage Treatment Plant Inventory, CPCB,2021). These STPs treat around 2715 MLD, around 83% of total wastewater generation (Fig. 5.18). The influent and effluent of wastewater in different STPs are shown in Figs.5.21 a & b; it has been observed that around 60% of STPs are not maintaining BOD and COD effluent levels, 10 mg/l and 50 mg/l, respectively, which CPCB prescribes for effluent standard. 68% of STPs use the activated sludge process, and the removal efficiencies of BOD of these STPs are 65%-85%. Effluents from these STPs are discharged directly or indirectly through the drains to the Yamuna River. The BIOFORE technology used in Sen Nursing Home STPs and Delhi Gate Nallah is the most efficient technology used in Delhi. Najafgarh STP uses the Extended Aeration (ER) method and has 75% and 70% removal efficiency of BOD and COD, respectively. The Nazafgarh drain, the highest polluting source of this reach, absorbs the wastewater from this STP. The contributing BOD load from this drain is around 165 TPD (DPCC 2020). Fig. 3.5 shows the STPs locations and numbers used in this study.

Table 5.6 Different treatment methods used in STPs of Delhi

Name of the Treatment Methods	No of STPs	Wastewater treatment (MLD)
ASP	26	2575
EA	4	69
FAB	1	3
SBR	4	245
MBR	1	4
BIOFORE*	2	20

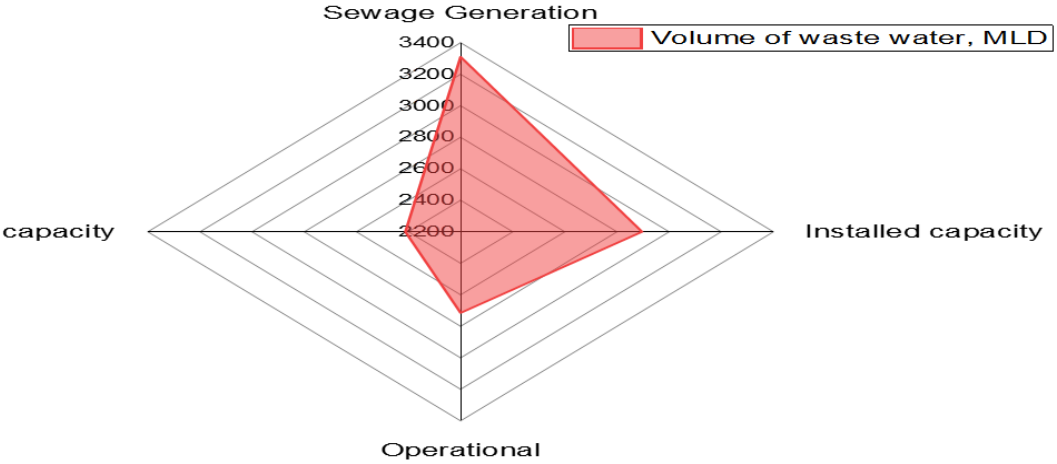


Figure 5.18 Wastewater generation, installed, operational capacity in Delhi (Data from Sewage Treatment Plant Inventory, CPCB, 2021)

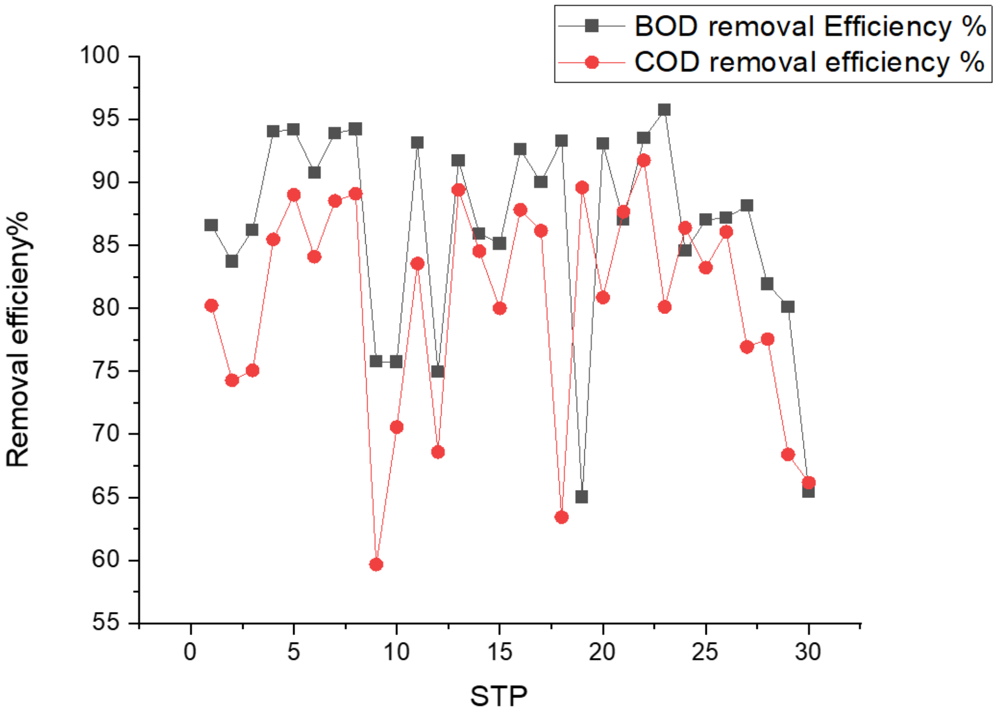
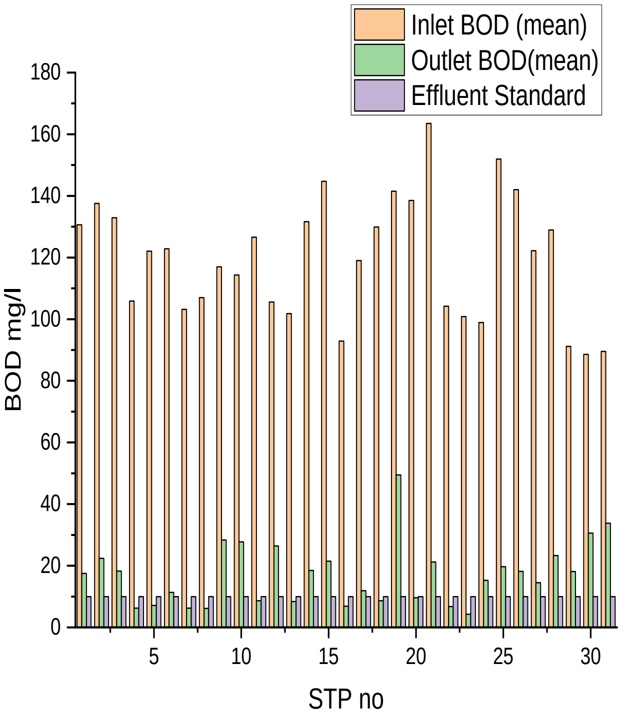


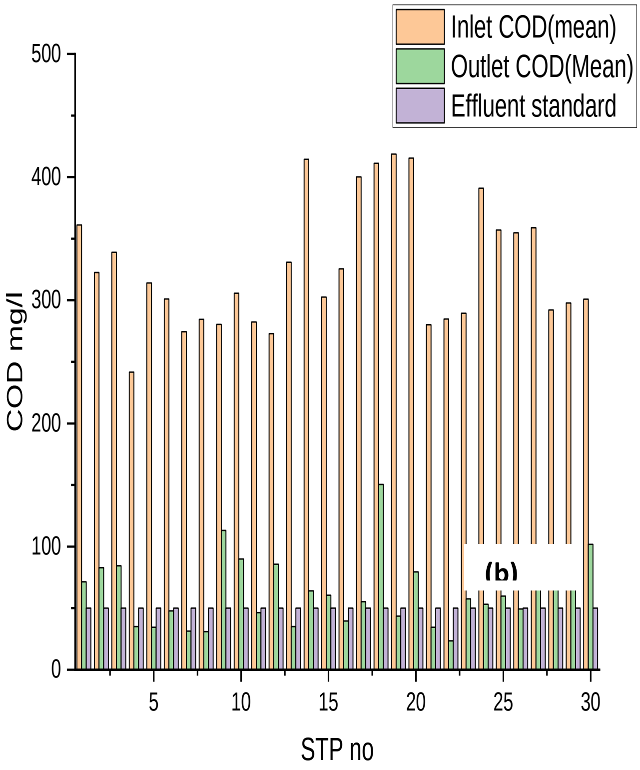
Figure 5.19 Removal Efficiencies of Different STPs



STPs Identity	Name of STPs	Technology Use
1	Molarband (Mini STP)	FAB
2	Coronation Pillar I	ASP
3	Coronation Pillar	ASP
4	Delhi gate New	ASP
5	Delhi Gate Old	BIOFORE
6	Keshopur STP(New)	ASP
7	Sen Nursing Home (SNH	BIOFORE
8	Nilothi New	SBR
9	Nilothi	ASP
10	Najafgarh	EA
11	Rithala 2	ASP
12	Pappankalan(Old)	ASP
13	Pappankalan PH- II (New	SBR
14	Rohini	ASP
15	Narela	ASP
16	Okhla New	ASP
17	Kondli	ASP
18	Kondli II	ASP
19	Kondli New	ASP
20	Kapasahera	SBR
21	Yamuna Vihar Ph-III	ASP
22	Chilla	SBR
23	Akshardham	MBR
24	Mehrauli	EA
25	Vasant Kunj I	EA
26	VasantKunj II	EA
27	Yamuna Vihar I	ASP
28	Yamuna Bihar II	ASP
29	Okhla I	ASP
30	Keshopur	ASP

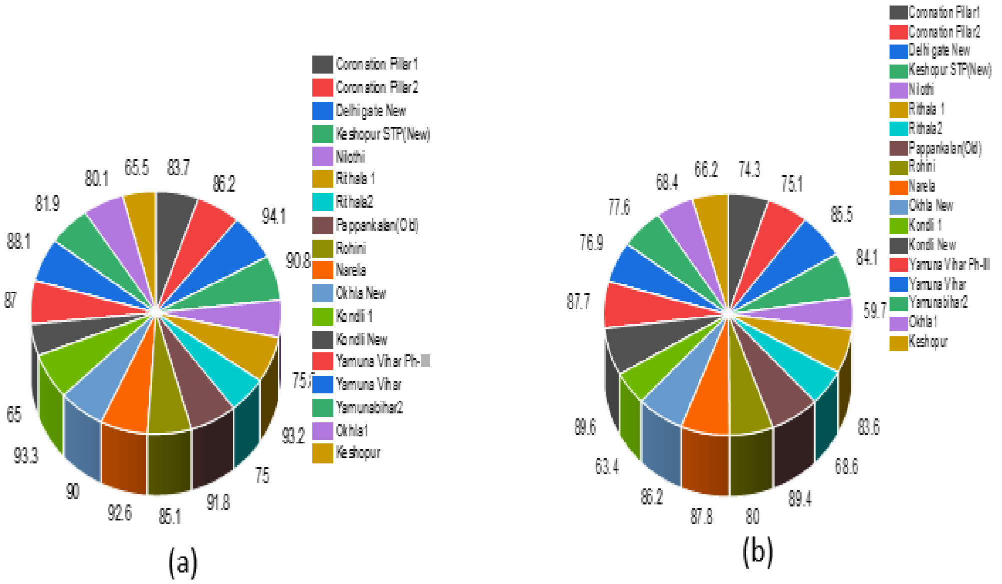
(a)

Figure 5.20 (a) Influent and Effluent BOD for different



STPs Identity	Name of STPs	Technology Use
1	Molarband (Mini STP)	FAB
2	Coronation Pillar I	ASP
3	Coronation Pillar	ASP
4	Delhi gate New	ASP
5	Delhi Gate Old	BIOFORE
6	Keshopur STP(New)	ASP
7	Sen Nursing Home (SNH	BIOFORE
8	Nilothi New	SBR
9	Nilothi	ASP
10	Najafgarh	EA
11	Rithala 2	ASP
12	Pappankalan(Old)	ASP
13	Pappankalan PH- II (New	SBR
14	Rohini	ASP
15	Narela	ASP
16	Okhla New	ASP
17	Kondli	ASP
18	Kondli II	ASP
19	Kondli New	ASP
20	Kapasahera	SBR
21	Yamuna Vihar Ph-III	ASP
22	Chilla	SBR
23	Akshardham	MBR
24	Mehrauli	EA
25	Vasant Kunj I	EA
26	VasantKunj II	EA
27	Yamuna Vihar I	ASP
28	Yamuna Bihar II	ASP
29	Okhla I	ASP
30	Keshopur	ASP

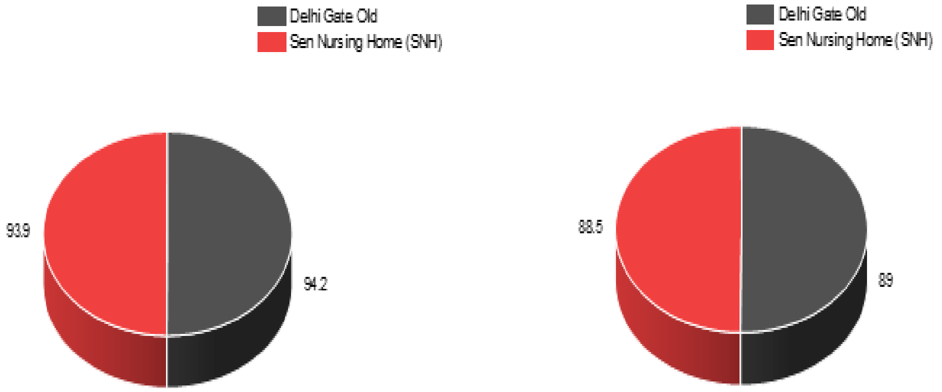
Figure 5.20 (b) Influent and Effluent COD for different STP



(a)

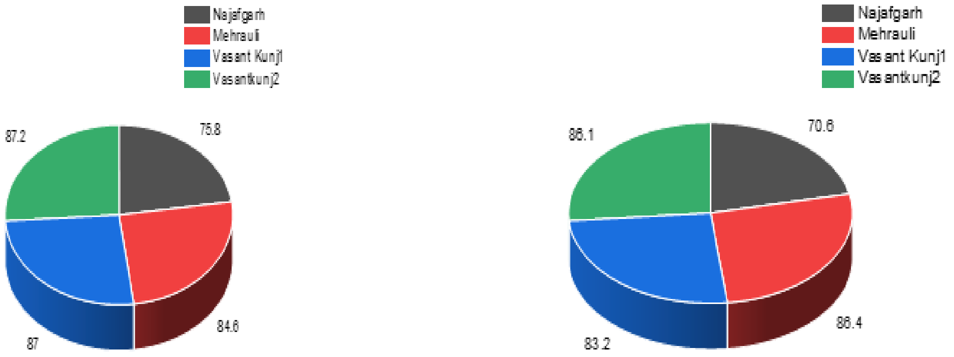
(b)

Figure5.21 (a-b) BOD and COD removal efficiency for different STPs by ASP methods



(a) (b)

Figure 5.22 (a-b) BOD and COD removal efficiency for different STPs by BIOFORE method, respectively.



(a) (b)

Figure 5.23 (a-b) BOD and COD removal by ER method, respectively

Fig 5.21 shows the removal efficiency of STP used ASP was between 65%-94 %. The STPs use BIFORE technology can remove more than 93% of BOD (Fig. 5.22). Removal efficiency for Extended aeration varied from 70% to 85% (Fig. 5.23). The efficiency of these STPs can be increased with advanced treatment methods shown in Table 5.6. Cho et al. (2004) suggested that ASP removes 87.5% BOD from wastewater, and efficiency can be increased by coagulation, filtration, and absorption process, including the existing system. Hence, an advanced treatment process is required to improve the ER used in Nazafgarh STP, which discharges effluent in the Nazafgarh drain, the most significant pollutant contributor to the Yamuna River, and can be enhanced by rotating biological contractors. Although, the treatment cost also increases with the advancement of the process.

Table 5.7 Advanced wastewater treatment methods (Cho et al., 2004)

Methods	BOD removal efficiency %
ASP	87.5
ASP+ C +F	95
ASP+C+F+ A	98
R	87.8
Rotating +C+F+A	98.1

ASP= Activated Sludge process, C= coagulation, F= Filtration, A=Adsorption
R= Rotating biological contractors

5.6 Summary

The Yamuna River Delhi stretch is a leading source of water for Delhi. The river stretch is a receptacle of urban liquid waste caused by human interference from domestic and industrial fields and leads to the most contaminant reach of the country. The present study used multivariate techniques to represent the spatiotemporal water quality variations and interpreted a large hourly complex dataset (March 2021-February 2022) obtained from two real-time monitoring stations upstream and downstream of this reach. Eleven water quality parameters were assessed, and Box Whisker plots were drawn monthly. The increased concentrations of conductivity, BOD COD, TOC, NH4, and low DO downstream indicated the influence of outfalling drains and diffused sources contributing pollutants into the river stretch. A higher BOD, COD, and TOC concentration was observed downstream in monsoon attributed to the organic substance in surface runoff. FA and PCA were implemented in the standardized data set to reveal the correlation between the water parameters. For upstream, Turbidity, TOC, COD, and TSS have strongly positively loaded for factor 1 for all the seasons except monsoon. For downstream, TOC and COD contributed strongly positive load except in winter. River water quality management is a tedious job as it comprises multiple variables. It has been observed that there is very little rainfall except during the monsoon period The River Yamuna, Delhi's urban reach, is highly contaminated with very low or zero freshwater flow during the non-monsoon periods. A sharp declination of dissolved oxygen and acceleration of BOD was observed after the outfall of drain 1. The wastewater treatment plants data for 2020-2022 have been analyzed, and the removal efficiencies of BOD and COD were found between 65%-94%. The BIOFORE technology has shown maximum removal efficiencies, around 94% and 89% for BOD and COD, respectively.

CHAPTER 6

SIMULATION OF WATER QUALITY WITH MODEL QUAL2KW AND ASSESSMENT OF ASSIMILATION CAPACITY

6.1 Introduction

This chapter includes assessing the requirement of load reductions and flow augmentation to enhance the assimilation yield of the Yamuna River, Delhi. The framework QUAL2kw was used to predict river quality. The model was calibrated and confirmed in critical flow conditions of pre-monsoon periods. Three strategies were established for varying pollutant loads. The DO concentration was predicted with changing BOD and COD loads. The sixteen outfalling drains were considered pollutant sources between the 22 km stretch of the river. Four cases with 41 scenarios were studied with varying flow augmentation upstream and varying load.

6.2 Model calibration and validation

Fig.6(a-d) visually represents the calibration and validation of key parameters. Notably, Fig 6(a) starkly illustrates the impact of the highest pollutant load contributor, D1, on the dissolved oxygen levels in the river. After D1, which accounts for a staggering 58% of the total pollutant load, the dissolved oxygen levels plummeted to zero, painting a grim picture of the river's health (Paliwal et al., 2007). Due to the high oxygen-demanding substances and low fresh flow, this river reach has become a sewerage line without DO. Table 6.1 shows the RMSEV for calibration and validation. Fig 6(b) and (c) show that after the outfalling of D1, BOD and COD values increased sharply. Some errors are unavoidable as the single average values have been taken as monthly averages, and sampling times might be varied for different monitoring stations of 22 km long reach. Furthermore, the quality of the wastewater of the point sources might vary depending on collection time and sampling procedure. More accurate predictions may be possible by collecting samples hourly for each monitoring station. Despite some inaccuracy, the QUAL2Kw framework has shown to be quite applicable for this river reach and can be adopted for water quality management purposes for data-limited conditions (Sharma & Kansal, 2011). Table A11 shows the rate sheets used for calibration and validation.

Table 6.1 RMSEV for calibration and validation (Verma et al., 2023b)

RMSE Values (%)	DO	BOD	COD	pH
Calibration	16.28	24.55	24.09	4.5
Validation	17.03	24.6	35.19	4

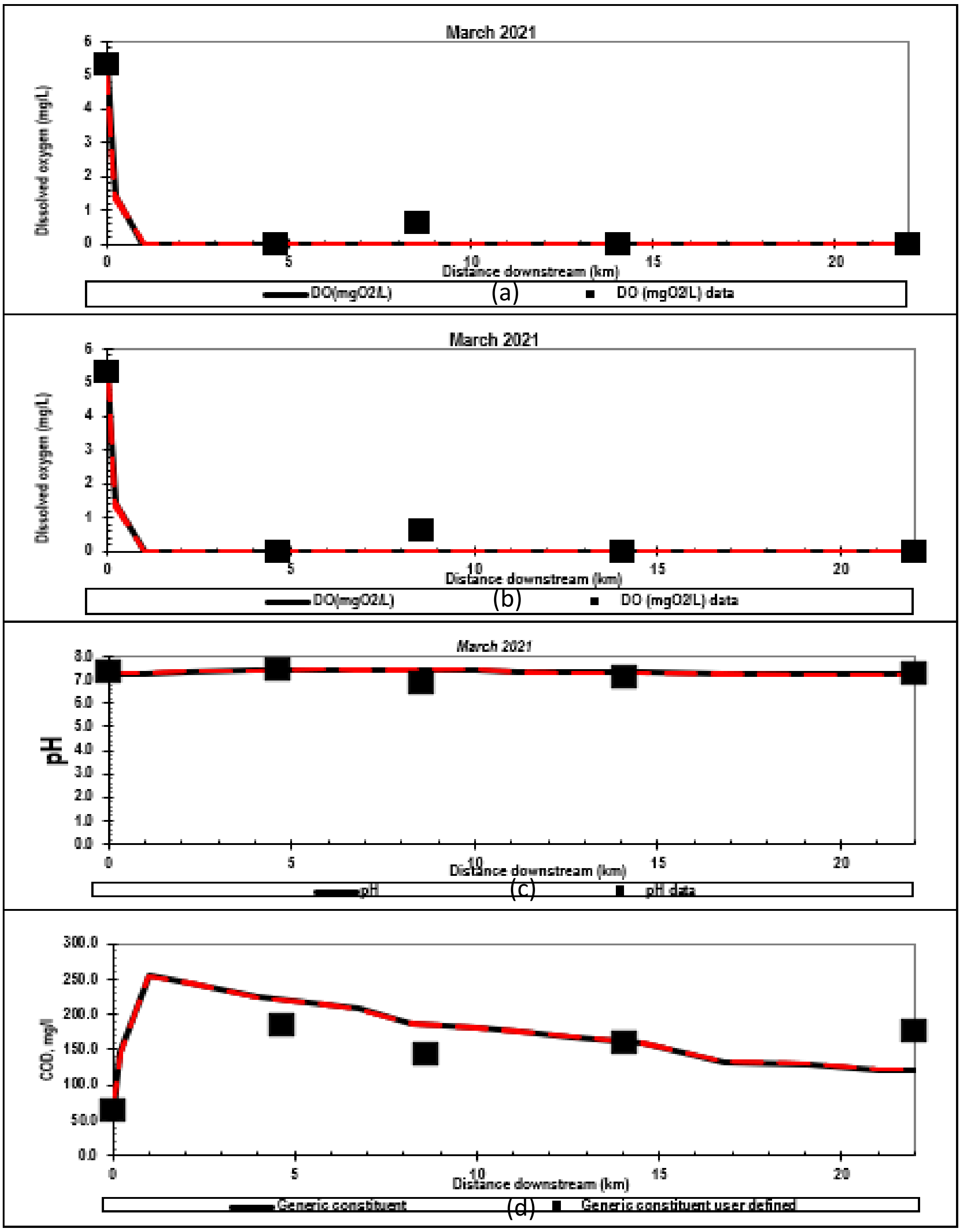


Figure 6.1 (a-d) Calibration results for DO, BOD, pH, and COD, respectively.

