WATER QUALITY MODELING FRAMEWORK FOR RIVER HEALTH

A Thesis submitted to Gujarat Technological University
for the Award of

Doctor of Philosophy

in

Environment Engineering

by

Darji Jalpaben Shashikant
Enrollment No. 199999916501

under supervision of

Dr. Pradeepkumar P. Lodha,
GEC Bharuch

GUJARAT TECHNOLOGICAL UNIVERSITY

AHMEDABAD

August - 2026

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ABSTRACT

Water quality modeling estimates the river's carrying capacity, which is essential for determining its pollution load. This is the key step in assessing and maintaining the river’s health. It involves identifying significant variables that influence spatial and temporal variations in the water quality. The water quality of the Sabarmati River is substantially influenced by various anthropogenic sources. This study provides a framework for preserving the health of the Sabarmati River by examining 17 water quality parameters across 11 monitoring sites (upstream US-1 to US-4, middle stream MS-1 to MS-3 and downstream DS-1 to DS-4). The study demonstrates the application of multivariate statistical analysis methods and a water quality model to estimate and maintain the river’s water quality for the specified purpose.

Multivariate statistical analysis helps identify significant water quality variables and determine pollution sources. The box-whisker plots illustrated the spatial and temporal variations in water quality. Pre-monsoon and winter seasons were found to be critical due to higher chemical loads. The plots revealed that water quality deteriorates with increasing distance downstream. It showed the highest chemical pollution in the downstream stretch, largely due to wastewater discharges. Cluster analysis (CA) categorized the sites into three groups: sites US-1 to US-4 and MS-1 as less polluted (LP) sites with minimal anthropogenic impact, sites MS-2, MS-3, and DS-1 as moderately polluted (MP) sites affected primarily by recreational and anthropogenic activities, and Sites DS-2 to DS-4 as highly polluted (HP) sites facing pollution from various discharges. Principal component analysis (PCA) / factor analysis (FA) highlights the significance of water quality parameters across spatially distinguished sites. TDS, Cl, COD, DO, sulphate, and nitrate were significant for all sites, indicating the influence of runoff and anthropogenic activities. Sample temperature predominated at LP and MP sites, while pH and NH_3-N were more prevalent at MP and HP sites, underscoring the sources of contamination at the respective locations. The higher levels of chemical pollution at HP sites indicate wastewater discharges.

QUAL2Kw proved effective in determining river’s carrying capacity and establishing water quality management scenarios. The model was applied to the individual stretch for six identified water quality parameters: inorganic suspended solids (ISS), dissolved oxygen

(DO), CBOD slow (CBODs), CBOD fast (CBODf), ammonia N (NH_3-N), and pH. The sensitivity analysis, conducted through upstream stretch water quality simulation, revealed that the model is sensitive to headwater flow, hydrolysis rate for CBODs, oxidation rate for CBODf, and depth coefficient. The water quality simulated for the middle and downstream stretches for the critical period of winter and pre-monsoon seasons depicted the self-purification capacity and water quality management scenarios. The simulation results showed that a minimum flow of 10 m^3/s during winter and 13.11 m^3/s during pre-monsoon is required to maintain the water quality of the middle stream stretch for outdoor bathing water quality Class B with the existing pollution load. It can be improved further by reducing the existing pollution load by 20% or by increasing river inflow by 50% (29.85 m^3/s for winter and 28.10 m^3/s for pre-monsoon). Downstream stretch water quality simulations revealed that with a river inflow of 235.93 m^3/s and a 50% reduction in the current pollution load, the discharge standard requirement can be met. The subsequent simulation showed that a DO of 4.0 mg/L can be maintained by reducing the existing wastewater flow and pollution load by 50% with a river inflow of 377.50 m^3/s during winter and 353.90 m^3/s during summer.

The study finds that utilizing multivariate statistical analysis techniques along with QUAL2Kw for water quality modeling has been highly effective in assessing and maintaining the health of the river. The methods, ANOVA, box-whisker plots, CA and PCA analysis, clearly demonstrate water quality variations and depict variables that significantly affect water quality. Water quality simulations by QUAL2Kw provide the best management scenarios to maintain assimilative capacity and pristine river sources. The study provides a robust framework that can be applied to other studies for restoring and maintaining river health.

Acknowledgement and / or Dedication

I, hereby, wish to express my heartfelt gratitude to everyone who directly or indirectly supported me in completing my PhD. It requires a lot of dedication and ongoing effort, from the research proposal to the final thesis, which wouldn't be possible without support from different perspectives.

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Table of Contents

Declaration i
Certificate ii
Course-work Completion Certificate iii
Originality Report Certificate iv
Copy of Originality Report v
Ph.D. Thesis Non-Exclusive License vii
Thesis Approval Form ix
Abstract x
Acknowledgement and / or Dedication xii
Table of Contents xiii
List of Abbreviations xvi
List of Figures xviii
List of Tables xix
List of Appendices xxi
CHAPTER 1 1
INTRODUCTION 1
1.1 Background 1
1.2 Importance of River Water Quality Assessment 1
1.3 Statistical Analysis of Water Quality Data 2
1.4 Why to Measure River Health? 2
1.4.1 Self-Purification Capacity of a River 2
1.4.2 Water Quality Modeling: 4
1.5 Definition of the Problem 4
1.6 Objectives of the Study 5
1.7 Scope of the Work 5
1.8 Significance of the Study 6
1.9 Methodology 6
CHAPTER 2 8
LITERATURE REVIEW 8
2.1 Multivariate Statistical Techniques 8
2.1.1 ANOVA 8