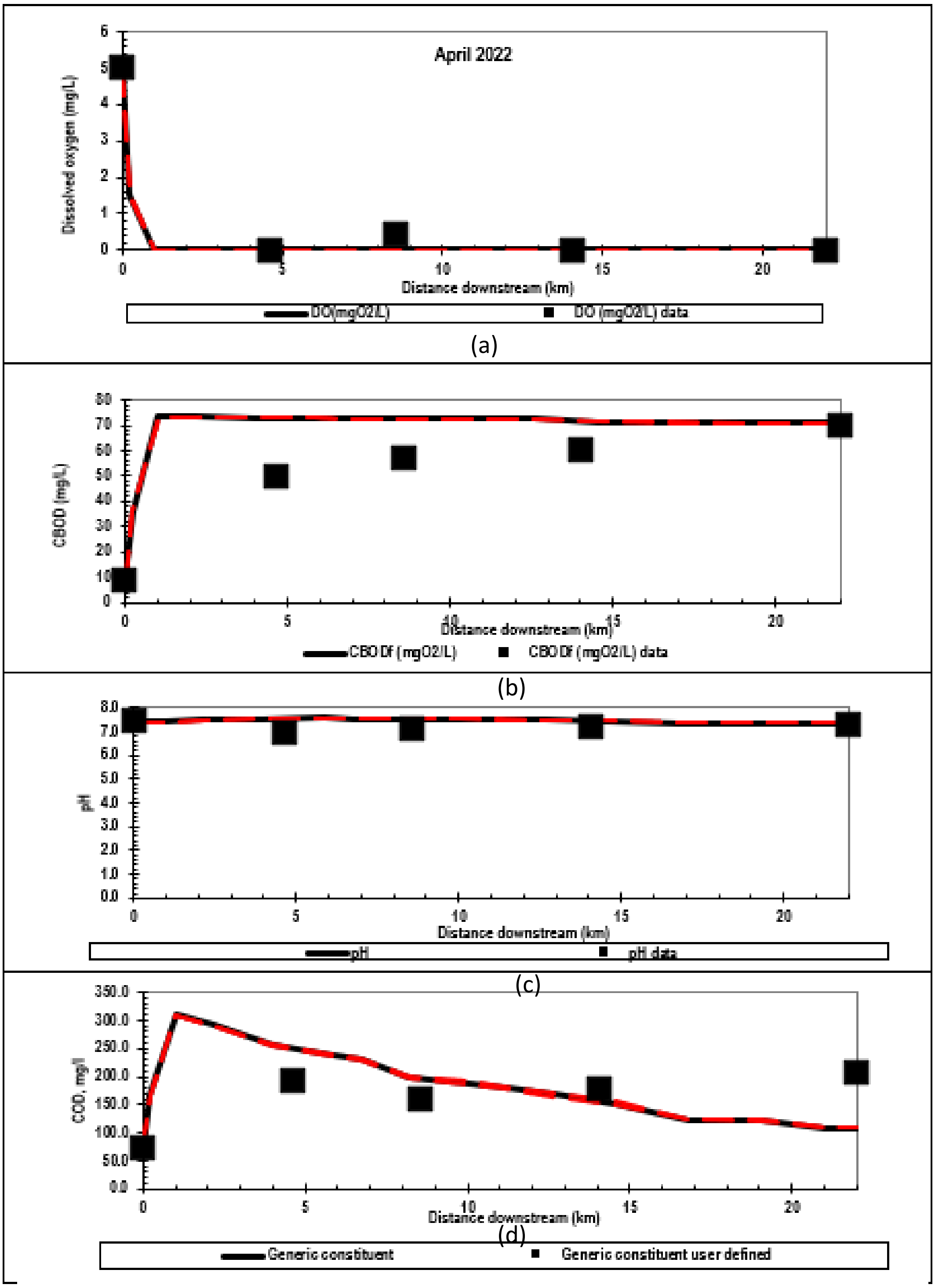


Figure 6.2 (a-d) Validation Results for DO, BOD, pH, and COD, respectively

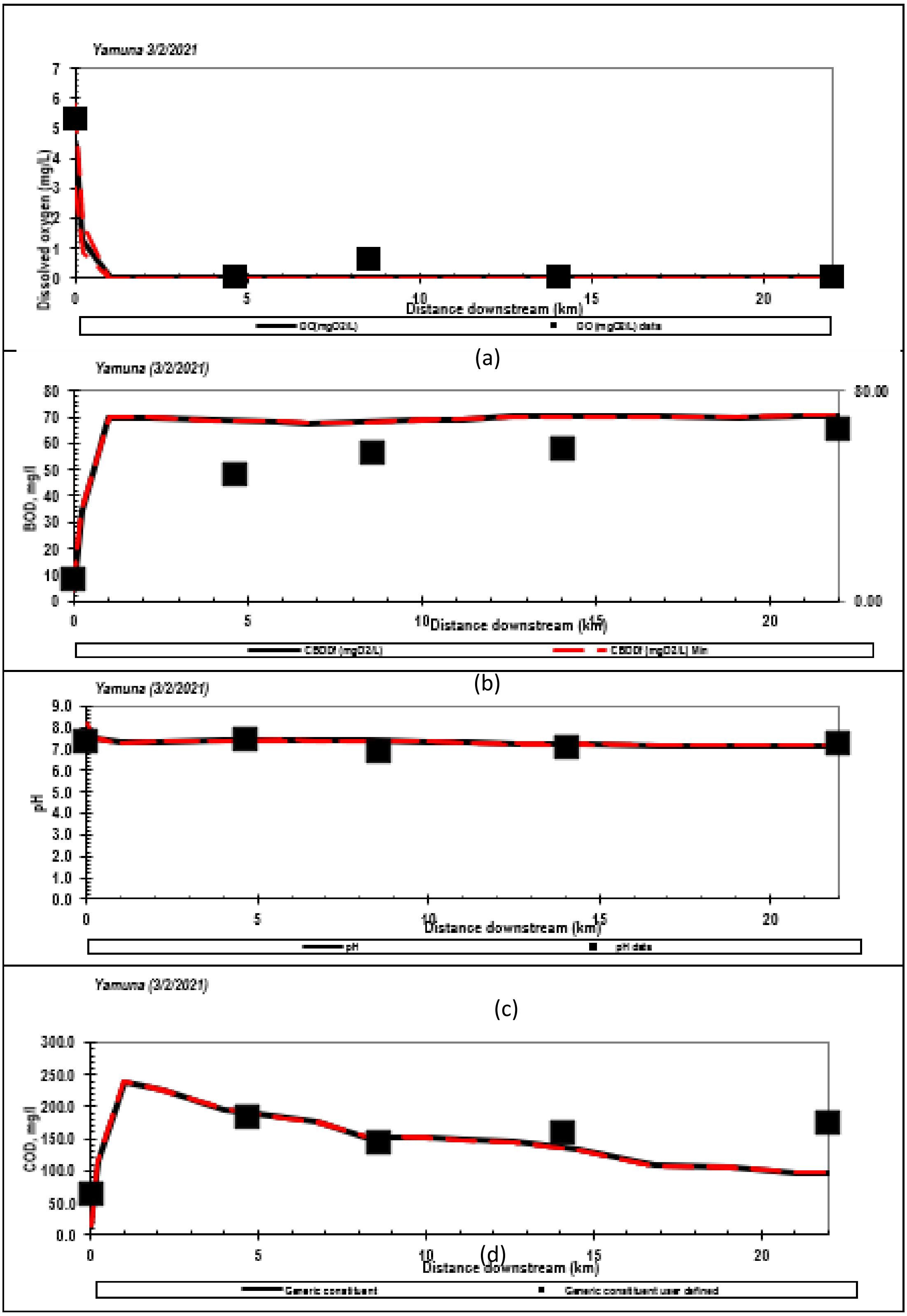
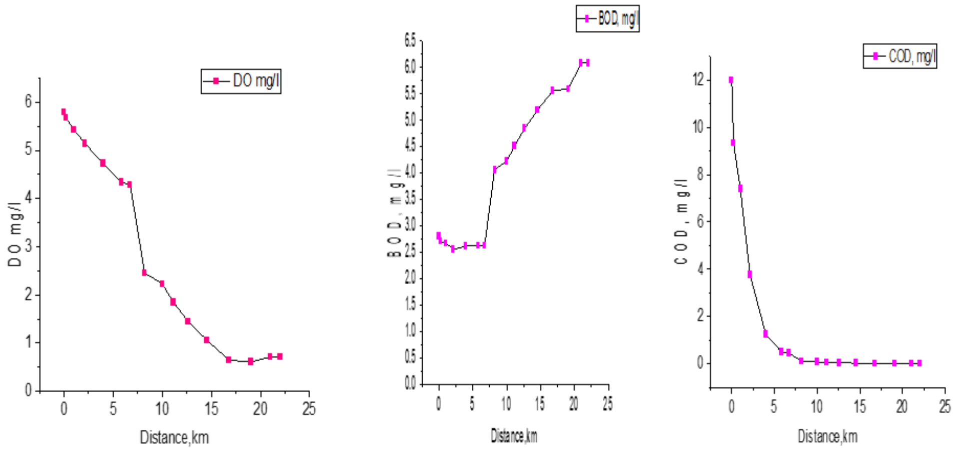


Figure 6.3 (a-d) Validation with hourly water quality data for DO, BOD, pH, and COD, respectively.

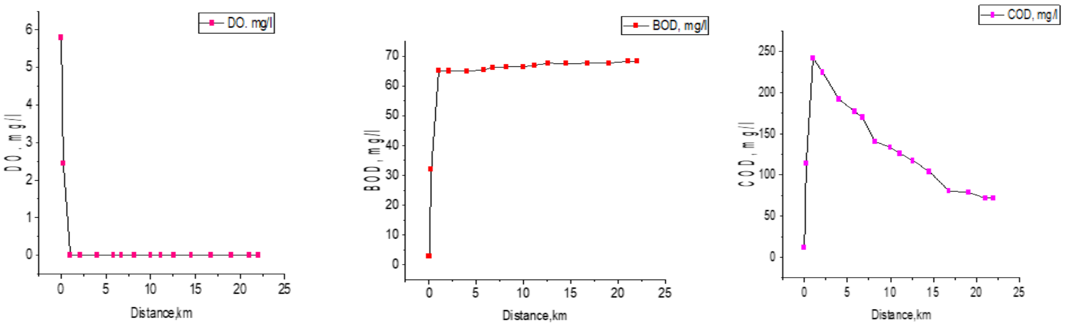
6.3 Strategies for assessment of the assimilation capacity of the river reach

Three strategies have been studied for the assessment of assimilation capacity. Table 3.4 shows the strategy adopted to evaluate the assimilation capacity. Fig 6.4 shows the BOD, COD, and DO profiles without BOD and COD with headwater input, as shown in Table 4.8. It can be concluded that with the flow one cumec with 2.8 mg/l BOD and 12 mg/l COD, River Reach is not able to maintain the required DO (≥ 4 mg/l) and BOD (≤3 mg/l). Hence, this reach is needed to increase upstream flow. As flow is deficient, the stream's reaeration capacity becomes poor; therefore, after some distance, DO reduction happens, and BOD increases. From Fig. 6.4, it was observed that COD decreased, and thus, the oxygen requirement for COD was high. So, COD load needs to be considered, which was not considered in previous studies (Paliwal et al., 2007).



(a) (b) (c)

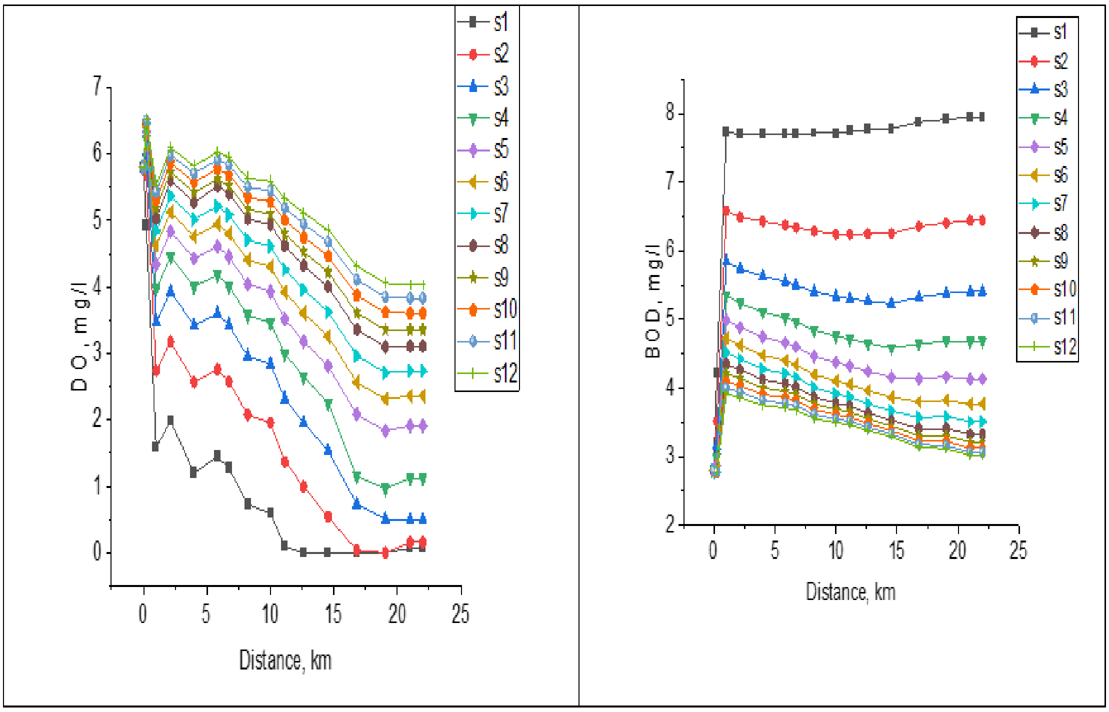
Figure 6.4(a-c) Predicted DO, BOD, and COD without load



(a) (b) (c)

Figure 6.5(a-c) DO, BOD, and COD profiles with existing load

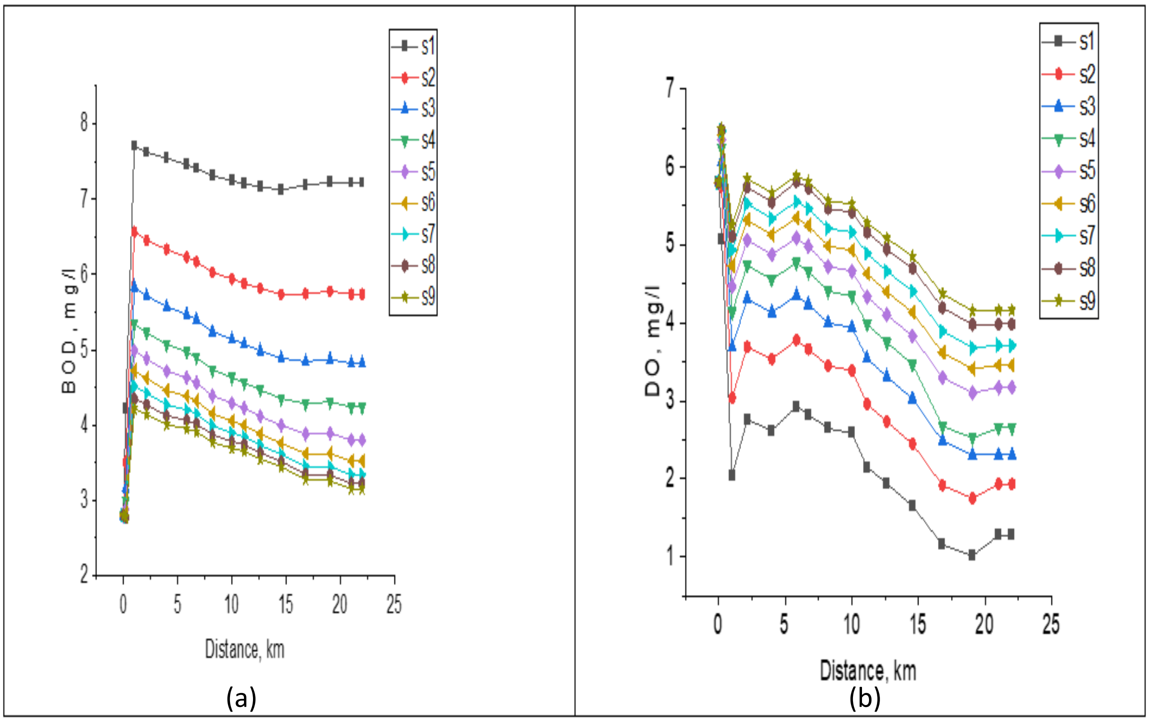
Fig 6.5 shows that with the existing flow and pollutant load, DO concentration decreased to zero throughout the river reach, and BOD concentration was also above 60 mg/l after D1 outfalling. Hence, flow augmentation at the upstream must also reduce pollutant load. In strategy 3, the flow has been increased from 10 cumecs to 120 cumecs for scenarios s1-s12, and BOD and COD loads have kept changing, as shown in Table 4.10.



(a) (b)

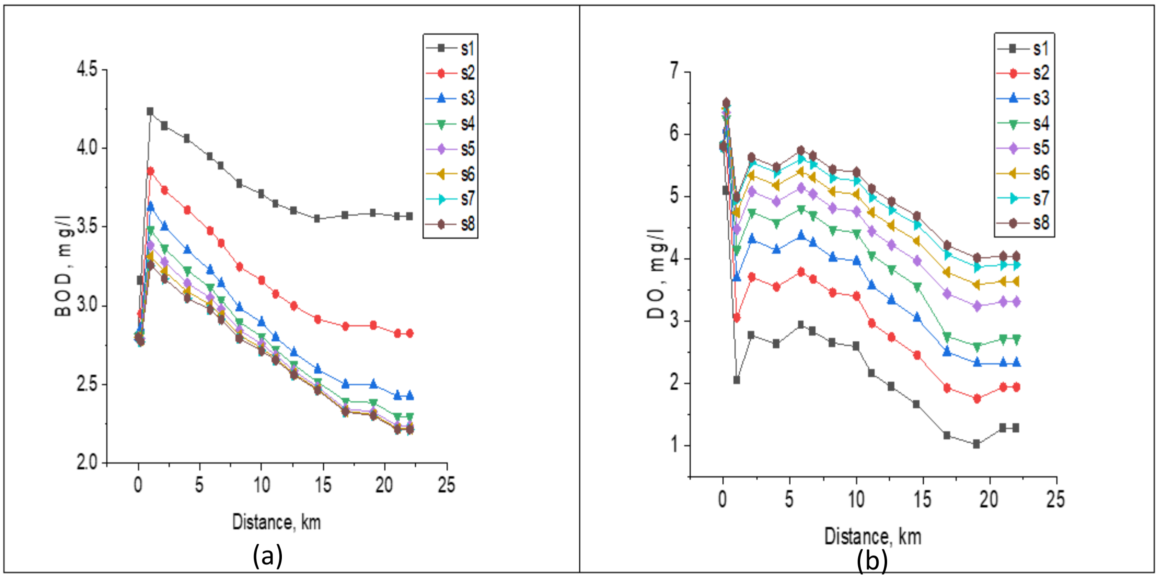
Figure 6.6 (a-b) Variation of DO and BOD for case 1 with different flow

Fig. 6.6 shows that with flow 120 cumecs, scenario12(s12), the reach can assimilate 10 mg/l of BOD and 50 mg/l of COD from each point source. Although the DO value maintained the required standard throughout the reach, the BOD level was higher than 3 mg/l. In case 2, BOD was kept at 10 mg/l, and COD was reduced to 25 mg/l at each point source. Fig 6.7 shows that around 90 cumecs of flow augmentation upstream can maintain DO concentration above 4 mg/l throughout the reach. Although, at some distance, BOD is higher than 3 mg/l. In case 3, BOD has been reduced to 5 mg/l in each point source, and COD has been kept at 25 mg/l. BOD has been observed to be maintained below 3 mg/l after 5 km upstream. Maintaining DO above 4 mg/l requires around 90 cumecs of flow upstream. Therefore, in case 4, BOD has been reduced in D1, D11, D12, and D15 to 5 mg/l; the rest have been kept at 10 mg/l. COD is also marked as the effluent standard prescribed by NGT. Fig 8 shows that 120 cumecs upstream flow can maintain BOD and DO within the specified values. In case 3, (Fig. 6.8), with 80 cumecs of upstream flow, the reach can assimilate 31.33 TPD of BOD and 142.85 TPD of COD load. Kazmi & Hansen. (1997) concluded that BOD and DO concentrations for effluent drains should be 10 mg/l and 4 mg/l to maintain the river water quality. Hence, the increase of DO in the point sources may be increased to improve assimilation capacity. They also suggested a 40 cumecs flow increment upstream. Paliwal and Kansal (2007) indicated that some drains need to be diversified, and flow augmentation is required to maintain the required standard.



(a) (b)

Figure 6.7(a-b) BOD and DO variation for case 2 with varying flow



(a) (b)

Figure 6.8 (a-b) BOD and DO variation for case 3 with varying flow

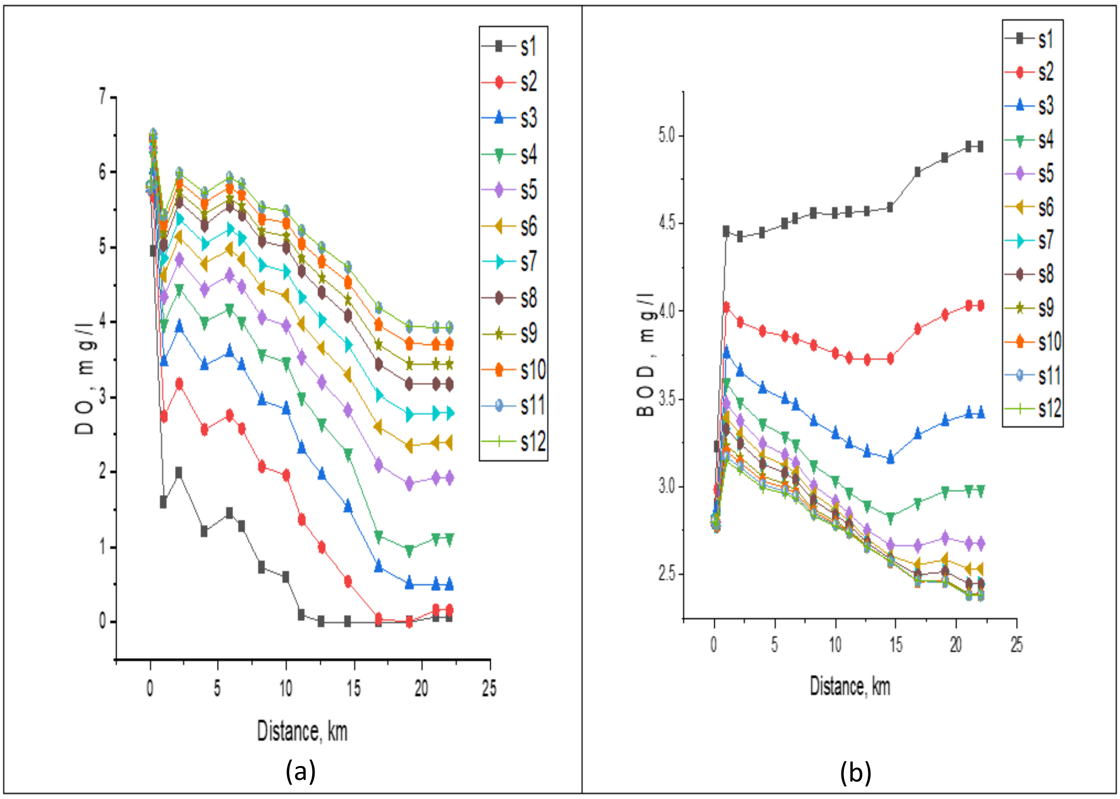


Figure 6.9 (a-b) DO and BOD variation for Case 4 with varying flow

6.4 Summary

The QUAL2Kw model assessed the assimilation capacity of Yamuna's most polluted stretch. The model is appropriate for this reach as it can be simulated with low data availability. Thus, it is ideal for decision-making tools like India, where limited data is available. This study revealed that the river's assimilation capacity was low due to high BOD and low DO levels. The wastewater enters the river from 16 drains and also diffused sources. Najafgarh drains added the highest wastewater quantity with elevated BOD and COD levels; thus, after adjoining this drain, the river's water quality fell to inferior. These conditions prevailed over the 22 km of this reach. In this study, the upstream flow increment with reduction of BOD and COD has been studied. In strategy 1, wastewater from all drains was curtailed, and desired standard of reach was not found. Improvement of the assimilation capacity of this river is a very challenging job, as the less upstream water also has low DO and high BOD. In strategy three, four cases were established with 41 scenarios with an increment of flow and reductions of BOD and COD. These cases suggested that load reduction and flow increment can improve the assimilation capacity of the river reach. It has been observed that with 80 cumecs of upstream flow, the reach can assimilate 31.33 TPD of BOD and 142.85 TPD of COD load, maintaining the desired level of DO (≥ 4 mg/l) and BOD (≤3 mg/l) throughout the reach. This reach required substantial load cutting with flow dilution to enhance the water quality. Both the remedy options, while complex and economically unfeasible, hold the potential to improve the situation significantly. The study also revealed that COD and BOD are responsible for DO deterioration. It is also noted that the nitrogenous substances would improve the estimation of dissolved oxygen. As these drains carry domestic water containing nitrogenous waste, it has been suggested that regular monitoring of ammonium, organic nitrogen, and nitrate nitrite is also required.

CHAPTER 7

ASSESSMENT OF TOTAL MAXIMUM DAILY LOAD

7.1 Introduction

In this chapter, a TMDL implementation plan was created to address the BOD impairment of the Yamuna River Delhi reach. This river stretch is impaired with high BOD and low DO conditions. The main goal is to reduce the BOD level below 3 mg/l for this river reach. This river reach is associated with environmental pollution, resulting in high mortality among fish. The increase in population and urbanization resulted in the deterioration of this river's reach. However, with the implementation of the TMDL plan, there is a potential for significant improvement in the water quality, leading to a healthier ecosystem and reduced fish mortality. Ten scenarios have been generated by reducing BOD load and flow augmentation upstream, offering a range of possibilities for water quality improvement.

7,2 Scenario analysis on responses to load reduction

After calibration and validation, using the framework QUAL2Kw framework, scenarios are analyzed by deducting the pollutant input to satisfy the prescribed standard. BOD has been chosen as the target water quality parameter for TMDL development at the Yamuna Delhi reach. Central Board of Pollution Control (CPCB), Delhi, has suggested that BOD concentration should be less than 3mg/l for this reach to achieve the Class C category, which is suitable for bathing and can be used after conventional treatment. This study included only BOD and COD, as the oxygen-demanding substances, nutrients, and fecal coliforms were not added to this study. It has been assumed that all drains contributed to BOD load except D5, which led to no flow (Yamuna, 2020). The average flow and BOD pollutant load were collected from Yamuna in 2020 and are shown in Table 3.6. Under scenario A, five simulation analyses were constructed, as shown in Fig 7.1. The input pollutant loadings for Scenario A have been shown in Table 3.6. From Fig 7.1, simulation 3 shows that the predicted BOD is under the prescribed BOD (less than 3 mg/l). In simulation 4, the Predicted BOD level was higher after 15 km. In simulation 5, the predicted BOD was below 3 mg/l throughout the reach. However, in these simulations, the predicted DO profile did not meet the standard throughout the spread. Although simulation 5 shows a compelling BOD management scenario, DO concentration could not satisfy the target value (Fig 7.2). For Scenario A, upstream flow has been assumed as 10 cumecs suggested as the environmental flow for this river stretch. As the flow is low, reaeration capability is lacking in this reach, and hence, artificial aeration is required to maintain the minimum 4 mg/l of suggested DO concentration (Paliwal et al., 2007). For simulation 5, the maximum daily load was 7.58 TPD, and the observed average daily load was 177.99 TPD, around 23 times higher than the daily load can assimilate to achieve the required standard. Paliwal & Sharma (2007) concluded that this reach could purify 9.33 TPD BOD load, and the disposed quantity of BOD was 296.1 TPD, 33 times higher than the assimilated values. However, for simulations 1-5, DO concentration was lower than the required 4 mg/l minimum criteria (Fig 7.2). It's suggested that external reaeration is required. Kazmi & Hansen (1997) suggested that 10% of the point source load could be assumed as distributed sources. As BOD is an explicit component of safety management, the MOS for BOD is 10% of the total load (Dors & Tsatsaros, 2012). Table 7.1 shows the WLA, LA, and MOS values for the simulation 5. Fig. 7.2 shows the predicted DO for simulation 5, concluding that a vigorous amount of local aeration is needed to attain the minimum 4 mg/l of DO.

7.3 Scenario analysis with flow augmentation

Scenario B was analyzed with the increasing flow upstream. Different simulations have been done with the increment of flow 10 cumecs. Table 3.7 shows the BOD and flow used to construct simulations 6-10. Simulations 6-9 have been done with the upstream flow variations from 20-50 cumecs. Fig 7.3 shows the BOD and DO profiles for changing the upstream flow, and flow augmentation increases the DO profile with BOD assimilation capacity. Scenario C and simulation 10 were done with 50 cumecs of upstream flow and drains 11-15 with 4 mg/l DO. Fig.7.3 shows simulation 10 attained the BOD level within the required standard. Hence, with the 50 cumecs upstream flow, the allowable load was 14.353 TPD. Thus, with the 40 cumecs upstream flow increment, around 77% of the assimilated load increased. The DO profile has also been improved up to about 12 km downstream, and external reaeration at the river can improve the conditions.

Tables 3.6 and 3.7 show the potential BOD load reduction for each scenario, and Table 7.3 shows the total maximum daily load calculations for scenarios. Scenario 5 has chosen the best options with a suggested flow of 10 cumecs. However, this reach maintains a fresh flow that is almost nil except during the monsoon period (Paliwal et al., 2007). Based on simulation 5, all outfalling drains required 95% load reductions. Furthermore, the effluent standard for this reach is 10 mg/l, used in simulation1. If this standard could be maintained for effluent, then 66% load reductions are required to attain the condition for simulation 5. Hence, effluent from all industries should be lowered to 10 mg/l. The BOD loads outlined in the selected simulations can be achieved by adopting proper control strategies for the wastewater discharged from all point sources. Treatment facilities should be available to treat the wastewater before outfalling into the river and spreads.

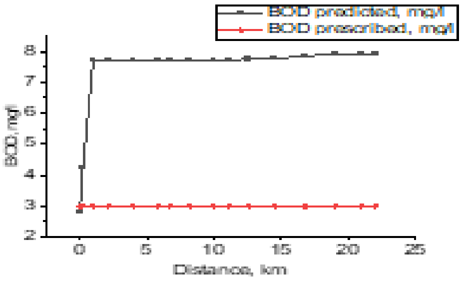
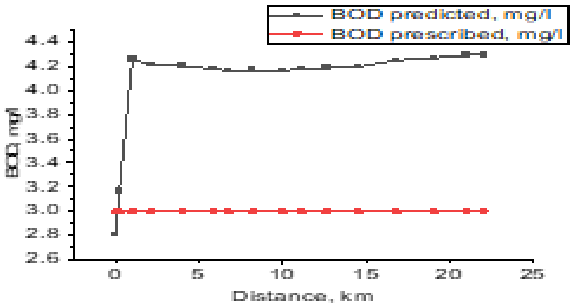
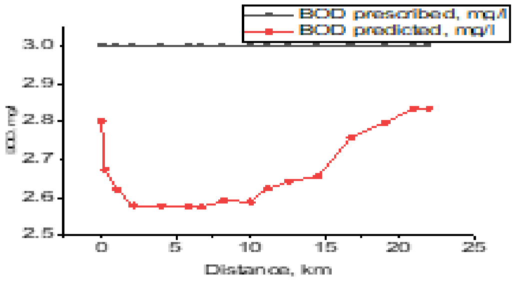
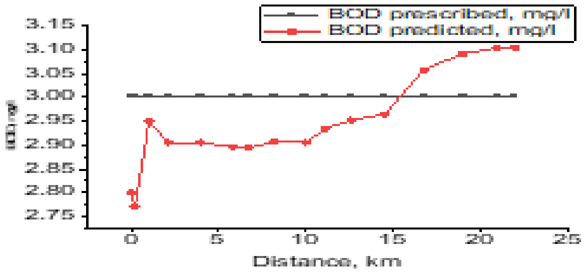
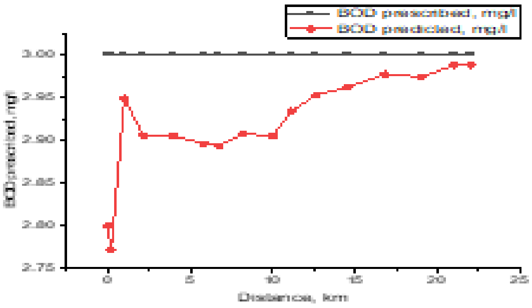
Scenarios A	BOD predicted
Simulation1	
Simulation2	
Simulation3	
Simulation4	
Simulation5	

Figure 7.1 BOD profiles for Scenario A

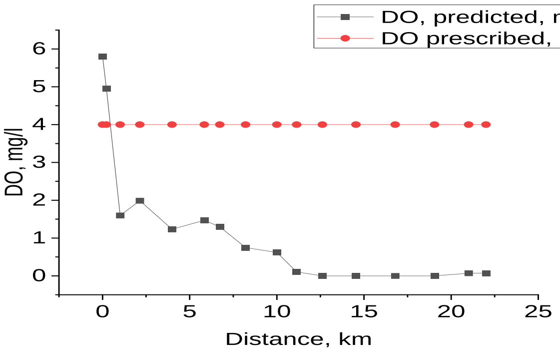


Figure 7.2 DO Profile for Simulation 5

Table 7.1 TMDL calculations

Simul -ation	ΣLA TPD	ΣWLA TPD	MOS TPD	TMDL TPD	Upstream flow, m3/s	% reduction	DO satisfied	BOD satisfied
1	19.15	2.39	2.39	23.93	10	86.17	No	No
2	9.56	1.2	1.2	11.96	10	93.08	No	No
3	5.7	0.71	0.71	7.12	10	95.88	No	Yes
4	6.2	0.77	0.77	7.74	10	95.71	No	Yes, up to 15 km
5	6.06	0.76	0.76	7.58	10	95.62	No	Yes
6	19.93	2.39.	2.39.	23.93	20	86.17	No	No
7	9.56	1.2	1.2	11.96	30	93.09	No	After 12 km
8	8.03	1.0	1.0	10.03	40	94.20	Up to 7.5 km	Except for some distance
9	10.21	1.23	1.23	12.67	50	92.68	After 1 km,it is below the desired limit	Quite below the desired level except around 2-3 km
10	11.47	1.44	1.44	14.35	50	91.7	After 10 km, it is below the desired limit	BOD is low

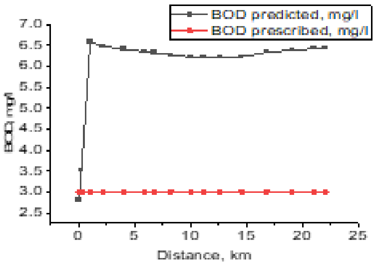
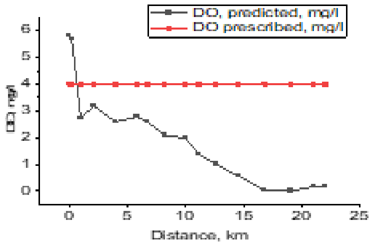
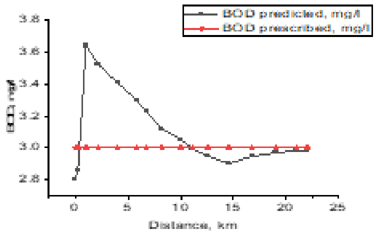
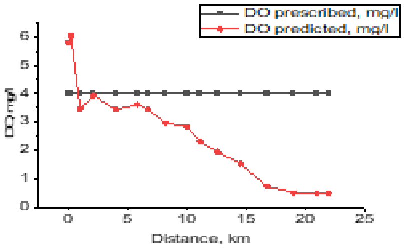
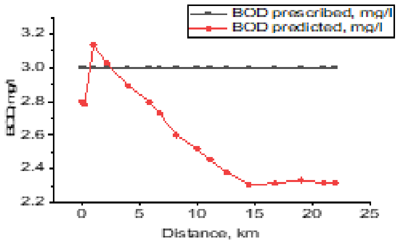
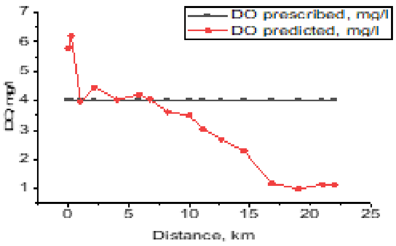
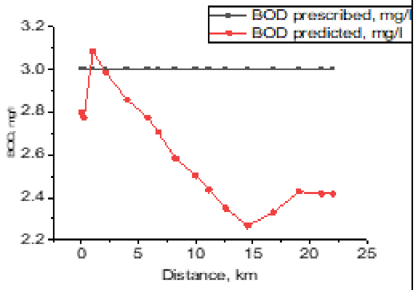
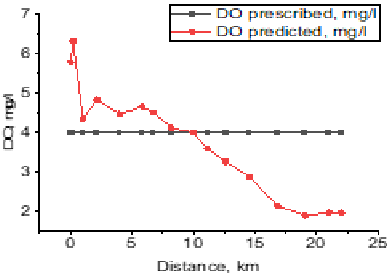
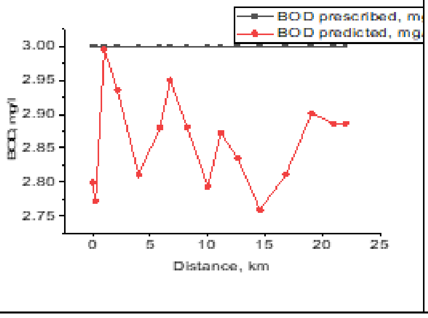
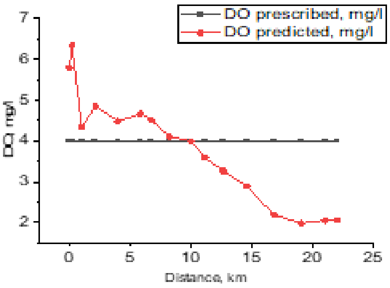
ScenarioB	BOD profile	DO profile
Simulation 6		
Simulation 7		
Simulation 8		
Simulation 9		
Simulation 10		

Figure 7.3 BOD and DO profiles for scenario B

Plants containing advanced technologies such as membrane bioreactors, sequencing batch reactors, and microbubble flotation systems can be established to remove the organic and inorganic substances (Osmi, 2016). The removal efficiencies of the sewage treatment plant of Delhi show that extended aeration, BIOFORE, and oxidation ponds can remove oxygen-demanding substances more efficiently (Jamwal et al., 2009).

Although this area has scanty rainfall, this study includes 10% of the point load as nonpoint sources. Due to scarce rain during the pre-and post-monsoon period, the surface runoff is nil, but cattle bathing, washing clothes, and household uses of water by the slum dwellers near the river bank have been added to the waste load in the river water (Kazmi & Hansen, 1997). The control of these uses of river water can control the pollutant load of this river reach. However, wetland riparian zones have been suggested as the controlling strategy for nonpoint sources. Local oxygenation is required to increase the dissolved oxygen concentration, and a series of weirs can be constructed in critical locations (Kannel et al., 2007). Flow augmentation studied in scenarios B and C also suggested the increase of dissolved oxygen concentration and assimilation capacity.

7.4 Summary

The QUAl2Kw framework has been used to assess the total maximum daily load for this river reach. Three scenarios with 10 simulations have been constructed with varying BOD load, upstream flow, and local oxygenation. With 10 cumecs upstream flow, the required TMDL was 7.58 TPD of BOD load to maintain the BOD concentration below 3 mg/l throughout the spread. As fresh flow is scarce and low reaeration, DO concentration could not reach the required minimum standard of 4 mg/l. A vigorous amount of local oxygenation may be required in the critical points. With the 40 cumecs increment of upstream flow, the TMDL of BOD was found 14.532 TPD, and DO concentration was more than 2 mg/l throughout the reach. Meanwhile, advanced treatment, flow augmentation, and construction of a series of weirs for local oxygenation can improve the ecological conditions of the Yamuna River, Delhi spread.

CHAPTER 8

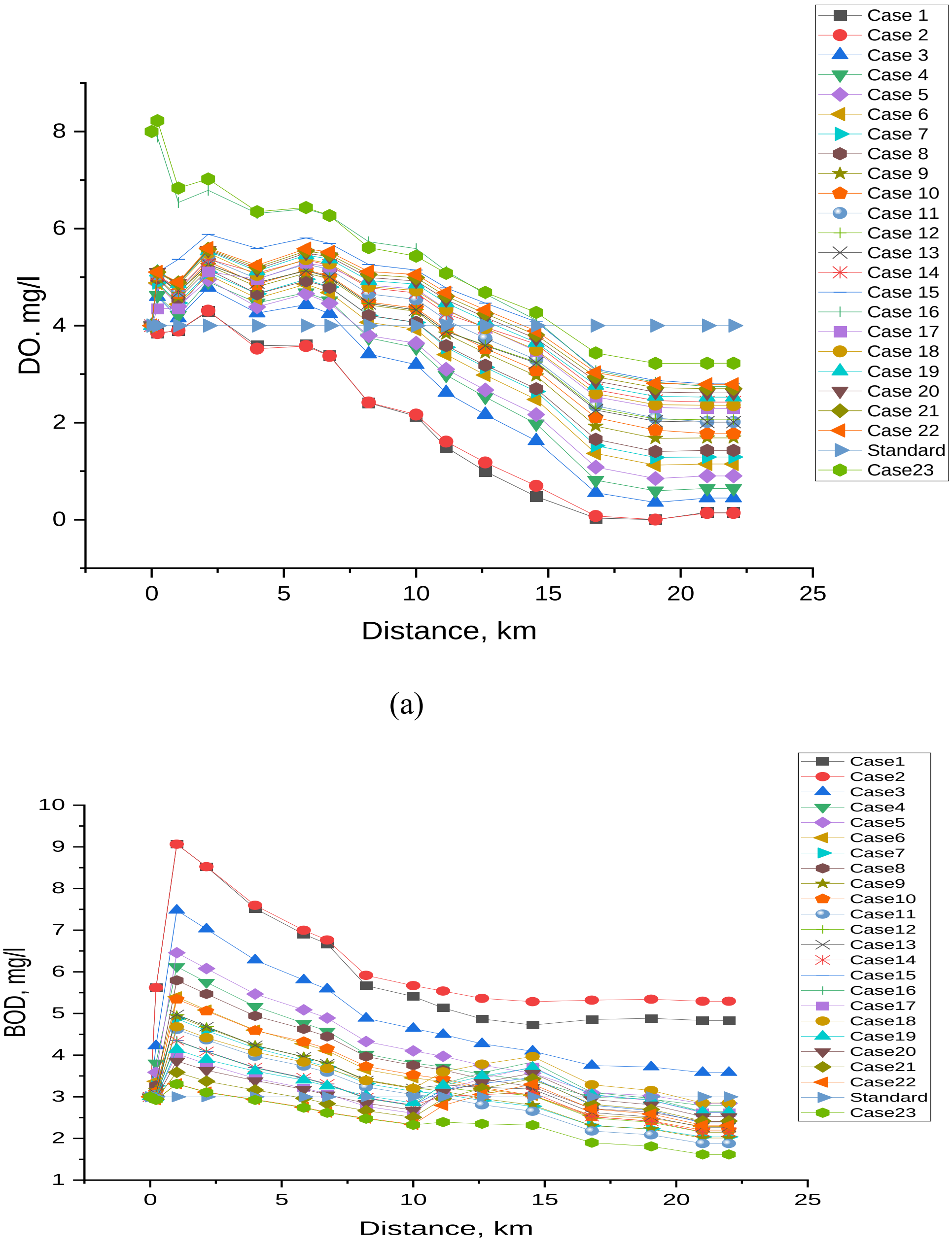
DEVELOPMENT OF A WATER QUALITY MANAGEMENT PLAN

8.1 Introduction

This chapter deals with developing a suitable plan to improve the urban river reach of Yamuna, Delhi. The Yamuna River, Delhi's water quality is simulated with a receiving water quality model to improve the DO concentration above 4 mg/l and lower the BOD concentration below 3 mg/l. Two approaches were developed. In the first approach, scenarios were constructed with varying the pollutant load modification and increasing upstream flow. In the second approach, keeping the minimum e flow and water quality standard, upstream two weirs were assumed at the critical points, and simulations were built to improve the water quality of the river reach.

8.2 Water quality management by pollutant load modification and flow augmentation

Table 3.8 shows the headwater flow and water quality for different cases, and Table 3.9 shows the point load positions and load implementation for different scenarios. In plan 1, the upstream flow increased to 50 cumecs, and 23 cases were produced. Figs 8.1 (a-b) show these cases' DO and BOD profiles. Fig 8.1 (a) shows that in case 22, the reach has DO concentration of about 2.5 mg/l and BOD level below 3 mg/l throughout the reach. Some drains were tapped and showed no flow(GONCT, DOE 2022). Hence, small drains were diverted, and six drains were assumed to be used to develop the management plan. The locations of the drains are shown in Table 8.2. Case 22 is shown in Fig 8.2, which shows the best approaches. For this management approach, continuous external aeration should be adopted after 15 km of downstream reach to increase the DO concentration of the river water. Case 23 was established by keeping the BOD 5 mg/l for the D1 and 10 mg/l for the rest of the drains, and COD was kept 25 mg/l. Upstream DO was also kept 8 mg/l. In this case, it was shown that DO concentration was more than 3.22mg/l throughout the reach. Hence, the case 23 is required low external reaeration. Meanwhile, in case 22, the allocated waste load is much higher. Therefore, case 22 is adopted for a management approach of the Yamuna River, Delhi, which includes flow augmentation, wastewater treatment, and external reaeration at the critical points. Management approach 1 consists of 50 cumecs of upstream flow with 4 mg/l DO, 3 mg/l BOD and 25 mg/l, D1 at 0.44 km downstream with 20 cumecs wastewater containing 4 mg/l of DO, 5 mg/l of BOD and 50 mg/l of COD, D2-D3 at 5 km and 8 km of downstream respectively with 2 cumecs of wastewater with 4 mg/l of DO, 10 mg/l of BOD and 50 mg/l of COD, D4-D6 at 11 km, 13km and 15 km downstream, respectively with 2 cumecs of flow with 5 mg/l of DO, 25 mg/l of BOD and 50 mg/l of COD. After 12 km (28°37'11"N, 77°15'17"E) near Pragati Thermal Power Plant, external reaeration has been suggested to increase the DO concentration from 2 mg/l to 4 mg/l. Fig 8.2 shows the river segment with different point sources and prescribed loads.



(a)

(b)

Figure 8.1 (a-b) DO and BOD profiles for different cases of water quality management plan1

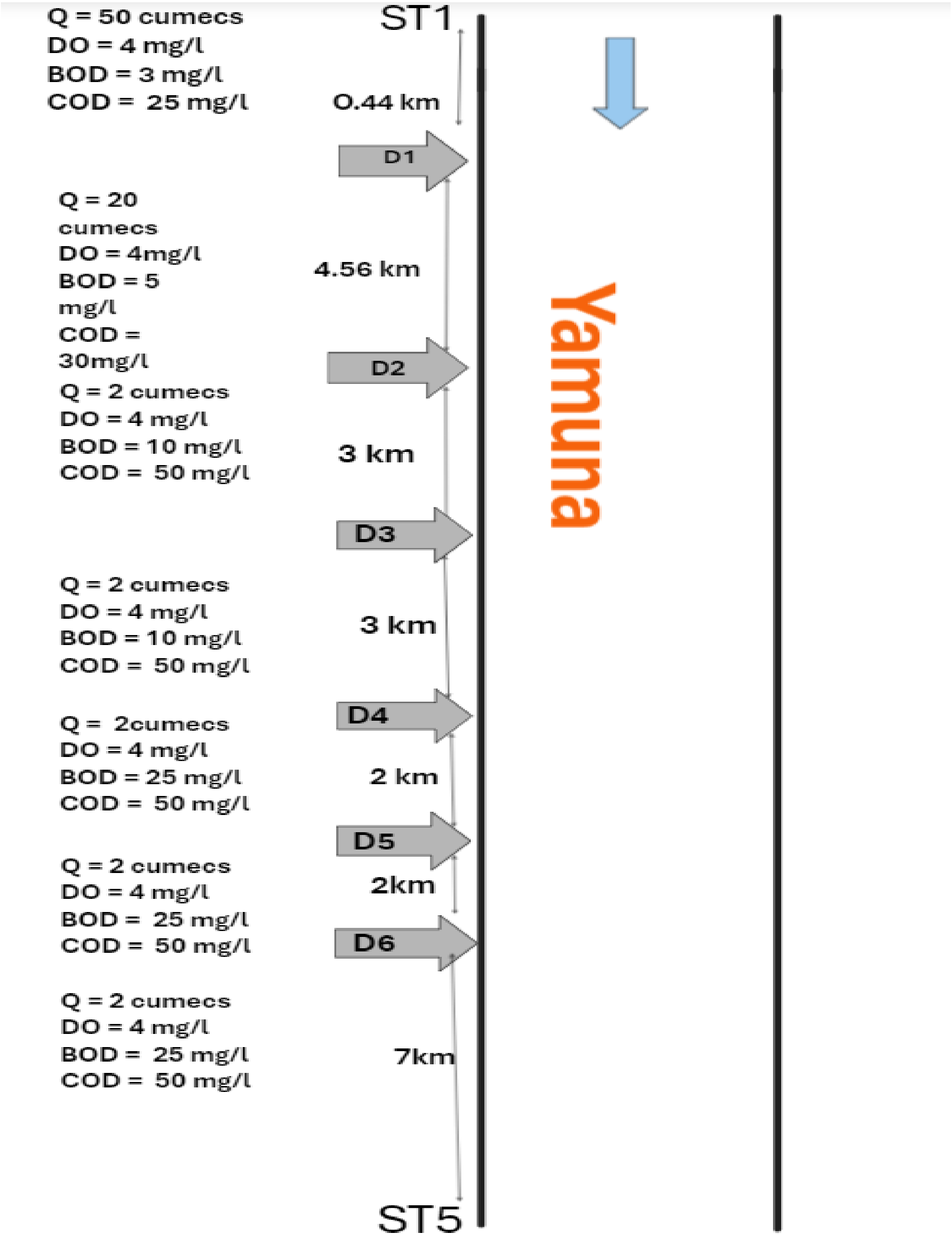
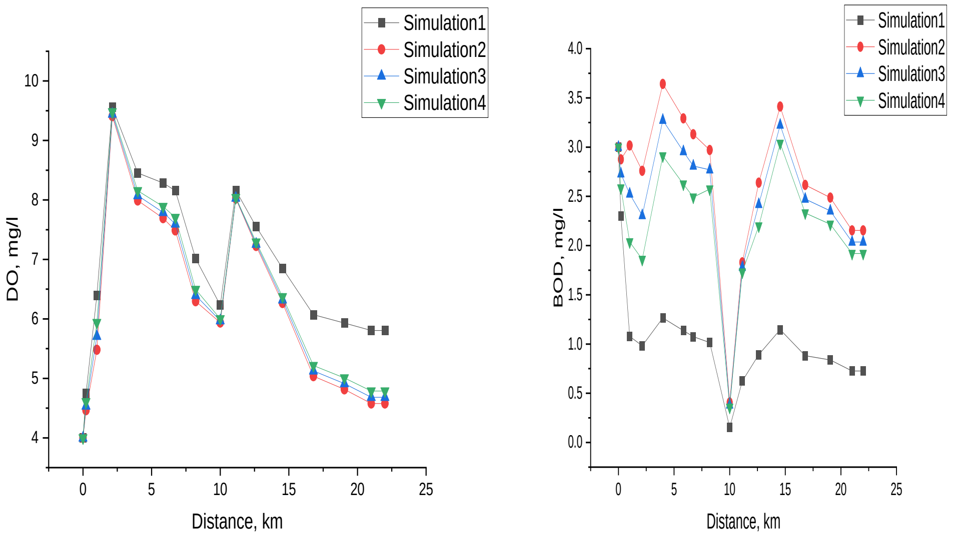


Figure 8.2 Management approach with flow augmentation, load modification, and external reaeration.

8.3 Management approach using weir at critical points

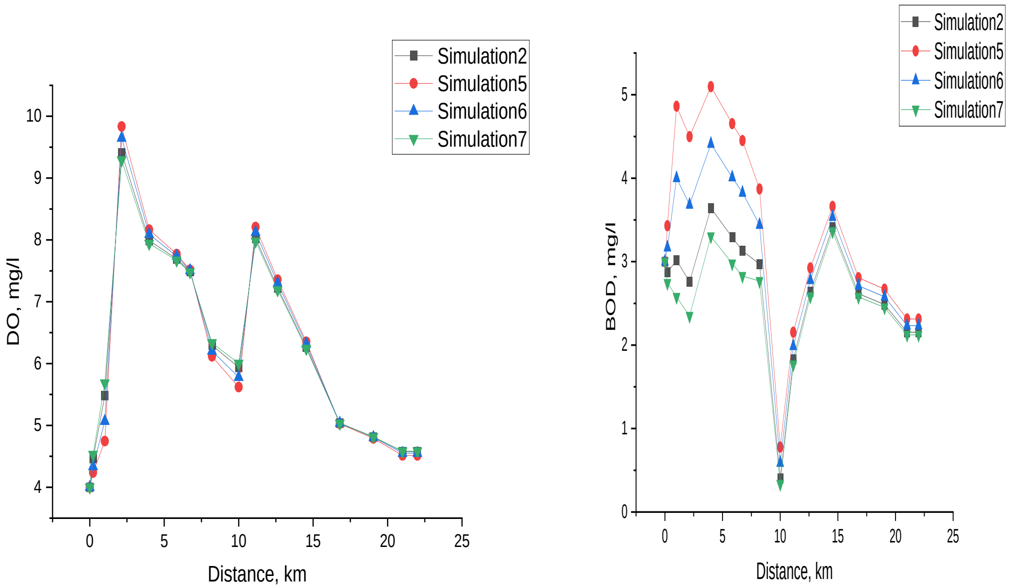
The model was run by adjusting the BOD load of D1, keeping upstream flow 10 cumecs with 4 mg/l concentration of DO and 3 mg/l of BOD. However, these values differ from the original values; a model has been established by assuming that the upstream river water is maintained at the desired standard with the e flow. Two weirs at the reach 2 and 8 were considered. If weir height is entered in reach sheets, the model is implemented with weir options (Pelletier & Chapra, 2008). The first weir after the outfalling of D1 with 0.8m height and 0.05m width and the second weir after 10 km downstream with 0.9 m height and 0,05 m width were assumed. Table 3.10 shows the weir's height and width for generating different scenarios. Table 3.11 shows the point load used for generating scenarios. Three cases with nine simulations were constructed. In the first case, four simulations had varying BOD of the point sources. Fig 8.3 shows the DO and BOD profiles for different simulations of water quality management with weir case 1. In simulation 1, all six outfalling drains carried 10 mg/l BOD load, the effluent discharge standard, into this river (NGT 2020). It has been observed that after adopting weir options, the DO concentration was higher than 4 mg/l, and the BOD concentration was lower than 3 mg/l throughout the river reach. Earlier studies showed that flow over a weir could produce high oxygenation by entrapping air (Campolo et al., 2002). The quantity of DO in the river can be quantified by an empirical relation associated with the DO deficit above and below the dam and the geometric characteristics of the weir, including its type, water temperature, and qualities (Pelletier et al., 2006). The BOD for all drains increased to 30 mg/l, and simulation 2 has been considered. It has been observed that the predicted BOD level is slightly higher than 3 mg/l at 3.99 km and 14.56 km downstream. Therefore, the BOD of D1 and D5 has been lowered to 25 mg/l and 20 mg/l for simulations 3 and 4, keeping the weir height and width constant. Simulation 4 shows that the DO and BOD levels are within the standard criteria.



(a) (b)

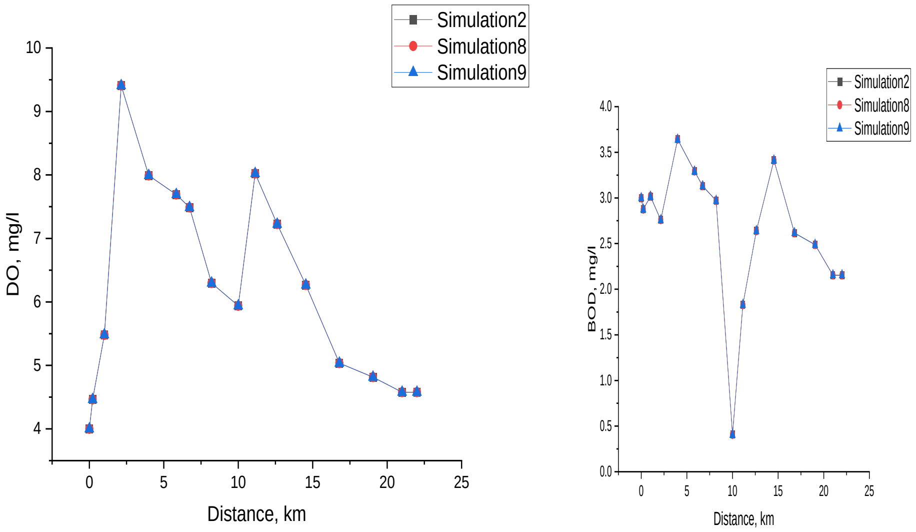
Figure 8.3(a-b) DO and BOD profiles for different simulations of water quality management with weir case 1

In case 2, the BOD level has been kept at 30 mg/l for all the point sources, and the weir width has been changed to 0.1, 0,075, and 0.04 m for simulations 5, 6, and 7, respectively. Fig 8.4 shows the DO and BOD profiles for simulations 2, 5, 6, and 7. It has been observed that with decreasing crest width, BOD profiles improved. DO profiles were not affected by the change in crest width. In case 3, the height of the weir was varied to 0.7 and 0.9m for the weir at reach 2 and 0.8 and 1 m for the weir at reach 8. Simulations 8 and 9 were constructed with a BOD level of 30 mg/l for all the point sources. Fig. 8.5 shows low differences between simulations 2, 8, and 9 with varying weir heights. After these simulations, the weirs are suggested at two critical positions at reach 2 and reach 8 for installation. The weir heights needed were 0.8 m and 0.9 m. Management approach 2 suggested 10 cumecs upstream flow with 4 mg/l DO, 3mg/l BOD and 50 mg/l COD, D1 with 25 cumecs of wastewater with no DO, 20 mg/l of BOD and 50 mg/l of COD, D2-D5 with 2 cumecs of wastewater with no DO, 30 mg/l of BOD and 50 mg/l of COD have been suggested. Fig.8.6 shows the prescribed load for the Water quality management approach with constructing weirs.



(a) (b)

Figure 8.4(a-b) DO and BOD profiles for different simulations of water quality management with weir case 2



(a) (b)

Figure 8.5 (a-b) DO and BOD profiles for different cases of water quality management with weir case 3

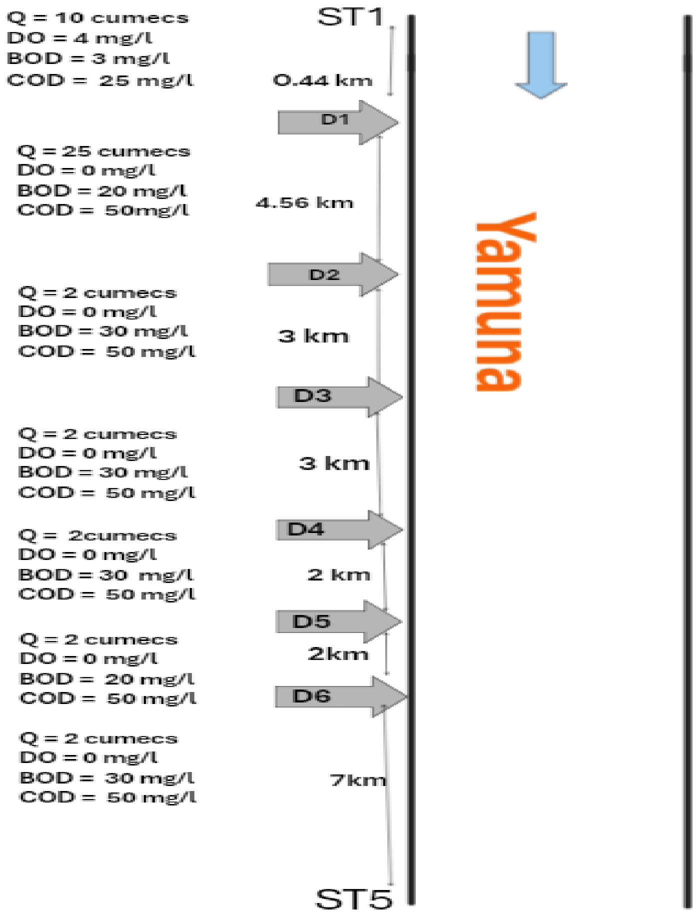


Figure 8.6 Water Quality Management Approach with Construction Weir

8.4 Summary

The model QUAL2Kw was used to manage the severely polluted river reach of the Yamuna River, Delhi. Two water quality management approaches have been proposed to restore the water quality of the reach to Class C, as India's Central Pollution Control Board (CPCB) suggested. This study includes secondary monthly data monitored by the Delhi Pollution Control Board (DPCC). This study revealed that the flow augmentation and load modification could improve the BOD concentration to below 3 mg/l, and DO concentration could not get above 4 mg/l throughout the reach. A higher volume of headwater flow may improve the condition, though it may be challenging to maintain the flow due to the shallow depth of the river. Hence, external reaeration is suggested after 12 km downstream of Wazirabad. For the proposed flow in plan 1, an upstream reservoir may be constructed to maintain the flow. In proposed plan 2, the weir is proposed at the critical points to increase the dissolved oxygen concentration in the water. The present study has some limitations in terms of data. Regular monitoring of water quality and hydraulic data can improve the results.

CHAPTER 9

Conclusions, Future Scope, and Social Impacts

9.1 Conclusions and contribution of the study

The present work is an attempt to propose a suitable water quality management plan for the long-term sustainability of an urban river reach, Yamuna Delhi. As a general conclusion, the findings from this study have contributed to the spatiotemporal variations of water quality, assessing assimilation capacity, and a few suggestions for TMDL implementation and suggested loads to maintain the most viable parameters. The study aimed to evaluate water quality, and it was observed that river water is highly polluted with oxygen-demanding substances such as BOD and COD. Hence, the river water is completely devoid of DO, which is the most critical parameter for maintaining the ecological health of a water body. Multivariate analysis found that upstream of the river reach also flows with high nutrients. The following are the important findings from this study:

- Spatiotemporal variations reveal that the water quality in the river reach of study, downstream to the Najafgarh drain, is severely poor throughout the year due to the point and diffused sources of pollution.
- Although sufficient flow is available during the monsoon season, the water quality does not meet the prescribed standards due to the surface runoff containing high organic substances.
- In contrast, upstream river reach is less polluted. However, high turbidity, COD, NO_3, and conductivity describe the river flowing with nutrients, as well as inorganic substances.
- The results obtained from factor analyses supported the box whisker plots. The principal component analysis was applied for four seasons to observe the correlation and variability among different parameters.
- The varifactors from factor analysis specified that upstream water is less polluted with organic substances than downstream water.
- Downstream water is polluted with organic and inorganic substances from drains (untreated/ partially treated domestic and industrial wastewater) and monsoon surface runoff with highly demanding oxygen substances.
- The study emphasizes that reducing pollutant load from different sources can improve this river's reach and can be helpful in the management of the riverine ecosystem.
- The QUAL2Kw model is used to assess the assimilation capacity of the study reach. The model is appropriate for this reach as it can be simulated with low data availability. This study reveals that the river’s assimilation capacity was low due to high BOD and low DO levels.

- The wastewater enters the river through 16 drains and diffused sources. Najafgarh drain adds the highest quantity of wastewater with elevated BOD and COD levels, resulting in poor water quality.
- These conditions prevail over the 22 km of this reach. In this study, the upstream flow increment with the reduction of BOD and COD was studied.
- In strategy 1, wastewater from all drains was curtailed in the model, but the desired standard of reach could not be met. Improvement of the assimilation capacity of this river is a very challenging job, as the less upstream water with low DO and high BOD. In strategy three, four cases were considered, with 41 scenarios comprising an increment of flow and reductions of BOD and COD.
- Three scenarios with 10 simulations have been constructed with varying BOD load, upstream flow, and local oxygenation. With an upstream flow of 10 cumecs, the required TMDL was 7.5 TPD of BOD load to maintain the BOD concentration below 3 mg/l throughout the river reach.
- Due to the low availability of fresh water and reaeration capacity, the DO concentration could not reach the required minimum standard of 4 mg/l.
- A higher amount of local oxygenation may be required at the critical points. With the 40 cumecs increment of upstream flow, the TMDL of BOD was found about 14.5TPD, and the DO concentration was more than 2 mg/l throughout the reach.
- Two approaches have been developed for the management of river water quality.
- In the first approach, 23 scenarios have been constructed with varying pollutant load modification and increasing upstream flow. Results indicate that 50 cumecs of upstream flow and load modification improve the river water quality, and 12 km downstream from Wazirabad, it requires external aeration.
- The second approach evaluated the weir function at the critical points to entrap the oxygen and increase the level of DO concentration. Two weirs were assumed at the crucial points, and the river quality was assessed by constructing nine scenarios with varying pollutant load, weir height, and width.
- It was observed that two weirs, 0.8 and 0.9 m in height at 0.44 km and 10 km downstream, can improve the assimilation capacity of the reach due to flow over weirs producing intense oxygenation through air entrainment.
- This study reveals that the urban river reaches of Yamuna, Delhi, require substantial load reduction with flow dilution and external reaeration to enhance the water quality. Of course, the remedial options are complicated and may be challenging to implement. However, the possibility of instream regeneration may be feasible, but further study is required to arrive at a final design of the structure, such as weirs or any other kind of oxygenator system.

9.2 Limitations

However, challenges were discovered during the study, such as implementing a water quality management plan and implementation of TMDL. The specific act or enactment is necessary to implement TMDL. Effective planning and continuous monitoring are required to implement TMDL. Besides the poor data management system and data transparency, river reach management is becoming more complicated. For the river management approaches, a massive amount of data is required; the absence of some data might affect the simulation, and hence, the TMDL approach and water quality management approaches are concerned. Another major obstacle is the ineffective and nontransparent enforcement of laws, which leads to massive untreated and partially treated wastewater input into this river reach. The local communities' lack of awareness also increases the disposing of contamination in the river.

9.3 Future Scopes and Recommendations

The water quality of River Yamuna has continuously degraded throughout its Delhi stretch. The capital must be laid with proper sewerage lines, and all the wastewater generated from plain and low-lying areas should be sent for treatment and disposal of the river, maintaining the standards. Upgradation of the existing STPs is required. Wastewater that enters the river directly should be tapped and treated. This can be achieved by establishing alternative drainage systems. Water can be stored upstream of the reach during the monsoon periods and maintain the required flow to increase the assimilation capacity. A modeling approach should be implemented to assess the required load to maintain the river quality. More water quality parameters should be monitored, and a TMDL assessment should be done. Nonpoint sources of pollution can be minimized by installing rainwater harvesting systems and sustainable sewerage systems. The agriculture runoff directly entering the reach can be deducted by building filters around farming land near the reach. Artificial aeration facilities should be adopted to increase the DO and assimilation capacity of the reach. Pollutant inventory can be improved by estimating loadings from solid waste and religious activities and assessing their effect on the river's water quality. Hence, diffused sources can be invented. In addition, studies on water quality models and comparisons of various water quality models are essential. Furthermore, a suitable water quality surveillance system is required to apply to these models. Subsequently, the comparative interpretation of the QUAL2Kw model with other models like MIKE II, WASP, SWAT, etc., can be used to determine the reliability of modeling studies in the stretch. Studying TMDLs for other parameters like COD, ammonia, nutrients, etc. is required. In addition, afforestation along the riverbanks would help control siltation, erosion, agricultural runoffs containing pesticides and fertilizers, etc. NBOD plays a vital role in this river reach, and DO deficit can slow down or even prohibit the nitrification process in the river water. The initiation timing of the nitrification is uncertain and requires further study. Lab-based research is needed to quantify the CBOD deoxygenation rate to improve the water quality model approaches for managing water resources. With the modification of treatment plant effluents and the addition of advanced treatment facilities, especially nitrification, the deoxygenation rate for CBOD should be assessed. Further studies are also required to explore the options of in-stream oxygenation, channelization, or diversion of existing waste load to ensure that the acceptable water quality in the study is maintained.

9.4 Social Impacts

Developing a suitable water quality management approach for urban rivers significantly affects society. These are as follows:

- Maintaining water quality can reduce the prevalence of waterborne diseases and pollution-related health issues.
- Clean water bodies enhance mental health through recreational activities like walking, fishing, and boating, creating a more optimistic community environment.
- Properties near clean and well-maintained rivers tend to have higher values.
- Clean rivers can attract tourists and residents, stimulate the local economy through recreational and tourism-related activities, and inspire economic growth and development.
- Communities often take pride in cleaner local environments, fostering a sense of belonging and community spirit.
- By inspiring local residents to participate in environmental stewardship and volunteer activities, successful water management projects empower communities to take responsibility for their local environment.
- Clean water and better-managed urban rivers contribute to an overall higher quality of life for all residents, particularly for marginalized communities who may have been disproportionately affected by poor water quality.
- Clean rivers provide schools and educational programs opportunities to teach students about ecology, conservation, and sustainability.
- Local governments and organizations can develop programs that educate the public on the importance of maintaining water quality and engaging in sustainable practices.

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APPENDICES

Table A1: Comparison of the Models Review

	AQUATOX	QUAL2Kw	WASP	MIKE-11	EPDRIV1	CE-QUAL-W2	HEC-RAS
Model Type	1D dynamic	1D steady/dynamic	1D,2D,3D dynamic	2-D steady/dynamic	1-D dynamic	2D	1D steady, 2D steady/ dynamic
Receiving water type	River, Lake, Reservoir, Estuary	River	River, Lake, Reservoir, Estuary	River, Lake, Reservoir, Estuaries	River	River, Lakes, Reservoirs Estuaries	River
Modeling approach	4th and 5th order differential equations RungeKutta integration method	The advection-dispersion reaction with unequal spacing reach	The advection-dispersion equations	Finite difference equations for solving Saint Venant equations	Continuity, Momentum, and transport equation	laterally averaged equations of fluid motion	Implicit Finite difference method

	AQUATOX	QUAL2Kw	WASP	MIKE-11	EPDRIV1	CE-QUAL-W2	HEC-RAS
Capabilities	DO, CBOD, NH3, NO3, OP, PO4, Temp, Sediment	Temp, pH, P (OP, PO_4), DO, CBOD, SOD, N (ON, NO_2, NO_3), alkalinity, phytoplankton, bottom-algae, detritus, pathogen	DO, CBOD, NH3, NO3, NO2, OP, PO4, temperature, sediment, Metals, Toxics	Temp, DO, BOD, NO3, NH3, sediments, coliform bacteria	DO, BOD, NH3, NO3, NO2, OP, PO4, temperature, Bacteria, Metals	temperature, Salinity, DO, C, N, P, algae, Sediment Pathogen	temperature. Salinity, DO, C, N, P, algae, Sediment, Pathogen
Limitatio-ns	Not simulate metals and organometal	not stimulate river branches, toxic metals	Requires extensive data, linked sub-models	Extensive data required	not simulate the sediment transport process	Complex and required high time	Highly dynamic streams and rivers
Availability/ Training	Limited Training/ Public Domain	Limited training/ Public domain	Adequate training/ Public Domain	Adequate training/ Significant Cost	Adequate training/ Limited distribution	Public domain/ Adequate training	Public domain/ Training

Table A2: Capabilities of Water Quality Models

Model	1D	2D	3D	Temp	salinity	DO	P,N,C	algae	Sediment	Pathogen	Toxic	Metal	River	Lakes	Estuaries	Reservoirs
AQUATOX	-	√	-	-	√	√	-	-	√	-	√	-	√	√	√	√
WASP[l]	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
CE-QUAL-W2	-	√	-	√	√	√	√	√	√	√	-	-	√	√	√	-
EPD-RIV1	√	-	-	√	-	√	√	√	√	-	-	√	√	-	-	-
MIKE-11	√	-	-	√	√	√	√	√	√	√	-	-	√	√	√	√
QUAL2Kw	√	-	-	√	-	√	√	√	√	√	-	-	√	-	-	-
HEC-RAC	√	-	-	√	√	√	√	√	√	√	-	-	√	-	-	-

Table A3 Statistics for the Station ST1

Month	DO mg/L	Cond- (µs/cm)	NO3 mg/l	TOC mg/l	TSS mg/l	pH	Temp °C	NH4 mg/l	Turbidity NTU	BOD mg/l	COD mg/l
March	7.87±4.99	1181.92±197.48	2.08±0.53	9.31±2.28	23.92±8.8	7.99±0.5	24.04±1.49	1.2±0.52	10.38±3.85	4.96±1.11	22.38±5.34
April	4.64±1.91	674.92±342.9	1.52±1.88	23.61±31.36	76.95±117.14	7,47±0.997	26.31±3.12	0.53±0.62	54.65±89.34	1.37±1.34	64.09±88.7
May	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
June	6.42±1.79	626.97±194.05	2.22±0.28	4.45±0.59	10.99±1.5	7.36±0.33	33.9±0.58	0.87±0.15	15,5±3.31	6.65±0.8	18.88±1.6
July	6.65±2.91	384.80±124.28	1.47±0.59	8.3±8.24	29.05±37.96	7.17±0.69	30.55±2.24	0.3±0.33	61,26±76.86	3.4±1.88	33.05±33.16
August	6.34±2.65	351.35±99.47	3.69±1.16	1.44±0.99	33.64±23.6	7.14±0.52	30.57±1.88	0.82±0.76	96.67±445.1	2.32±0.7	8.15±3.5
September	8.34±1.68	471.23±225.05	3.55±1.21	2.69±1.4	44.62±23.6	7.36±0.56	28.94±1.72	0.09±0.14	733.88±489.4	3.19±0.56	10.23±5.45
October	7.91±1.54	380.33±69.45	2.98±1.16	2,56±1.3	29.99±15.73	7.42±0.21	26.82±2.53	0.02±0.004	312.01±115.87	3.53±0.48	23.9±14.74
November	11.70±2.02	485.21±97.42	2.30±1.21	6.37±4.7	31.21±12.13	7,52±0.17	20.12±1.57	0.19±0.29	219.49±73.2	3.58±1.88	31.22±13.16
December	12.84±2.96	817.54±133.17	2.13±0.47	10.22±5.14	32.73±12.14	7.26±0.27	16.25±1.99	0.55±0.21	197.95±114.6	3.02±2.11	41.08±27.15
January	10.70±	694.05±212.37	2.13±0.4	7.89±1.9	23.73±5.84	7.22±0.44	13.99±1.1	0.65±0.07	142.4±43.3	2.48±1.1	32.77±9.68
February	11.87±	558.2±92.73	1.84±0.39	6.49±1.83	21.61±5.28	7.79±0.2	17.4±2.37	0.64±0.24	127.45±38.04	3.45±0.4	26±9.5

Table A4 Statistics for the Station ST5

Month	DO mg/L	Cond-u (μs/cm)	NO3 mg/l	TOC mg/l	TSS mg/l	pH	Temp °C	NH4 mg/l	Turbidity NTU	BOD mg/l	COD mg/l
March	3.88±3.96	1575.1±234.7	1.07±0.57	47.49±37.5	63.3±53.6	7.3334±0.25	23.37±1.49	17.65±8.97	68.9±46.07	23.23±8.12	93.02±36.4
April	2.55±0.76	1406.6±58.6	1.5±0.31	47.5±13.5	43.87±34.4	7.28±1.3	23.56±1.07	59.13±6.78	18.68±33.12	11.97±6.98	76.23±30.98
May	1.62±1.72	1494.7±86.9	1.24±0.26	76.8±45.4	147.5±138.6	7.97±0.29	27.92±0.68	10.93±2.31	47.5±138.7	5.61±1.76	143.44±103.4
June	5.23±1.94	1251.6±170.2	0.79±0.3	34.87±3.12	30.68±5.56	7.27±0.14	30.06±1.05	17.38±10.02	8.8±0.96	9.74±1.88	51.13± 3.81
July	4.55±2.18	871.87±45.78	0.74±0.3	93.04±125.3	138.64±236.8	7.47±0.34	29.06±1.5	10.84±8.21	39.9±66.6	16±11.58	157.02±228.5
August	4.76±3.75	912.19±34.4	0.68±0.23	89.72±127.3	128.83±234.95	7.0±0.27	30.4±1.15	9.45±6.07	38.5±65.43	15.67±12.28	157.02±221.9
September	4.98±4.47	841.3±32.55	0.7±0.16	71.88±81.14	88.26±151.8	7.01±0.2	28.04±1.08	10.97±5.35	39.74±106.6	21.09±7.42	118.73±99.4
October	3.15±0.93	826.19±48.7	1.24±0.39	58.69±44.9	77.69±88.3	7.12±0.22	27.5±1.62	8.67±2.8	220.9±14.6	14.42±5.3	110.35±50.2
November	2.03±0.09	724.62±17.16	1.1±0.14	39.87±8.68	34.5±7.9	6.16±0.17	20.14±0.4	11.05±0.5	18.9±6.7	12.75±4.43	108.57±25.9

Month	DO mg/L	Cond-u (µs/cm)	NO3 mg/l	TOC mg/l	TSS mg/l	pH	Temp °C	NH4 mg/l	Turbidity NTU	BOD mg/l	COD mg/l
December	2.34±0.11	606.8 ±54.86	1.5±0.19	61.69 ±30.4	75.8±59.2	6.74±0.63	16.86±1.5	8.58±0.83	226.01±14.13	18.81±9.73	133.46±52.25
January	2.43±±0.26	548.55 ±34.7	1.05±0.38	79.48 ±31.1	96.8±50.3	6.09±0.8	15.23±0.96	8.39±0.5	239.85±26.43	25.98±13.95	182.54±94.24
February	3.27±0.32	646.79 ±60.1	0.87±0.24	74.29 ±57,9	110.3±104.8	7.18±0.7	17.96±1.67	9.8712±0.92	0.67±1.18	9.17±2.98	100.56±41.93

Table A5 Water quality data for five stations for the water quality trend analysis (DPCC domain)

Time step		ST1			ST2		ST3			ST4			ST5		
	DO	BOD	COD	DO	BOD	COD	DO	BOD	COD	DO	BOD	COD	DO	BOD	COD
02.01.2013	6.4	7.6	56	0	75	280	0	30	108	0	22	84	2	22	72
12.02.2013	8	3	32	0	20	72	0.4	20	96	0.5	20	96	1.2	18	48
03.03.2013	6.8	3	36	0	21	68	0	28	76	0	30	104	0	20	64
03.04.2013	6.6	5	36	0	28	72	0	34	96	0.4	35	132	2.6	22	68
03.05.2013	7	4.8	24	0	30	84	0	30	80	0	42	160	0.8	35	160
27.08.2013	3	3	16	0	27	92	0	28	96	2.5	28	116	3.3	28	72
25.09.2013	4.6	3	24	0	28	92	0	36	152	3.6	26	124	7.1	19	36
24.10.2013	5.6	3.2	28	0	30	84	0	40	104	0.9	18.5	40	1.5	20	60
25.11.2013	7	3	20	0	30	104	0	29	92	1.5	27	156	2.1	23.5	80
25.12.2013	10	3	24	0	35	96	0	25	84	0	23	80	0	22	96
07.01.2014	8.2	2.6	20	0	32	112	0	28	96	0	30	88	0.9	29	80
11.02.2014	9.7	3	24	0	48	180	0	34	100	0	30	96	0	27	76
07.03.2014	9.2	3.2	24	0	42	196	0	32	104	0	38	130	0	32	92

Time step		ST1			ST2		ST3			ST4			ST5		
	DO	BOD	COD	DO	BOD	COD	DO	BOD	COD	DO	BOD	COD	DO	BOD	COD
07.05.2014	6.2	2.6	16	0	30	104	0	22	72	1	30	96	1.9	27	70
03.06.2014	6.1	3.2	24	0	31	100	0	29	80	0.3	36	100	0	24	72
07.07.2014	6.3	2.8	26	0	36	112	0	37	120	0	28	80	0	32	100
06.08.2014	5.8	2.4	16	0	30	108	0	32	100	4	18	56	3	26	64
08.09.2014	7.3	3.4	26	0	33	116	0	38	160	1.9	22	76	1.7	27	88
10.10.2014	0	4.2	20	0	48	140	0	35	106	0.9	18.5	40	1.5	20	60
13.11.2014	4.6	5	20	0	42	132	0	31	84	1.5	27	156	2.1	23.5	80
04.12.2014	4.1	8.4	36	0	35	128	0	39	96	0	23	80	2	22	96
21.01.2015	8	4.2	20	0	37	148	0	35	112	0	26	108	0	42	140
11.02.2015	7	9.2	37	0	42	148	0	26	88	0	40	104	0	50	176
11.03.2015	7	6.6	24	0	45	144	0	31	56	0	28	96	0	27	72
08.04.2015	8	9.2	24	0	43	140	0	30	100	0	33	116	0	29	88
22.05.2015	7	4.8	16	0	32	132	0	25	84	0	40	136	0	29	80
06.07.2015	6	5.4	20	0	39	124	0	28	88	0	32	104	0	33	96
21.09.2015	6.8	4.6	32	0	39	116	0	31	96	0	37	116	0	38	112
20.10.2015	7	6.4	20	0	28	92	0	29	88	0	28	96	0	30	104
30.11.2015	8	6.4	16	0	35	136	0	34	92	0	41	140	0	34	100
29.12.2015	9	4.6	20	0	46	124	0	32	100	0	43	156	0	31	96
27.01.2016	8.3	5.7	24	0	47	136	0	30	96	0	32	128	0	30	96
30.03.2016	8	4.6	20	0	32	128	0	28	92	0	30	88	0	30	88
26.04.2016	6	4.8	24	0	38	124	0	29	100	0	28	84	0	29	84
23.05.2016	8	4.4	24	0	38	132	0	30	92	0	27	80	0	32	88
22.06.2016	8	4.2	20	0	32	96	0	28	92	0	28	88	0	28	72
19.07.2016	8.4	4	16	3.6	25	84	3	24	88	6	24	80	5	22	62
19.08.2016	8.8	3.6	16	3.3	26	88	2.9	20	68	5.5	22	64	4.9	23	60

Time step		ST1			ST2		ST3			ST4			ST5		
	DO	BOD	COD	DO	BOD	COD	DO	BOD	COD	DO	BOD	COD	DO	BOD	COD
07.10.2016	7.5	4.4	20	0	25	80	0	24	76	1.2	33	40	0	34	108
26.11.2016	5.3	5.6	28	0	28	88	0	25	80	0	28	92	0	40	128
26.12.2016	6.8	4.8	8	0	28	96	0	22	68	0	27	84	0	32	112
20.01.2017	8	4	24	0	52	158	0	29	92	0	24	76	0	28	92
24.02.2017	8.2	4.2	24	0	54	152	0	26	92	0	22	74	0	26	84
18.03.2017	7.4	5.6	20	0	42	128	0	23	72	0	25	76	0	36	172
26.04.2017	7.4	5.8	16	0	28	96	0	24	72	0	30	92	0	37	108
31.05.2017	7.6	5.4	20	0	27	84	0	25	76	0	28	88	0	35	108
17.06.2017	6.5	5.2	16	0	24	76	0	25	84	0	27	92	0	33	112
22.07.2017	7.4	3.1	16	0	22	64	0.8	17	54	0.5	20	64	0	20	72
29.08.2017	7.5	1.8	12	0.8	16	44	1	15	48	1.2	16	52	0.8	21	60
25.09.2017	7.4	4.6	16	0	18	58	0.7	16	52	0	22	68	0.5	18	52
28.10.2017	7.3	2	12	0	23	72	0	21	56	0	21	56	0	20	64
04.11.2017	7.6	2.2	8	0	24	72	0	20	60	0	19	64	0	21	72
29.12.2017	7.3	3.2	12	0	25	76	0	22	68	0	23	72	0	22	68
20.01.2018	6.4	4.1	16	0	27	84	0.2	21	68	0	22	76	0	23	72
17.03.2018	7.9	3.4	12	0	26	80	0	24	76	0	26	80	0	24	72
25.04.2018	7.5	3.2	16	0	28	88	0	30	90	0	29	88	0	28	92
18.05.2018	6.4	7.8	12	0	32	90	0	27	76	0	25	80	0	24	76
21.07.2018	7.2	4	16	0	28	92	0	24	76	0	20	68	0	28	84
10.08.2018	7.2	2.2	12	0	40	112	0	28	94	0	24	72	0	28	80
11.09.2018	5.9	4	12	2.4	16	52	0	14	40	0.9	21	69	0	20	64
18.10.2018	7	3.2	16	0	12	44	0	12	44	2.1	12	40	0	18	60
17.11.2018	6.2	3.6	12	3.6	31	92	0	2.2	104	0	39	108	0	20	60
17.12.2018	6.8	3.2	12	0	38	116	0	24	76	0	25	84	0	28	88

Time step		ST1			ST2		ST3			ST4			ST5		
	DO	BOD	COD	DO	BOD	COD	DO	BOD	COD	DO	BOD	COD	DO	BOD	COD
19.02.2019	6.6	2.8	12	0	28	80	0	26	76	0	22	68	0	26	84
16.03.2019	6.2	4	12	0	26	72	0	20	68	0	22	72	0	24	60
23.04.2019	5.8	2.8	12	0	24	76	0	28	68	0	20	68	0	24	68
20.05.2019	6.8	3	12	0	22	68	0	26	72	0	14	48	0	20	64
13.06.2019	5.7	2.2	12	0	24	80	0	28	96	0	22	68	0	22	72
22.07.2019	8.2	4	16	0	22	68	0	17	52	0	19	68	0	26	80
26.08.2019	7.9	3.4	20	2.2	20	64	2.6	16	56	2.8	14	52	3.2	10	24
12.09.2019	5.8	2	8	0	11.6	40	0	18.5	40	1.8	22	64	0	50	152
04.10.2019	5	4	16	0	7.6	28	0	11	40	1.2	16	56	0	14	56
04.11.2019	3.8	2.5	12	0	24	80	0	24	72	1.2	23	72	0	32	96
03.12.2019	6.8	4.5	20	0	30	106	1.3	22	76	3.3	20	68	0	21	84
06.01.2020	4.2	4	12	0	32	92	0	28	72	1.9	28	76	0	38	108
13.02.2020	4.3	3	8	0	28	88	0	32	96	1.9	32	80	0	32	132
16.03.2020	4.8	3	10	0	28	40	0	25	76	0	24	76	0	42	132
06.04.2020	6.8	3.8	16	0	25	60	2.3	22	32	2.3	16	42	4.8	16	42
02.06.2020	7.3	4	18	0	32	82	2	28	76	1.6	22	68	0	32	98
06.07.2020	7.3	6.6	28	0	24	80	0	28	88	3.5	13	30	0	16	52
17.08.2020	4.8	1	4	0	9	28	0	13	64	3.2	9	44	0	12	36
01.09.2020	7.4	4	18	2.3	16	48	1.7	20	68	0.9	24	62	3.1	18	60
02.10.2020	4	3	16	0	50	128	0	28	92	4	16	80	3.1	14	52
02.11.2020	6.3	4.4	20	0	16	52	0	10	28	0	21	72	0	12	32
01.12.2020	7.4	2.6	24	0	42	116	0	40	104	0.7	36	100	0	30	84
04.01.2021	6.7	4.8	28	0	36	128	0	32	96	0	34	110	0	36	108
03.02.2021	7.4	3	24	0	24	112	0	28	100	0	24	120	0	40	180
02.03.2021	4.6	2.2	32	0	26	80	0	30	140	0	28	128	0	30	112

Time step		ST1			ST2		ST3			ST4			ST5		
	DO	BOD	COD	DO	BOD	COD	DO	BOD	COD	DO	BOD	COD	DO	BOD	COD
08.06.2021	6.2	2	42	1.6	10	76	0	22	88	0	30	152	0	10	56
01.07.2021	6	7	52	1.1	38	168	2	42	152	0	22	120	0	37	152
03.08.2021	6.6	6	88	1.5	52	168	0	66	288	0	42	176	0	58	240
03.09.2021	1.9	10	56	0.6	34	128	1.2	26	120	1.9	22	80	0.3	40	136
04.10.2021	4.5	8	48	1.6	34	136	1.8	46	192	3.2	26	96	2.9		160
08.11.2021	3.2	9	53	0	38	176	0	48	232	0	34	144	0	22	144
01.12.2021	8.3	8	44	0	38	104	0	62	200	0	48	168	0	56	192
04.01.2022	6.2	9	48	0	42	120	0	58	184	0	40	152	0	52	176
08.02.2022	6.8	10	56	0	45	186	0.4	62	152	0	65	168	0	55	192
03.03.2022	5.3	8.5	64	0	48	184	0.6	56	144	0	58	160	0	65	184
04.04.2022	5	9	72	0	50	192	0.4	57	160	0	60	176	0	70	208
04.05.2022	5.4	8.4	74	0	55	186	0.5	52	165	0	64	192	0	75	274
01.06.2022	5.1	8.8	69	0	60	176	0.6	54	154	0	63	184	0	73	208
08.07.2022	5.6	8	64	0	58	192	0.4	55	176	0	66	208	0	70	224
01.08.2022	6.4	7	69	0	48	208	0.8	50	181	0	58	224	0	70	240
12.09.2022	5.9	8	64	0	50	192	0.8	53	176	0	58	240	0	73	256
03.10.2022	5.2	8.5	69	0	52	208	0.5	53	181	0	58	256	0	76	272
02.11.2022	5.4	8	64	0	50	192	0.7	52	186	0	58	224	0	79	256
08.12.2022	5.8	9	53	0	46	176	0.8	42	160	0	53	185	0	68	240

Table A6 Statistics for time series analysis

DO					
Statistics	ST1	ST2	ST3	ST4	ST5
Square Root of Mean Deviation	1.518	0.74072	0.6541	1.18946	1.25756
Mean Absolute Deviation	1.08682	0.37235	0.35584	0.68396	0.80756
Mean Squared Deviation	2.30432	0.54866	0.42784	1.41481	1.58145
Mean Absolute Percentage Error	20.40636	8.48014	13.7289	24.49394	12.45119
Alpha	0.12462	0.2	0.054	0.54	0.099
BOD					
Square Root of Mean Deviation	1.53241	10.03756	7.29693	7.10301	9.19056
Mean Absolute Deviation	1.10379	7.24303	5.13537	5.54482	6.60117
Mean Squared Deviation	2.34828	100.7526	53.24514	50.45276	84.46634
Mean Absolute Percentage Error	28.86203	27.5838	25.86318	20.92502	24.96366
Alpha	0.37	0.26	0.377	0.52	0.39
COD					
Square Root of Mean Deviation	8.99265	34.41257	27.31521	26.5136	35.21609
Mean Absolute Deviation	5.89921	22.95522	17.96053	19.78284	23.93104
Mean Squared Deviation	80.86773	1184.225	746.1206	702.9711	1240.173
Mean Absolute Percentage Error	27.84227	25.06539	20.88116	22.92224	27.41393
Alpha	0.46	0.53	0.33	0.42	0.34

Table A7 Forecast for water quality trend analysis(8 Values)

DO								
ST1								
Forecasts	5.58485	5.58485	5.58485	5.58485	5.58485	5.584	5.58485	5.58485
Standard Error of Forecasts	1.23207	1.2416	1.25106	1.26045	1.26976	1.279	1.28819	1.29731
95% LCL of Forecasts	3.17004	3.15136	3.13282	3.11442	3.09616	3.078	3.06004	3.04217
95% UCL of Forecasts	7.99967	8.01835	8.03688	8.05528	8.07354	8.091	8.10967	8.12754
ST2								
Forecasts	0.03897	0.03897	0.03897	0.03897	0.03897	0.038	0.03897	0.03897
Standard Error of Forecasts	0.86065	0.87769	0.89441	0.91082	0.92695	0.942	0.95838	0.97371
95% LCL of Forecasts	-1.64787	-1.68128	-1.71405	-1.74621	-1.77781	-1.808	-1.83942	-1.86947
95% UCL of Forecasts	1.72581	1.75922	1.79198	1.82415	1.85575	1.886	1.91735	1.94741
ST3								
Forecasts	0.50132	0.50132	0.50132	0.50132	0.50132	0.501	0.50132	0.50132
Standard Error of Forecasts	0.80876	0.80995	0.81114	0.81232	0.81351	0.814	0.81587	0.81704
95% LCL of Forecasts	-1.08383	-1.08615	-1.08848	-1.0908	-1.09312	-1.095	-1.09775	-1.10005
95% UCL of Forecasts	2.08647	2.0888	2.09112	2.09345	2.09576	2.098	2.10039	2.1027
ST4								

Forecasts	3.48E-05	3.48E-05	3.48E-05	3.48E-05	3.48E-05	3.48E-05	3.48E-05	3.48E-05
Standard Error of Forecasts	1.09062	1.24271	1.37812	1.50136	1.61523	1.721	1.82173	1.91666
95% LCL of Forecasts	-2.13755	-2.43564	-2.70103	-2.94258	-3.16575	-3.3742	-3.5705	-3.75655
95% UCL of Forecasts	2.13762	2.43571	2.7011	2.94265	3.16582	3.374	3.57057	3.75662
ST5								
Forecasts	0.14267	0.14267	0.14267	0.14267	0.14267	0.142	0.14267	0.14267
Standard Error of Forecasts	1.12141	1.12695	1.13247	1.13796	1.14343	1.14887	1.15428	1.15967
95% LCL of Forecasts	-2.05525	-2.06612	-2.07693	-2.08769	-2.0984	-2.10906	-2.11967	-2.13023
95% UCL of Forecasts	2.34059	2.35146	2.36227	2.37304	2.38375	2.39441	2.40502	2.41558

BOD								
ST1	Forecasts	1.23791	1.322	1.40106	1.47589	1.5471	1.61518	1.6805
	Standard Error of Forecasts	6.00855	5.84373	5.68878	5.54212	5.40254	5.26911	5.14108
	95% LCL of Forecasts	10.86105	11.02588	11.18083	11.32749	11.46706	11.60049	11.72852
	95% UCL of Forecasts	49.58383	49.58383	49.58383	49.58383	49.58383	49.58383	49.58383
ST2	Forecasts	3.16821	3.2748	3.37803	3.47819	3.57555	3.67033	3.76272
	Standard Error of Forecasts	43.37425	43.16534	42.96302	42.7667	42.57587	42.39011	42.20903
	95% LCL of Forecasts	55.79341	56.00232	56.20464	56.40096	56.59178	56.77754	56.95863
	95% UCL of Forecasts	48.59894	48.59894	48.59894	48.59894	48.59894	48.59894	48.59894

ST3	Forecasts	2.70128	2.88767	3.06274	3.22832	3.38582	3.53631	3.68065
	Standard Error of Forecasts	43.30452	42.93921	42.59609	42.27155	41.96286	41.6679	41.385
	95% LCL of Forecasts	53.89336	54.25867	54.60179	54.92633	55.23502	55.52998	55.81288
	95% UCL of Forecasts	55.52181	55.52181	55.52181	55.52181	55.52181	55.52181	55.52181
ST4	Forecasts	2.66515	3.01049	3.3201	3.6032	3.86563	4.11134	4.34317
	Standard Error of Forecasts	50.29821	49.62136	49.01453	48.45966	47.94531	47.46373	47.00935
	95% LCL of Forecasts	60.7454	61.42225	62.02908	62.58395	63.0983	63.57988	64.03427
	95% UCL of Forecasts	72.45198	72.45198	72.45198	72.45198	72.45198	72.45198	72.45198
ST5	Forecasts	3.03159	3.2588	3.47117	3.67128	3.86103	4.04188	4.21497
	Standard Error of Forecasts	66.51017	66.06485	65.64861	65.25641	64.88451	64.53005	64.19079
	95% LCL of Forecasts	78.3938	78.83912	79.25536	79.64756	80.01946	80.37391	80.71318
	95% UCL of Forecasts							
COD								
		59.90934	59.90934	59.90934	59.90934	59.90934	59.90934	59.90934
		2.99877	3.30236	3.58029	3.83815	4.07975	4.30781	4.5244
	Forecasts	54.03185	53.43683	52.89209	52.3867	51.91318	51.46618	51.04168
	Standard Error of Forecasts	65.78683	66.38184	66.92658	67.43198	67.90549	68.35249	68.77699
ST1	95% LCL of Forecasts	185.5651	185.5651	185.5651	185.5651	185.5651	185.5651	185.5651
	95% UCL of Forecasts	5.86622	6.65345	7.35692	7.99876	8.59279	9.14833	9.67201
	Forecasts	174.0675	172.5246	171.1458	169.8878	168.7236	167.6347	166.6083
	Standard Error of Forecasts	197.0627	198.6056	199.9844	201.2424	202.4067	203.4955	204.5219
ST2	95% LCL of Forecasts	172.616	172.616	172.616	172.616	172.616	172.616	172.616
	95% UCL of Forecasts	5.2264	5.51972	5.79823	6.06396	6.31852	6.56321	6.79911

	Forecasts	162.3724	161.7975	161.2517	160.7309	160.2319	159.7523	159.29
ST3	Standard Error of Forecasts	182.8595	183.4344	183.9803	184.5011	185.0001	185.4796	185.942
	95% LCL of Forecasts	211.4149	211.4149	211.4149	211.4149	211.4149	211.4149	211.4149
	95% UCL of Forecasts	5.14914	5.57758	5.97538	6.34831	6.70051	7.0351	7.35448
	Forecasts	201.3228	200.483	199.7033	198.9724	198.2821	197.6263	197.0004
ST4	Standard Error of Forecasts	221.507	222.3467	223.1264	223.8573	224.5476	225.2034	225.8294
	95% LCL of Forecasts	247.2559	247.2559	247.2559	247.2559	247.2559	247.2559	247.2559
	95% UCL of Forecasts	5.93431	6.27715	6.6022	6.91198	7.20846	7.49323	7.76755
ST5	Forecasts	235.6248	234.9529	234.3158	233.7086	233.1275	232.5694	232.0318
	Standard Error of Forecasts	258.8869	259.5589	260.1959	260.8031	261.3842	261.9423	262.48
	95% LCL of Forecasts							
	95% UCL of Forecasts							

Table A8 Point Source Data (July 2019-November 2023) (BOD and COD are mg/l)

Month		Najafgarh		Meltcalf				Khyber Pass			Sweeper Colony	
	BOD	COD	pH	BOD	COD	pH	BOD	COD	pH	BOD	COD	pH
Jul-19	24	76	7.8	15	52	7.6	12	40	7.7	11	40	7.7
Aug-19	20	56	7.7	11	56	7.7	11	40	7.8	12.5	52	7.8
Sep-19	26	80	8.9	11	40	7.9	26	96	8.1	7.6	28	8
Oct-19	40	132	8	20	60	7.8	30	96	8	35	144	8
Nov-19	45	160	7.7	NF	NF	NF	12	40	7.6	10	32	7.7
Dec-19	45	120	7.7	NF	NF	NF	24	96	8.1	12	48	8.1
Jan-20	72	220	7.4	NF	NF	NF	16	52	7.7	65	184	7.9

	BOD	COD	pH	BOD	COD	pH	BOD	COD	pH	BOD	COD	pH
Feb-20	62	152	7.4	NF	NF	NF	14	48	7.7	30	92	7.4
Mar-20	84	220	7.8	NF	NF	NF	20	72	7.8	58	160	7.8
Apr-20	35	104	7.53	NF	NF	NF	8	44	7.63	6	20	7.58
May20	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Jun-20	82	268	7.8	NF	NF	NF	24	80	8.4	68	210	8.4
Jul-20	46	150	7.3	NF	NF	NF	47	144	7.5	48	148	7.2
Aug-20	95	180	7.2	NF	NF	NF	6	24	7.4	12	56	7.4
Sep-20	38	120	7	48	148	7	16	56	7.4	18	60	7
Oct-20	30	124	7.5	22	52	7.21	14	48	7.6	70	220	7.5
Nov-20	35	96	7.6	NF	NF	NF	29	112	7.6	38	126	7.6
Dec-20	50	160	7.1	NF	NF	NF	96	336	7.4	40	124	7.2
Jan-21	38	136	7.23	NF	NF	NF	34	88	7.4	20	56	7.31
Feb-21	35	88	7.4	NF	NF	NF	16	80	7.5	36	144	7.2
Mar-21	54	272	7.26	NF	NF	NF	60	180	6.43	135	476	6.31
Apr-21	56	304	7.26	NF	NF	NF	80	288	7.18	NF	NF	NF
May21	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Jun-21	52	256	7.12	34	144	6.8	NF	NF	NF	120	544	6.85
Jul-21	70	384	7.5	NF	NF	NF	20	64	7.44	140	544	7.55
Aug-21	70	256	7.34	30	96	7.25	68	280	7.36	58	184	7.26
Sep-21	100	496	7.06	24	88	7.36	30	120	6.84	26	96	7.48
Oct-21	90	272	7.29	NF	NF	NF	36	152	7.19	80	384	7.06
Nov-21	48	208	7.66	NF	NF	NF	34	144	6.44	160	728	6.92
Dec-21	82	288	7.5	NF	NF	NF	44	168	7.45	160	392	7.49
Jan-22	80	304	7.3	NF	NF	NF	50	176	7.32	75	224	7.4
Feb-22	85	320	7.34	NF	NF	NF	NF	NF	NF	NF	NF	NF
Mar-22	75	336	7.42	NF	NF	NF	46	208	7.23	70	288	7.36

	BOD	COD	pH	BOD	COD	pH	BOD	COD	pH	BOD	COD	pH
Apr-22	80	352	7.41	NF	NF	NF	NF	NF	NF	78	272	7.69
May22	76	320	7.37	NF	NF	NF	44	192	7.35	74	266	7.49
Jun-22	70	346	7.48	70	348	7.25	NF	NF	NF	60	266	7.42
Jul-22	73	373	7.51	24	64	7.32	NF	NF	NF	58	240	7.45
Aug-22	75	384	7.43	30	64	7.2	NF	NF	NF	52	224	7.4
Sep-22	70	352	7.49	28	80	7.18	NF	NF	NF	50	208	7.54
Oct-22	65	336	7.3	26	88	7.2	NF	NF	NF	48	192	7.3
Nov-22	66	320	7.4	28	96	7.1	NF	NF	NF	50	176	7.4
Dec-22	68	384	7.5	NF	NF	NF	NF	NF	NF	55	192	7.4
Jan-23	53	272	7.3	NF	NF	NF	NF	NF	NF	40	168	7.3
Feb-23	55	288	7.5	NF	NF	NF	NF	NF	NF	NF	NF	NF
Mar-23	58	293	7.3	NF	NF	NF	NF	NF	NF	NF	NF	NF
Apr-23	60	272	7.1	NF	NF	NF	NF	NF	NF	NF	NF	NF
May23	48	224	7.2	20	80	7.1	NF	NF	NF	NF	NF	NF
Jun-23	50	213	7.5	NF	NF	NF	NF	NF	NF	NF	NF	NF
Jul-23	46	192	7.4	NF	NF	NF	NF	NF	NF	NF	NF	NF
Aug-23	42	186	7.5	28	112	7.2	30	128	7.4	40	176	7.6
Sep-23	44	208	7.4	NF	NF	NF	NF	NF	NF	NF	NF	NF
Oct-23	48	240	7.2	NF	NF	NF	NF	NF	NF	NF	NF	NF
Nov-23	52	264	7.3	NF	NF	NF	NF	NF	NF	NF	NF	NF

Month		Magazine Road			ISBT			Tonga			Civil Mill	
	BOD	COD	pH	BOD	COD	pH	BOD	COD	pH	BOD	COD	pH
Jul-19	35	140	7.6	37	116	7.7	36	112	7.6	65	184	7.5
Aug-19	15.5	68	7.6	38	112	7.7	90	340	7.7	70	256	7.6
Sep-19	39	156	8.2	12	44	8.1	37	144	8.1	23.5	88	7.9
Oct-19	46	156	7.9	40	128	7.9	50	156	7.7	70	224	7.8
Nov-19	95	332	7.4	28	80	7.7	38	120	7.9	88	284	7.9
Dec-19	95	260	8.1	96	184	8	49	132	7.9	49	132	7.9
Jan-20	180	420	7.4	132	390	7.9	90	240	7.2	120	360	7.3
Feb-20	210	520	7.6	62	192	7.4	60	172	7.6	130	400	7.4
Mar-20	72	180	7.9	70	180	7.7	62	100	7.9	72	200	7.9
Apr-20	305	900	7.16	9	64	7.77	8	64	7.76	27	92	7.71
May-20												
Jun-20	40	140	7.9	72	200	8.2	28	88	8	130	400	8.1
Jul-20	70	218	7.4	48	154	7.1	60	184	7.1	68	210	7.2
Aug-20	120	320	7.4	10	44	7.3	11	36	7.4	76	256	7.3
Sep-20	56	170	7.3	18	68	7.2	52	160	7.3	68	210	7.4
Oct-20	42	156	7.6	32	112	7.4	12	48	7.4	48	184	7.4
Nov-20	28	104	7.6	74	232	7.5	32	108	7.4	58	168	7.5
Dec-20	65	196	7.9	150	360	7.7	NF	NF	NF	62	220	6.8
Jan-21	72	196	7.35	56	140	7.16	NF	NF	NF	59	152	7.28
Feb-21	NF	NF	NF	59	272	7.1	17	84	7.3	45	172	7.2
Mar-21	30	144	6.76	80	288	7.38	26	84	6.66	26	80	6.79
Apr-21	NF	NF	NF	78	256	6.85	50	120	6.91	33	64	6.8
May-21	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
Jun-21	NF	NF	NF	42	152	6.75	NF	NF	NF	35	160	7.01

	BOD	COD	pH	BOD	COD	pH	BOD	COD	pH	BOD	COD	pH
Jul-21	90	416	7.23	100	464	7.23	16	56	7.52	70	160	7.32
Aug-21	52	240	7.4	34	152	7.41	32	136	7.47	62	344	7.44
Sep-21	40	128	6.75	24	104	7.4	42	208	7.38	30	120	7.24
Oct-21	50	176	7.5	56	224	7.27	60	240	7.45	20	88	7.56
Nov-21	47	192	7.18	46	184	7.43	50	176	7.3	46	176	7.31
Dec-21	NF	NF	NF	70	288	7.28	40	168	7.1	66	208	6.88
Jan-22	NF	NF	NF	62	208	7.31	48	160	7.24	60	192	7
Feb-22	70	304	6.72	64	224	7.12	42	160	6.94	55	208	7.27
Mar-22	NF	NF	NF	60	240	7.26	34	149	7.1	50	192	7.16
Apr-22	NF	NF	NF	68	256	6.96	40	165	7.58	60	224	7.86
May-22	NF	NF	NF	66	272	7.42	35	138	7.39	56	288	7.1
Jun-22	NF	NF	NF	68	288	7.34	33	101	7.39	54	240	7.44
Jul-22	NF	NF	NF	66	304	7.39	30	90	7.44	68	320	7.48
Aug-22	NF	NF	NF	56	320	7.38	33	85	7.21	58	336	7.33
Sep-22	NF	NF	NF	54	288	7.3	33	88	7.21	56	304	120
Oct-22	NF	NF	NF	52	272	7.2	32	80	7.2	54	288	7.1
Nov-22	NF	NF	NF	54	256	7.3	33	69	7.1	56	272	7.2
Dec-22	NF	NF	NF	53	272	7.3	34	80	7.2	52	288	7.1
Jan-23	NF	NF	NF	44	208	7.2	25	64	7.2	46	246	7.3
Feb-23	NF	NF	NF	50	272	7.2	NF	NF	NF	40	256	7
Mar-23	NF	NF	NF	46	272	7.3	NF	NF	NF	42	266	7.2
Apr-23	NF	NF	NF	48	256	7.4	NF	NF	NF	42	248	7.3
May-23	NF	NF	NF	40	240	7.3	NF	NF	NF	NF	NF	NF
Jun-23	NF	NF	NF	42	224	7.7	NF	NF	NF	NF	NF	NF
Jul-23	NF	NF	NF	38	208	7.5	NF	NF	NF	NF	NF	NF
Aug-23	38	148	7.3	38	192	7.2	NF	NF	NF	52	260	7.1

	BOD	COD	pH	BOD	COD	pH	BOD	COD	pH	BOD	COD	pH
Sep-23	NF	NF	NF	40	198	7.5	NF	NF	NF	42	248	7.1
Oct-23	NF	NF	NF	44	213	7.4	NF	NF	NF	NF	NF	NF
Nov-23	NF	NF	NF	48	208	7.5	NF	NF	NF	NF	NF	NF

Month	Power house				Sen nursing Home			Drain 14			Barapulla	
	BOD	COD	pH	BOD	COD	pH	BOD	COD	pH	BOD	COD	pH
Jul-19	75	228	7.4	55	172	7.7	10	32	7.7	36	116	7.5
Aug-19	60	236	7.7	84	320	7.4	10	32	7.7	28	76	7.7
Sep-19	42	156	7.9	90	308	7.5	27	96	7.7	120	364	7.9
Oct-19	68	216	8.2	76	248	8.1	14	48	8	26	76	7.4
Nov-19	24	80	8.2	60	200	7.8	8	32	7.9	64	216	7.9
Dec-19	34	118	8	65	192	7.9	8	26	7.9	45	172	7.8
Jan-20	120	340	7.3	84	260	7.2	72	220	7.3	78	210	7.5
Feb-20	52	152	7.4	180	450	7.7	40	128	7.7	92	272	7.5
Mar-20	68	192	7.7	40	120	7.9	54	160	8	92	240	7.5
Apr-20	27	96	7.12	89	192	7.3	19	72	7.85	124	260	7.3
May20	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Jun-20	62	194	8.1	68	208	7.9	38	120	8	48	156	7.8
Jul-20	96	244	7.2	90	272	7.3	64	144	7.6	36	110	7.6
Aug-20	42	120	7.3	56	100	7.2	65	128	7.4	12	48	7.2
Sep-20	30	98	7.4	40	126	7.3	68	172	7.3	18	68	7.3
Oct-20	70	292	7.3	34	168	7.3	23	96	7.2	62	240	6.8
Nov-20	48	156	7.4	65	192	7.4	34	112	7.3	18	60	7.3
Dec-20	142	412	7.1	76	236	6.9	54	160	7	7.2	260	-
Jan-21	94	288	6.56	108	324	7.13	15	52	7.24	62	176	7.25

	BOD	COD	pH	BOD	COD	pH	BOD	COD	pH	BOD	COD	pH
Feb-21	65	260	7.4	72	316	7.2	31	116	7.5	42	204	7.2
Mar-21	68	200	6.6	118	480	6.46	31	86	6.88	63	176	6.88
Apr-21	72	240	6.82	84	368	6.95	29	64	7.22	58	344	6.95
May21	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Jun-21	54	218	7	22	92	6.8	6	60	6.72	32	176	7.06
Jul-21	90	336	7.45	86	432	7.25	31	88	7.47	28	160	7.35
Aug-21	100	328	7.55	88	408	7.43	90	368	7.57	52	224	7.44
Sep-21	90	384	7.28	58	264	7.27	36	152	7.48	26	96	7.04
Oct-21	50	192	7.54	110	368	7.07	77	320	7.04	52	184	7.18
Nov-21	100	368	7.16	94	344	7.09	56	192	7.55	60	232	7.8
Dec-21	70	296	7.3	153	384	7.21	32	128	7.03	93	352	7.64
Jan-22	65	320	7.22	90	336	7.13	36	144	7.35	60	293	7.46
Feb-22	70	272	7.46	86	320	7.21	20	74	7.54	63	266	7.34
Mar-22	65	288	7.38	83	352	7.31	16	64	7.45	73	293	7.36
Apr-22	75	288	7.59	73	336	7.11	30	136	7.06	66	346	7.62
May22	73	304	7.31	75	320	7.18	NF	NF	NF	70	336	7.46
Jun-22	63	293	7.48	73	304	7.22	22	80	7.56	67	300	7.55
Jul-22	48	266	7.33	63	258	7.2	20	88	7.58	60	300	7.57
Aug-22	63	256	7.26	65	352	7.22	29	112	7.42	60	320	7.45
Sep-22	60	240	7.46	60	336	7.39	28	72	7.25	56	266	7.4
Oct-22	56	224	7.2	55	320	7.3	28	80	7.2	60	240	7.4
Nov-22	63	176	7.4	60	304	7.2	27	72	7.3	56	266	7.3
Dec-22	60	224	7.5	62	336	7.4	36	96	7	50	240	7.3
Jan-23	53	224	7.6	50	266	7.3	21	88	7.5	43	213	7.6
Feb-23	58	240	6.5	56	304	7.2	NF	NF	NF	42	266	7.2
Mar-23	52	256	6.9	NF	NF	NF	NF	NF	NF	44	272	7.3

	BOD	COD	pH	BOD	COD	pH	BOD	COD	pH	BOD	COD	pH
Apr-23	55	293	7	52	304	7.4	NF	NF	NF	45	288	7.2
May23	48	272	7.2	50	288	7.1	NF	NF	NF	56	272	7.3
Jun-23	43	288	7	48	266	7.3	NF	NF	NF	52	240	7.9
Jul-23	38	240	7.2	40	224	7.4	NF	NF	NF	47	248	7.1
Aug-23	39	196	7.1	44	234	7.3	NF	NF	NF	50	252	7.8
Sep-23	38	176	7.2	46	234	7.3	NF	NF	NF	37	248	7.2
Oct-23	40	186	7	42	234	7.4	NF	NF	NF	38	170	7.3
Nov-23	44	192	7.6	45	232	7.2	NF	NF	NF	43	224	7.4

Month		Maharani Bagh			Sonia Vihar		Kailash Nagar			Shastri Park		
	BOD	COD	pH	BOD	COD	pH	BOD	COD	pH	BOD	COD	pH
Jul-19	45	136	7.3	NA	NA	NA	NA	NA	NA	NA	NA	NA
Aug-19	48	160	7.6	NA	NA	NA	NA	NA	NA	NA	NA	NA
Sep-19	90	272	7.7	NA	NA	NA	NA	NA	NA	NA	NA	NA
Oct-19	2	160	7.6	NA	NA	NA	NA	NA	NA	NA	NA	NA
Nov-19	84	248	7.8	NA	NA	NA	NA	NA	NA	NA	NA	NA
Dec-19	132	440	7.6	NA	NA	NA	NA	NA	NA	NA	NA	NA
Jan-20	120	340	7.8	NA	NA	NA	NA	NA	NA	NA	NA	NA
Feb-20	78	196	7.4	NA	NA	NA	NA	NA	NA	NA	NA	NA
Mar-20	78	196	7.4	NA	NA	NA	NA	NA	NA	NA	NA	NA
Apr-20	193	476	7.45	NA	NA	NA	NA	NA	NA	NA	NA	NA
May20	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Jun-20	88	284	7.9	NA	NA	NA	NA	NA	NA	NA	NA	NA
Jul-20	58	180	7.7	NA	NA	NA	NA	NA	NA	NA	NA	NA
Aug-20	60	236	7.2	NA	NA	NA	NA	NA	NA	NA	NA	NA

	BOD	COD	pH	BOD	COD	pH	BOD	COD	pH	BOD	COD	pH
Sep-20	54	168	7.3	NA	NA	NA	NA	NA	NA	NA	NA	NA
Oct-20	160	400	7	NA	NA	NA	NA	NA	NA	NA	NA	NA
Nov-20	46	156	7.4	NA	NA	NA	NA	NA	NA	NA	NA	NA
Dec-20	140	396	7.2	NA	NA	NA	NA	NA	NA	NA	NA	NA
Jan-21	108	324	7.13	NA	NA	NA	NA	NA	NA	NA	NA	NA
Feb-21	46	184	7.2	NA	NA	NA	NA	NA	NA	NA	NA	NA
Mar-21	138	464	7.2	NA	NA	NA	NA	NA	NA	NA	NA	NA
Apr-21	72	384	7.1	68	160	7.24	47	152	7.15	45	138	7.21
May-21	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Jun-21	70	360	7.2	44	148	6.4	20	80	6.74	44	192	6.02
Jul-21	72	240	7.5	24	104	8.5	93	320	7.74	54	208	7.68
Aug-21	47	176	7.36	NF	NF	NF	94	336	7.43	97	368	7.73
Sep-21	64	232	7.48	NF	NF	NF	60	304	7.33	27	128	6.84
Oct-21	34	152	7.14	88	408	7.27	44	184	7.18	86	344	7.26
Nov-21	74	280	7.6	67	272	7.68	43	160	7.12	40	168	7.35
Dec-21	60	208	7.8	42	160	7.5	123	352	7.29	83	272	7.34
Jan-22	55	266	7.74	75	240	7.48	80	368	7.34	86	256	7.28
Feb-22	45	186	7.63	95	384	7.27	90	352	7.42	66	240	7.14
Mar-22	48	266	7.58	85	368	7.29	105	320	7.33	76	224	7.2
Apr-22	56	213	6.91	80	400	7.46	86	368	7.91	NF	NF	NF
May-22	50	304	7.51	100	416	7.56	83	336	7.3	90	240	7.34
Jun-22	53	258	7.77	96	426	6.9	76	320	7.4	65	224	7.26
Jul-22	65	256	7.79	90	400	6.96	64	293	7.42	53	240	7.21
Aug-22	73	346	7.6	83	368	7.36	64	304	7.28	70	272	7.46
Sep-22	60	293	7.48	76	368	7.26	62	192	7.37	73	288	7.2
Oct-22	65	266	7.2	73	384	7.2	60	208	7.2	66	304	7.2

	BOD	COD	pH	BOD	COD	pH	BOD	COD	pH	BOD	COD	pH
Nov-22	53	293	7.2	76	368	7.1	62	160	7.3	63	304	7.4
Dec-22	54	266	7.4	80	372	7.3	58	248	7.5	57	256	7.1
Jan-23	46	186	7.4	63	320	7.2	58	176	7.4	40	208	7.5
Feb-23	48	293	7	58	368	7.1	45	160	7	38	304	6.9
Mar-23	50	288	7.4	60	368	7.3	44	168	7.2	40	152	7.1
Apr-23	50	266	7.5	62	373	7.4	46	192	7.3	45	288	7
May-23	46	256	7.4	54	320	7.4	42	180	7.2	34	144	7.1
Jun-23	45	272	7.4	53	304	7.6	40	184	7.5	30	152	7.3
Jul-23	42	256	7	44	288	7.3	30	164	7.6	28	144	7.2
Aug-23	46	224	7.3	48	266	7.4	36	170	7.5	34	160	7
Sep-23	47	206	7.1	58	266	6.9	34	168	7	28	160	7.4
Oct-23	46	266	7.7	42	192	7.1	35	160	7.4	31	154	7
Nov-23	43	224	7.4	39	186	7.6	33	148	7.2	30	148	6.9

NF= No Flow NA=Not availabl

Table A9 Frequencies of different BOD counts for sixteen-point sources

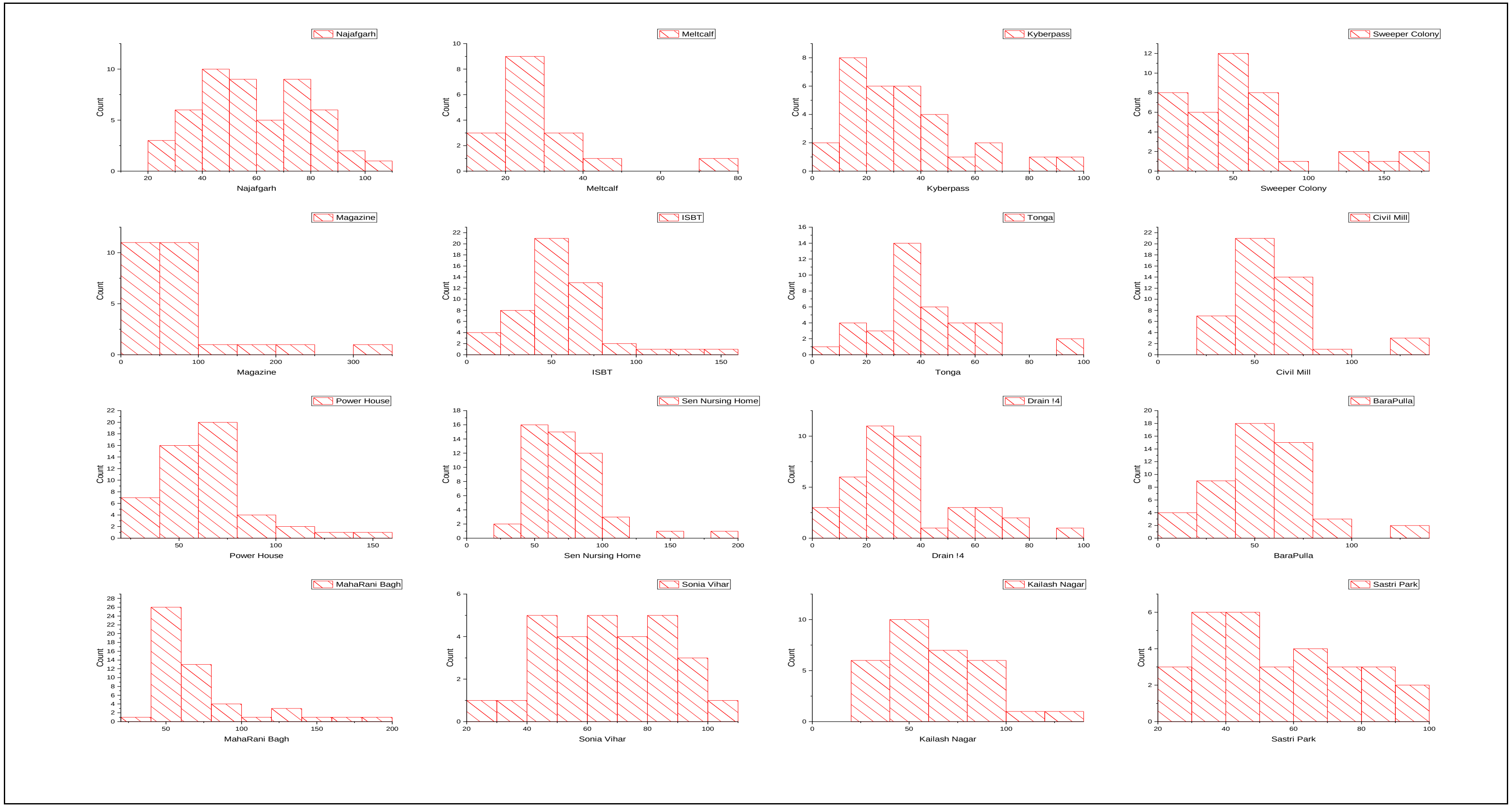
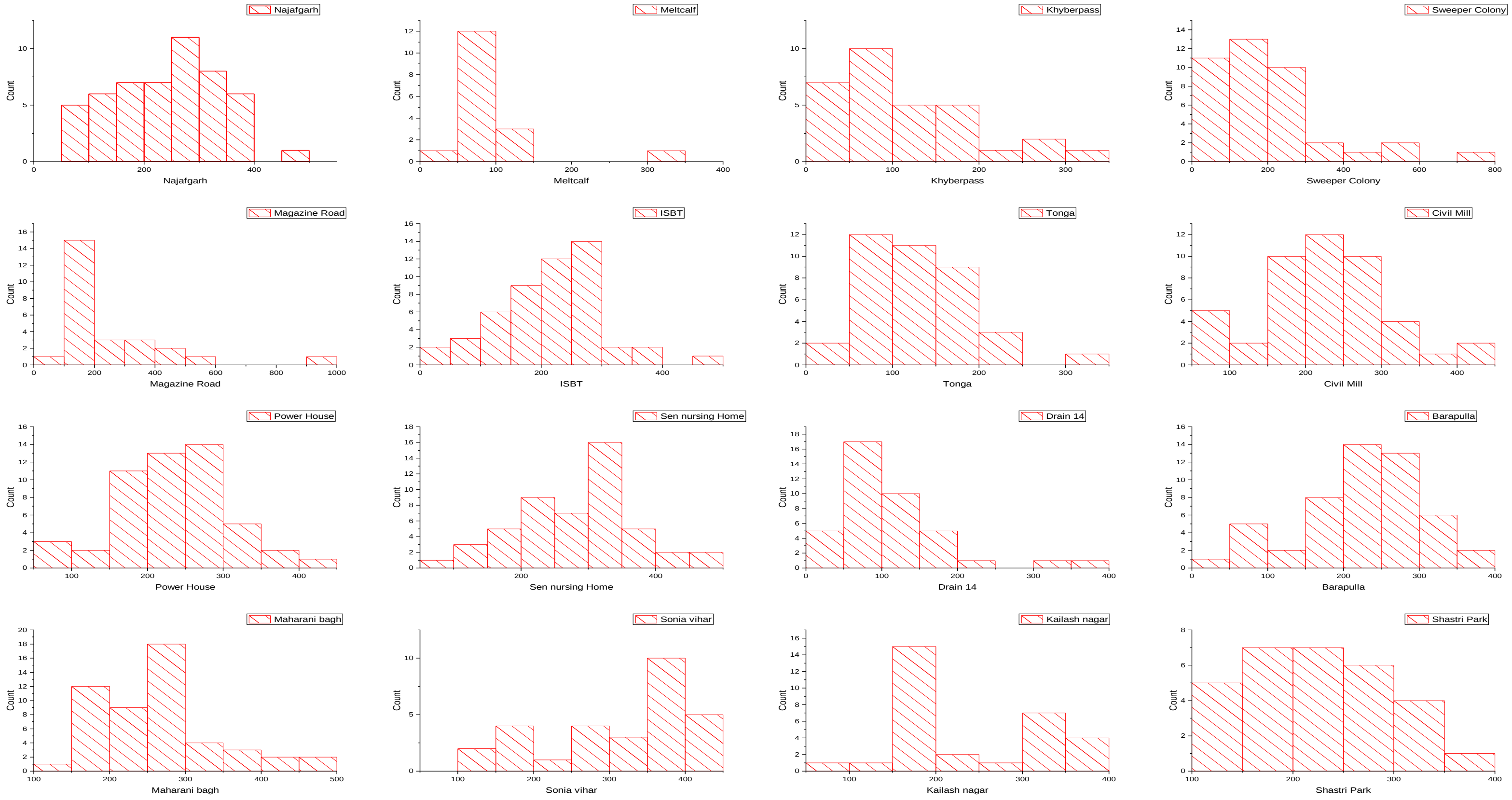


Table A10 COD counts for different point sources



A11 Rate Sheet

	Rate Sheet used for Premonsoon period	
Parameter	Value	unit
Nitrogen	7.2	gN
Phosphorus	1	gP
Dry weight	100	gD
Chlorophyll	1	gA
Inorganic suspended solids:		
Settling velocity	0.01	m/d
Oxygen:		
Reaeration model	O'Connor-Dobbins	
Temp correction	1.024	
Reaeration wind effect	None	
O2 for carbon oxidation	2.69	gO_2/gC
O2 for NH4 nitrification	4.57	gO_2/gN
Oxygen inhii model CBOD oxidation	Exponential	
Oxygen inhib parameter CBOD oxidation	0.60	L/mgO2
Oxygen inhib model nitrification	Exponential	
Oxygen inhib parameter nitrification	0.60	L/mgO2
Oxygen enhance model denitrification	Exponential	
Oxygen enhance parameter denitrification	0.60	L/mgO2
Oxygen inhib model phyto resp	Exponential	
Oxygen inhib parameter phyto resp	0.60	L/mgO2
Oxygen enhance model bot alg resp	Exponential	

Parameter	Value	unit
Oxygen enhance parameter bot alg resp	0.60	L/mgO2
Slow CBOD:		
Hydrolysis rate	0.05	/d
Temp correction	1.047	
Oxidation rate	3.6	/d
Temp correction	1.047	
Fast CBOD:		
Oxidation rate	1.11	/d
Temp correction	1.047	
Organic N:		
Hydrolysis	0.1	/d
Temp correction	1.07	
Settling velocity	0.06	m/d

Table A 12 Hourley data of March 2, 2021, Headwater quality for validation

Time step	DO, mg/l	TUR (NTU)	TOC (mg/l)	NO3 (mg/l)	BOD (mg/l)	NH4 (mg/l)	COD (mg/l)	pH	COND. (uS/cm)	TEMP°(C)	TSS(mg/l)
0.00	5.28	4.74	5.6	3.73	4.02	1.19	14.41	8.22	578	22.32	5.85
1.00	5.42	4.67	5.61	3.7	4	1.2	14.43	8.22	578.5	22.2	5.81
2.00	4.95	4.71	5.63	3.72	3.96	1.19	14.48	8.22	580.25	22.05	5.87
3.00	5.04	5.03	5.67	3.68	4.02	1.2	14.62	8.23	580.25	22	6.15
4.00	4.87	5.36	5.71	3.7	4.02	1.17	14.73	8.2	580.25	21.95	6.45
5.00	4.54	5.38	5.74	3.74	4.01	1.15	14.78	8.19	581	21.82	6.49
6.00	4.96	7.31	6	3.69	4.06	1.15	15.5	8.2	580.75	21.7	8.36
7.00	4.39	5.75	5.82	3.7	3.99	1.16	15.03	8.16	581	21.6	6.92
8.00	3.93	5.9	5.81	3.69	4.07	1.16	15	8.19	580.75	21.52	7

Time step	DO, mg/l	TUR (NTU)	TOC (mg/l)	NO3 (mg/l)	BOD (mg/l)	NH4 (mg/l)	COD (mg/l)	pH	COND. (uS/cm)	TEMP°(C)	TSS(mg/l)
9.00	3.99	6.11	5.81	3.69	3.98	1.17	14.98	8.2	576.75	21.52	7.26
10.00	5.44	5.92	5.8	3.73	3.99	1.18	14.96	8.17	577	21.65	7.03
11.00	5.77	6.28	5.88	3.68	3.97	1.19	15.16	8.17	577.75	21.83	7.39
12.00	4.26	5.51	5.84	1.81	4.4	1.57	14.2	7.88	960.11	22.29	16.53
13.00	5.27	5.84	5.88	1.77	4.15	1.56	14.29	7.89	955	22.35	16.83
14.00	5.16	5.82	5.88	1.74	4.32	1.6	14.3	7.89	955.21	22.6	16.81
15.00	4.23	5.96	5.97	1.98	4.1	1.61	14.52	7.86	960.75	22.72	16.92
16.00	3.7	6.02	5.93	1.97	4.19	1.62	14.44	7.86	959	22.85	16.96
17.00	3.04	6.69	6.03	1.96	4.17	1.57	14.74	7.9	963	22.8	17.51
18.00	3.03	5.99	5.98	1.84	4.24	1.55	14.56	7.94	963.25	22.62	16.96
19.00	4.13	6	5.99	1.79	4.27	1.53	14.59	7.93	964	22.45	16.96
20.00	3.89	6.03	5.98	1.84	4.29	1.54	14.56	7.91	965	22.2	16.97
21.00	3.69	5.67	5.98	1.77	4.31	1.52	14.56	7.92	968	21.98	16.73
22.00	3.6	5.98	6	1.74	4.37	1.52	14.61	7.93	972.5	21.72	16.95
23.00	3.36	5.55	5.99	1.77	4.38	1.51	14.57	7.9	969.5	21.55	16.59

Table A 13 Reaeration rates for Calibration and validation

Reach no	Reach level	Reaeration constant/d (March2021)	Reaeration constant/d (April 2022)
1	Wazirabaad	3.17	3.17
2	Najafgarh Drain	2.15	2.03
3	Khyber Pass Drain	1.34	1.28
4	ISBT+ Morigate Drain	1.074	1.026
5	Tonga Stand Drain	1.31	1.25
6	Shastri Park Drain	1.51	1.44

Reach no	Reach level	Reaeration constant/d (March2021)	Reaeration constant/d (April 2022)
7	Kailash Nagar Drain	1.24	1.18
8	Delhi gate Drain	1.32	1.23
9	Sen Nursing Home Drain	0.06	0.06
10	Drain 14	0.7	0.67
11	Nizamuddin	0.7	0.7
12	Barapulla Drain	0.51	0.49
13	Maharani Bagh Drain	0.17	0.19
14	Old Agra canal	0.17	0.19

Table A 14 Climatic characteristics for simulation (temperatures are in celsius)

Time	Calibration			Validation		
	Air temperature	Dew Point temperature	Wind speed	Air temperature	Dew Point temperature	Wind speed
00.00AM	19.00	15.30	7.00	26.00	6.10	1.90
1:00 AM	19.00	15.30	7.00	26.00	5.00	0.00
2:00 AM	18.00	13.70	7.00	26.00	5.00	0.00
3:00 AM	18.00	13.70	9.00	26.00	5.00	0.00
4:00 AM	17.00	12.70	9.00	25.00	6.10	1.00
5:00 AM	17.00	12.70	9.00	24.00	2.78	1.00
6:00 AM	17.00	12.70	9.00	24.00	0.00	1.00
7:00 AM	18.00	12.40	9.00	25.00	1.11	1.55
8:00 AM	19.00	12.00	9.00	26.00	3.89	3.10
9:00 AM	20.00	15.50	9.00	28.00	6.11	3.60
10.00AM	22.00	13.90	9.00	30.00	6.11	3.60
11.00AM	24.00	15.20	9.00	33.00	7.22	4.10

	Calibration			Validation		
	Air temperature	Dew Point temperature	Wind speed	Air temperature	Dew Point temperature	Wind speed
12.00PM	25.00	14.40	11.00	34.00	7.32	5.18
1:00 PM	27.00	15.00	11.00	35.00	2.78	4.10
2:00 PM	28.00	15.30	11.00	36.00	1.11	3.60
3:00 PM	28.00	15.30	26.00	36.00	0.00	4.01
4:00 PM	28.00	14.60	26.00	36.00	0.00	3.60
5:00 PM	27.00	14.40	26.00	36.00	0.00	3.60
6:00 PM	25.00	13.20	13.00	35.00	2.66	1.55
7:00 PM	23.00	12.60	13.00	32.00	2.78	1.04
8:00 PM	22.00	13.30	13.00	29.00	5.00	1.04
9:00 PM	21.00	12.90	7.00	25.00	6.11	1.55
10:00PM	20.00	13.20	7.00	25.00	7.22	0.00
11:00PM	19.00	13.00	7.00	24.00	7.78	6.00

Table A15 Light and heat sheet

Parameter	Value	Unit
Photosynthetically Available Radiation	0.47	
Background light extinction	0.2	/m
Linear chlorophyll light extinction	0.01	1/m-(ugA/L)
Nonlinear chlorophyll light extinction	0.054	1/m-(ugA/L)$^{2/3}$
ISS light extinction	0.052	1/m-(mgD/L)
Detritus light extinction	0.174	1/m-(mgD/L)
Macrophyte light extinction	0.02	1/m-(gD/m^3)
Atmospheric attenuation model for solar	Bras	
atmospheric turbidity coefficient (2=clear, 5=smoggy, default=2)	2	
atmospheric transmission coefficient (0.70-0.91, default 0.8)	0.8	
atmospheric longwave emissivity model	Brunt	
parameter for emissivity using the Brutsaert equation	1.24	
wind speed function for evaporation and air convection/conduction	Brady-Graves-Geyer	
parameter for attenuation of solar radiation by cloud cover	0.65	
parameter for cloud cover adjustment of sky emissivity	0.17	

Table A16: Removal efficiencies of BOD and COD for different STPs

NO	Name of STPs	Treatment methods	BOD removal efficiencies	COD removal efficiencies
1	Molarband (Mini STP)	FAB	86.6	80.23025
2	Coronation Pillar I	ASP	83.72309	74.29457
3	Coronation Pillar	ASP	86.24582	75.08197
4	Delhi gate New	Biofor	94.06994	85.48326
5	Delhi Gate Old	Biofor	94.17556	89.02171
6	Keshopur STP(New)	ASP	90.77466	84.11462
7	Sen Nursing Home (SNH)	BIOfor	93.91581	88.54001
8	Nilothi New	SBR	94.23676	89.09973
9	Nilothi	ASP	75.78348	59.65585
10	Najafgarh	EA	75.75316	70.57632
11	Rithala 2	ASP	93.15429	83.56189
12	Pappankalan(Old)	ASP	74.95576	68.60495
13	Pappankalan PH- II (New)	SBR	91.76021	89.42142
14	Rohini	ASP	85.94428	84.54566
15	Narela	ASP	85.14447	80.00901
16	Okhla New	ASP	92.5973	87.83101
17	Kondli	ASP	90.00934	86.17295
18	Kondli II	ASP	93.32867	63.4253
19	Kondli New	ASP	65.02355	89.59401
20	Kapasahera	SBR	93.06057	80.86887
21	Yamuna Vihar Ph-III	ASP	87.02194	87.6777
22	Chilla	SBR	93.52094	91.76254
23	Akshardham	MBR	95.76409	80.1235

NO	Name of STPs	Treatment methods	BOD removal efficiencies	COD removal efficiencies
24	Mehrauli	EA	84.55372	86.39468
25	Vasant Kunj I	EA	87.02097	83.2454
26	VasantKunj II	EA	87.21518	86.08672
27	Yamuna Vihar 1	ASP	88.1379	76.94541
28	Yamuna Vihar II	ASP	81.93379	77.56802
29	Okhla I	ASP	80.13208	68.40833
30	Keshopur I	ASP	65.45654	66.16873

Table A 17 Inlet and outlet values of BOD and COD for different STPs

	Nov-22	Oct-22	Sep-22	Aug-22	Jul-22	Jun-22	May-22	Apr-22	Mar-22	Feb-22	Dec-21
Name of the STPs	inlet BOD	inlet BOD	inlet BOD	inlet BOD	inlet BOD	inlet BOD	inlet BOD	inlet BOD	inlet BOD	inlet BOD	inlet BOD
Molarband (Mini STP)	130	125	110	114	90	104	112	112	110		90
Coronation Pillar1	140	130	155	140	165	205	130		175	155	165
Coronation Pillar2	120	115	135	110	145	175	118				115
Delhi gate New	110	105	106	155	84	94	98	70	85	220	85
Delhi Gate Old	115	105	112	125	100	98	92	90	80	105	232
Keshopur STP(New)	130	135	105	125	135	145	137			55	85
Sen Nursing Home	104	110	102	128	90	96	94	90	90	95	95
Nilothi New	105	110	66	72	110	102	100		95	120	100
Nilothi	125	124	95	120	96	106	112		135	148	145
Najafgarh	82	85	104	175	88	80	75		75	87	85

Name of the STPs	inlet BOD	inlet BOD	inlet BOD	inlet BOD	inlet BOD	inlet BOD	inlet BOD	inlet BOD	inlet BOD	inlet BOD	inlet BOD
Rithala2	86	86	115	108	80	88	84	92	80	115	100
Pappankalan(Old)	85	72	94	108	112	64	60		42	77	55
Pappankalan PH- II New	140	136	94	96	112	120	120		95	100	85
Rohini	145	140	100	102	84	135	142	120	135	150	145
Narela	92	95	84	68	54	68	72	90	60	110	90
Okhla New	106	100	88	88	96	110	120	150	112	105	110
Kondli 1	125	110	125	145	105	110	112	180	100	95	105
Kondli New	195	145	195	82	145	150	150	112	140	95	85
Kapasahera	78	80	76	130	80	82	78	280	75	80	85
Yamuna Vihar Ph-III	70	105	68	108	125	96	100		160	150	155
Chilla	102	90	100	96	92	98	92	110	90	100	96
Akshardham	106	130	104	112	105	100	98		95	60	75
Mehrauli	106	100	102	145	90	92	98	110	95	80	95
Vasant Kunj1	120	120	120	125	125	120	118	270	115	120	115
Vasantkunj2	16	120	115	84	216	110	110	240	120	120	110
Yamuna Vihar	56	100	54	225	92	98	100		95	85	180
Yamunabihar2	76	5.75	72		210	205	200		188	128	125
Okhla1	94	90	86	112	88	90	88	110	85	85	95
Keshopur	65	62	76	115	75	68	65		80	105	95
Keshopur2	65	62	76	115		68	65	....	80	105	95

Name of the STPs	inlet BOD	inlet BOD	inlet BOD	inlet BOD	inlet BOD	inlet BOD	inlet BOD	inlet BOD	inlet BOD	inlet BOD	inlet BOD
Molarband (Mini STP)											
Coronation Pillar1	110	120	130	114		236		100	210	70	295
Coronation Pillar2	155	160	170	140	106	132		68	108	62	90
Delhi gate New	110	100	95	110	106	140		240	88	240	130
Delhi Gate Old	90	85	105	155	124	62	114	106	126	110	40
Keshopur STP(New)	95	85	95	125	180	160	106	56	330	140	60
Sen Nursing Home	90	95	95	125	124	100	285	70	136	120	165
Nilothi New	90	93	110	128	144	110	104	124	106	72	95
Nilothi	90	85	130	72	140	170	155	120	110	110	85
Najafgarh	140	140	135	120	98	96	125	85	100	95	
Rithala2	80	70	65	175	180	218	122	165	190	140	60
Pappankalan(Old)	110	135	80	108	88	135	120	198	85	120	110
Pappankalan PH-II (New)	46	43	30	108	90	230	225	142	115	130	210
Rohini	95	110	80	96	150	280	275	155	160	95	170
Narela	140	125	120	102	104	205	195	250	125	125	295
Okhla New	95	95	115	68	64	106	100	64	185	94	175
Kondli 1	100	110	130	88	142	220	240	136	82	115	70
Kondli New	100	75	95	145	102	206	285	146	82	120	190
Kapasahera	100	85	125		116	260	205	114	138	170	165
Yamuna Vihar Ph-III	80	60	70	82	256	280	260	240	175	160	260

Name of the STPs	inlet BOD	inlet BOD	inlet BOD	inlet BOD	inlet BOD	inlet BOD	inlet BOD	inlet BOD	inlet BOD	inlet BOD	inlet BOD
Chilla	170	175	165	130	192	340	325	240	160	140	260
Akshardham	90	85	80	108	132	100	150	116	150	150	65
Mehrauli	80	72	94	96	110	122	118	134	17	180	110
Vasant Kunj1	80	70	60	112	96	120	92	70	88	85	190
Vasantkunj2	110	95	110	145	218	308	270	210	104	140	165
Yamuna Vihar	120	85	95	125	225	260	240	95	98	130	290
Yamunabihar2	90	95	115	84	112	256	154	90	124	72	290
Okhla1	120	115	85	225	92	152	140	120	100	60	160
Keshopur	90	80		112	0	170	138	90	90	72	50
Keshopur2	90	85	130	115	160	133		48	64	80	60

	Nov-22	Oct-22	Sep-22	Aug-22	Jul-22	Jun-22	May-22	Apr-22	Mar-22	Feb-22	Dec-21
Name of the STP\s	outlet BOD	outlet BOD	outlet BOD	outlet BOD	outlet BOD	outlet BOD	outlet BOD	outlet BOD	outlet BOD	outlet BOD	outlet BOD
Molarband (Mini STP)	20	18	22	20	16	14	12	10	13		18
Coronation Pillar1	16	18	18	12	20	22	34	0	19	17	21
Coronation Pillar2	6	8	4	8	6	14	16	0	0	0	27
Delhi gate New	6	6	5	6	6	4	6	8	6	8	5
Delhi Gate Old	15	6	4	6	8	8	8	8	6	8	8
Keshopur STP(New)	12	14	8	8	16	18	26	0	0	14	10
Sen Nursing Home (SNH)	5	8	6	3	6	6	6	7	6	8	5
Nilothi New	8	6	4	5	8	6	4	0	6	8	6
Nilothi	42	46	38	34	38	42	40	0	21	26	28

Name of the STP\s	outlet BOD	outlet BOD	outlet BOD	outlet BOD	outlet BOD	outlet BOD	outlet BOD	outlet BOD	outlet BOD	outlet BOD	outlet BOD
Najafgarh	20	18	22	28	40	38	35	0	25	16	26
Rithala2	14	14	8	8	6	6	6	10	10	7	8
Pappankalan(Old)	22	20	22	26	32	36	40	0	27	24	26
Pappankalan PH- II New	8	6	4	12	6	8	6	0	14	8	6
Rohini	24	22	16	18	12	22	34	24	18	18	14
Narela	30	18	20	22	16	22	58	20	52	10	12
Okhla New	14	14	6	6	8	6	6	8	6	5	5
Kondli 1	8	12	8	10	18	16	14	0	8	9	14
Kondli New	88	42	90	6	68	48	42	48	46	88	38
Kapasahera	6	6	5	24	5	6	6	18	16	8	8
Yamuna Vihar Ph-III	18	18	16	8	18	32	30	0	25	48	24
Chilla	12	6	6	2	4	8	6	12	6	5.5	6
Akshardham	3	4	2	30	2	3	4	0	1	1	2
Mehrauli	26	10	16	20	12	14	12	24	12	11	10
Vasant Kunj1	12	80	10	26	20	18	16	7	14	10	12
Vasantkunj2	5.78	12	18	20	30	16	14	12	12	11	8
Yamuna Vihar	16	10	16	20	12	10	10	0	14	16	12
YamunaVihar2	20	108	18		18	34	36	0	20	10	15
Okhla1	15	14	14	28	18	20	18	12	16	15	17
okhla2	12	4.6	12	20	14	16	26	18	16	14	13
okhla3	14	12	10	18	12	18	-	22	15	18	16
okhla4	16	14	12	12	12	14	12	20	14	14	20
Keshopur	32	30	34	14	10	10	10	-	29	35	40
Keshopur2	34	32	32	28	30	38	35	-	29	30	46

	Nov-21	Oct-21	Sep-21	Aug-21	Jul-21	Jun-21	Mar-21	Feb-21	Jan-21	Dec-20	Nov-20
Name of the STP\s	outlet BOD	outlet BOD	outlet BOD	outlet BOD	outlet BOD	Out let BOD	Out let BOD	outlet BOD	outlet BOD	outlet BOD	outlet BOD
Molarband (Mini STP)	22	13	24	20		16	22	20	12	16	22
Coronation Pillar1	20	22	30	12	36	36	50	25	18	36	50
Coronation Pillar2	72	21	29	8	38	32	40	40	60	32	40
Delhi gate New	6	7	6	6	10	6	6	5	4	6	6
Delhi Gate Old	8	6	8	6	8	5	2	7	4	5	2
Keshopur STP(New)	12	12	20	8	14	6	6	15	2	6	6
Sen Nursing Home (SNH)	8	10	8	3	8	6	4	5	6	6	4
Nilothi New	10	10	10	5	6	4	5	4	5	4	5
Nilothi	25	22	20	34	22	32	0	25	32	32	0
Najafgarh	25	20	24	28	80	36	18	20	16	36	18
Rithala2	8	10	10	8	12	5	6	88	98	26	36
Pappankalan(Old)	26	24	24	26	45	28	28	12	38	5	6
Pappankalan PH- II (New)	12	13	14	12	10	6	6	28	8	28	28
Rohini	11	14	12	18	30	16	10	7	8	6	6
Narela	14	17	16	22	6	16	16	8	13	16	10
Okhla New	7	6	8	6	6	4	2.8	8	6	16	16
Kondli 1	9	14	12	10	24	14	14	6	4	4	2.8
Kondli New	35	30	72	0	42	72	36	19	4	14	14
Kapasahera	10	10	14	6	14	5	6	0	0	0	
Yamuna Vihar Ph-III	28	19	20	24	20	16	18	46	24	72	36

Chilla	10	6	6	8	6	5	7	8	4	5	6
Akshardham	5	6	5	2	2	2.5	2.4	20	25	16	18
Mehrauli	12	14	14	30	10	16	12	5	2	5	7
Vasant Kunj1	14	20	14	20	32	12	18	4.2	4	2.5	2.4
Vasantkunj2	10	16	22	26	28	26	40	10	3.5	16	12
Yamuna Vihar	12	16	19	20	24	18	16	19	20	12	18
Yamunabihar2	18	17	16	20	14	10	22	15	4	26	40
Okhla1	16		27	28	20	14	16	9	3	18	16
okhla2	15	26.4	22	20	22	28	18	28	4	10	22
okhla3	16	21.99	18	18	18		22	14	42	14	16
okhla4	22	18.76	30	12	72	28	20	24	10	28	18
Keshopur	38	32	60	14	58	30	44	26	42	0	22
Keshopur2	40	35		28		38	32	13	22	28	20

	Nov-22	Oct-22	Sep-22	Aug-22	Jul-22	Jun-22	May-22	Apr-22	Mar-22	Feb-22	Dec-21
Name of the STPS	Inlet COD	Inlet COD	Inlet COD	Inlet COD	Inlet COD	Inlet COD	Inlet COD	Inlet COD	Inlet COD	Inlet COD	Inlet COD
Molarband (Mini STP)	248	240	208	280	296	404	416	418	416		368
Coronation Pillar1	240	232	240	300	288	248	224		418	480	512
Coronation Pillar2	296	304	284	284	296	296	304				464
Delhi gate New	208	212	200	180	184	268	272	464	260	80	336
Delhi Gate Old	248	256	260	260	264	272	264	440	224	272	90
Keshopur STP(New)	360	352	208	282	304	348	352			256	272

Sen Nursing Home (SNH)	184	188	180	204	208	248	248	24.4	244	384	320
Nilothi New	208	210	136	292	296	312	320		224	480	304
Nilothi	240	240	236	184	180	192	192		288	480	352
Najafgarh	264	256	192	204	200	204	200		284	400	368
Rithala2	208	208	224	200	208	212	204	240	248	428	400
Pappankalan(Old)	192	186	212	284	280	184	176		144	208	192
Pappankalan PH- II (New)	328	334	212	276	280	312	336		192	288	240
Rohini	344	344	248		248	308	348	480	368	476	448
Narela	184	184	172	184	184	268	284	440	240	320	304
Okhla New	224	216	204	284	288	304	324	432	352	448	336
Kondli 1	296	416	300	284	288	392	416	480	444	480	416
Kondli New	352	296	360	264	264	300	304	560	348	320	368
Kapasahera	168	264	168	284	256	264	252	496	244	336	304
Yamuna Vihar Ph-III	184	288	188	204	280	248	288		340	352	400
Chilla	208	240	204	160	200	248	244	336	232	352	304
Akshardham	176	184	172	252	164	292	300		292	320	256
Mehrauli	240	256	248	248	262	264	256	416	244	352	336
Vasant Kunj1	232	320	236	204	280	304	324	624	320	352	384
Vasantkunj2	21.56	296	240	204	115	268	292	448	288	512	464
Yamuna Vihar	128	272	108	424	208	288	280		276	400	85
Yamunabihar2	196	32.88	196		488	436	440		456	336	384
Okhla1	288	280	276	284	288	240	186	432	184	284	304
Keshopur	216	216	136	296	288	220	216		400	368	432
Keshopur2	216	216	136	296		220	216		400	368	432

	Nov-21	Oct-21	Sep-21	Aug-21	Jul-21	Jun-21	Mar-21	Feb-21	Jan-21	Dec-20	Nov-20
Name of the STPs	Inlet COD	Inlet COD	Inlet COD	Inlet COD	Inlet COD	Inlet COD	Inlet COD	Inlet COD	Inlet COD	Inlet COD	Inlet COD
Molarband (Mini STP)	432	400	560	280		432		488	136	200	640
Coronation Pillar1	496	368	496	300	316	364		280	160	192	296
Coronation Pillar2	464	224	352	284	112	424		560	132	640	380
Delhi gate New	320	246	304	180	308	128	256	236	260	320	96
Delhi Gate Old	352	336	352	260	600	408	512	184	480	412	164
Keshopur STP(New)	336	368	256	282	328	224	176	328	212	364	412
Sen Nursing Home (SNH)	304	288	304	204	320	458	528	472	208	280	240
Nilothi New	288	272	288	292	286	240	352	352	260	320	244
Nilothi	336	320	336	184	320	208	436	384	240	260	
Najafgarh	352	304	288	204	602	228	440	586	268	392	184
Rithala2	416	293	192	200	144	400	384	540	184	340	340
Pappankalan(Old)	176	160	176	284	192	352	480	512	260	460	620
Pappankalan PH-II (New)	224	208	192	276	582	512	576	544	216	380	440
Rohini	528	448	416	0	412	816	800	488	184	360	640
Narela	336	208	192	184	412	632	624	232	360	276	436
Okhla New	352	336	336	284	388	388	368	568	192	360	176
Kondli 1	400	384	416	284	460	416	664	512	192	392	472

Kondli New	352	320	464		564	616	704	592	416	460	412
Kapasahera	320	272	256	264	584	1500	1120	540	260	440	620
Yamuna Vihar Ph-III	416	384	368	284	478	1024	960	560	452	386	640
Chilla	320	336	320	204	318	332	296	448	296	420	144
Akshardham	272	288	336	160	324	388	336	640	48	520	260
Mehrauli	320	240	224	252	360	350	389.33	256	156	240	460
Vasant Kunj1	446	384	400	248	468	800	624	576	272	392	412
Vasantkunj2	512	288	272	204	424	530	448	760	228	360	680
Yamuna Vihar	304	432	464	204	468	800	592	464	344	184	724
Yamunabihar2	416	400	256	424	328	480	704	448	184	172	400
Okhla1	300	488		284		352	384	344	220	280	144
Keshopur	416	432	336	296	376	256		448	160	260	188
Keshopur2	416	432		296		256		608	160	260	188

	Nov-22	Oct-22	Sep-22	Aug-22	Jul-22	Jun-22	May-22	Apr-22	Mar-22	Feb-22	Jan-22
Name of the STPs	Outlet COD	Outlet COD	Outlet COD	Outlet COD	Outlet COD	Outlet COD	Outlet COD	Outlet COD	Outlet COD	Outlet COD	Outlet COD
Molarband (Mini STP)	72	68	60	60	60	56	64	72	68		80
Coronation Pillar1	76	72	44	38	42	48	80		86	96	80
`Coronation Pillar2	40	36	32	28	32	48	40				96
Delhi gate New	36	32	36	44	48	44	48	32	40	6	32
Delhi Gate Old	32	28	28	48	40	44	48	48	38	42.6	6
Keshopur STP(New)	64	32	24	32	56	64	68			48	37.3
Sen Nursing Home (SNH)	24	24	20	24	32	32	32	40	26	48	32

Nilothi New	32	32	24	20	20	20	16		37.4	48	36
Nilothi	152	154	138	96	96	132	136		74.5	80	96
Najafgarh	56	52	84	78	92	108	112		64	88	96
Rithala2	48	44	40	36	44	48	42	53.3	46	48	36
Pappankalan(Old)	64	68	52	40	96	96	104	0	69.3	96	85.3
Pappankalan PHII(n)	36	38	20	32	36	40	48	0	32	48	32
Rohini	76	72	48	68	52	68	72	78	74.6	68	58.6
Narela	72	40	56	52	56	80	132	84	126	38	58.6
Okhla New	40	36	32	40	40	48	44	48	48	36	37.3
Kondli 1	28	48	28	44	48	40	44		64	42	64
Kondli2	34	40	24								
Kondli New	208	132	208	48	148	136	132	208	144	244	16
Kapasahera	20	38	16	92	44	48	44	42.6	58	48	32
Yamuna Vihar PhIII	76	48	72	24	48	96	108		84	144	88
Chilla	36	44	20	18	24	48	48	48	48	21.3	32
Akshardham	16	12	12	64	28	32	28		18	24	26.6
Mehrauli	68	64	52	62	60	64	68	80	64	32	48
Vasant Kunj1	40	48	36	64	44	40	32	40	28	28	69.33
Vasantkunj2	0	48	60	32	18	48	44	56	48	96	64
Yamuna Vihar	52	36	56	60	36	36	40		21.4	32	14
Yamunabihar2	56	286	52		92	100	104		72	64	74.6
Okhla1	52	48	44	52	50	48	44	64	48	84	80
okhla2	28	25.34	32	32	36	32	14	96	26.6	72	69.4
okhla3	44	40	44	56	60	64		104	78	96	85.3
okhla4	48	44	40	60	64	68	64	96	68	92	96
Keshopur	88	80	92	36	32	36	32		90.6	116	152
Keshopur2	84	84	88	52	80	84	88		122.6	96	136

Name of the STPs	Dec-21	Nov-21	Oct-21	Sep-21	Aug-21	Jul-21	Jun-21	Mar-21	Feb-21	Jan-21	Dec-20	Nov-20
	Outlet COD	Outlet COD	Outlet COD	Outlet COD	Outlet COD	Outlet COD	Outlet COD	Outlet COD	Outlet COD	Outlet COD	Outlet COD	Outlet COD
Molarband (Mini STP)	76	80	80	60	0	144	-	108	80	64	76	76
Coronation Pillar1	72	56	96	38	96	198	-	76	92	108	164	164
Coronation Pillar2	90	80	72	28	126	268	-	132	128	108	136	136
Delhi gate New	40	32	32	44	44	36	32	26	28	32	28	28
Delhi Gate Old	40	32	40	48	40	44	40	16	24	20	12	12
Keshopur STP(New)	69	62	76	32	56	44	32	72	32	32	24	24
Sen Nursing Home (SNH)	48	38	40	24	40	32	36	28	24	32	16	16
Nilothi New	42	40	48	20	36	32	48	28	24	20	28	28
Nilothi	80	80	88	96	108	80	240	136	80	120		
Najafgarh	84	56	96	78	181	148	104	92	32	132	56	56
Rithala2	40	44	40	36	48	36	48	92	96	32	24	24
Pappankalan(Old)	80	88	104	80	138	152	132	148	28	92	72	72
Pappankalan PH-II (New)	42	40	44	32	42	48	36	34	32	30	28	28
Rohini	64	56	64	68	106	48	40	48	88	56	36	36
Narela	64	60	48	52	38	36	40	40	30	64	64	64
Okhla New	48	42	48	40	44	38	30	28	64	24	16	16

Kondli 1	64	60	84	44	70	72	52	82	64	64	56	56
Kondli2												
Kondli New	124	98	248	0	204	107	284	196	108	220	96	96
Kapasahera	40	48	56	48	58	40	48	60	22	20	36	36
Yamuna Vihar Ph-III	96	85	80	92	92	68	68	68	76	72	84	84
Chilla	40	42	48	24	36	38	28	24	36	28	28	28
Akshardham	32	32	36	18	18	16	12	16	16	20	16	16
Mehrauli	64	56	80	64	54	58	56	40	24	60	48	48
Vasant Kunj1	64	69	40	62	74	76	60	76	64	56	60	60
Vasantkunj2	80	72	48	64	88	70	56	80	40	84	120	120
Yamuna Vihar	64	69	64	32	82	62	52	64	36	60	68	68
Yamunabihar2	80	74	72	60	62	96	76	82	24	32	96	96
Okhla1	80		96	52	102	68	72	68	104	56	64	64
okhla2	68	28.33	80	32	108	120	76	96	48	108	68	68
okhla3	74	80.61	64	56	68	96	84	108	184		76	76
okhla4	84	67	96	60	206	98	106	72	56	96	76	76
Keshopur	140	96	115	36	172	176		96	76	84	136	136
Keshopur2	122	120		52		165		60	183.02	108	108	108

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2	B.E. (Civil Engineering)	1st	Bangladesh University of Engineering and Technology, Dhaka	1991-1992
3	Higher Secondary (12th)	1st	Comilla Board, Bangladesh	1988
4	Secondary (10th)	1st	Comilla Board, Bangladesh	1986

MASTER'S OF ENGINEERING THESIS TITLE :

Removal of Arsenic from Ground Water by Ferric Chloride, Department of Civil Engineering, Bangladesh University of Engineering and Technology, Dhaka, 1000 (available in BUET online library)

BACHELOR OF ENGINEERING THESIS TITLE :

Water Quality Assessment of River Buriganga, Dhaka

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