2.1.2 Cluster Analysis: 9
2.1.3 Principal Component Analysis (PCA)/ Factor Analysis (FA) 10
2.2 Water Quality Models 11
2.2.1 Model Selection Criteria 12
2.2.2 Classifications of Water Quality Models 13
2.3 Model Review 15
2.3.1 QUAL2Kw/Q2K 15
2.3.2 WASP 18
2.3.3 SWAT 21
2.3.4 SIMCAT: 23
2.3.5 MIKE-11: 26
2.3.6 CE-QUAL-W2 28
2.4 Comparison of Water Quality Models and Model Selected for the Study 30
2.4.1 Model Summary: 34
2.4.2 A Model Selected for the Study: 34
CHAPTER 3 36
STUDY AREA AND METHODOLOGY 36
3.1 Study Area 36
3.1.1 About the Sabarmati River 36
3.1.2 Stretches of the River Considered for the Study 39
3.2 Materials and Methods 42
3.2.1 Multivariate statistical analysis 44
3.2.2 Water Quality Modeling by QUAL2Kw 45
3.2.3 Framework for River Health 45
CHAPTER 4 48
MULTIVARIATE STATISTICAL ANALYSIS, RESULTS AND DISCUSSIONS 48
4.1 Data Collection and Preparation: 48
4.2 Data Analysis and Interpretation 52
4.2.1 Box and Whisker Plots 52
4.2.2 ANOVA Analysis 56
4.2.3 Cluster Analysis 56
4.2.4 Principal Component Analysis (PCA) / Factor Analysis (FA) 57
CHAPTER 5 62
QUAL2KW MODELING, RESULTS AND DISCUSSIONS 62

5.1 Input Data Requirements and Data Source 62
5.1.1 Water Quality Data 62
5.1.2 Meteorological Data 63
5.1.3 Reach Data 63
5.1.4 Headwater Data 64
5.1.5 Hydraulic Data 64
5.1.6 Light and Heat Rate Parameters 65
5.2 Model Calibration 66
5.3 Model Validation 67
5.4 Model Application 67
5.5 Upstream Stretch Simulation Run 68
5.5.1 Data Input to the Model 69
5.5.2 Warming up the Model 73
5.5.3 Calibration and Validation of the Model 74
5.5.4 Sensitivity Analysis 76
TABLE 5.13 A summary of the sensitivity analysis of the model 80
5.6 Middle Stream Stretch Simulation Run Output 80
5.6.1 Data Input to the Model 80
5.6.2 Calibration and Validation 86
5.6.3 Scenario Analysis 90
5.7 Downstream Stretch Simulation Run 93
5.7.1 Data Input to the Model 93
5.7.2 Calibration and Validation 98
5.7.3 Scenario Analysis 102
CHAPTER 6 110
CONCLUSIONS AND RECOMMENDATIONS 110
6.1 Conclusions 110
6.2 Major Findings 115
6.3 Recommendations 116
6.4 Limitations of the Study 118
6.5 Future Scope 119
List of References **120**
Appendices **137**
List of Publications **159**

List of Abbreviations

ANNs	:	Artificial Neural Networks
ANOVA	:	Analysis of Variance
APHA	:	American Public Health Association
BIS	:	Bureau of Indian Standards
BOD	:	Biological Oxygen Demand
CA	:	Cluster analysis
CBOD	:	Carbonaceous Biochemical Oxygen Demand
CBODf	:	Carbonaceous Biochemical Oxygen Demand fast
CBODs	:	Carbonaceous Biochemical Oxygen Demand slow
CE-QUAL-W2	:	Corps of Engineers-Quality-Width Averaged
CETP	:	Common Effluent Treatment Plant
COD	:	Chemical Oxygen Demand
CPCB	:	Central Pollution Control Board
cSAC	:	candidate Special Areas of Conservation
CSTRs	:	Continually Stirred Tank Reactors
CWC	:	Central Water Commission
DA	:	Discriminant Analysis
DO	:	Dissolved Oxygen
DS	:	Downstream
EC	:	Electrical Conductivity
EPA	:	Environmental Protection Agency
FA	:	Factor Analysis
GA	:	Genetic Algorithm
GEMI	:	Gujarat Environment Management Institute
GPCB	:	Gujarat Pollution Control Board
HEC-RAS	:	Hydrologic Engineering Center-River Analysis System
HP	:	Highly Polluted
HRU	:	Hydrologic Response Unit
IMD	:	Indian Meteorological Department
IOA	:	Index of Agreement
IQR	:	Interquartile Range
ISS	:	Inorganic Suspended Solids
IWMM	:	Integrated Watershed Management Model
KMO	:	Kaiser–Meyer–Olkin
LARM	:	Laterally Averaged Reservoir Model
Las	:	Nonpoint Source Loads
LP	:	Less Polluted
MANOVA	:	Multivariate Analysis of Variance
MBE	:	Mean Bias Error
MOS	:	Margin of Safety
MP	:	Moderately Polluted
MS	:	Middle stream

MSL	:	Mean Sea Level
NABL	:	National Accreditation Board for Testing & Calibration Laboratories
NH_3N	:	Ammonia Nitrogen
NH_4N	:	Ammonium Nitrogen
NO_3N	:	Nitrate Nitrogen
NPS	:	Non-Point Source
ON	:	Organic Nitrogen
PBIAS	:	Percent Bias
PCA	:	Principal Component Analysis
PCBs	:	Polychlorinated Biphenyls
PCs	:	Principal Components
PoMs	:	Programmes of Measures
QCI	:	Quality Council of India
RMSE	:	Root Mean Square Error
ScoRE	:	Scope-Record-Experience
SDBE	:	Standard Deviation Bias Error
SIMCAT	:	Simulation of Catchment
SOD	:	Sediment Oxygen Demand
SSNNL	:	Sardar Sarovar Narmada Nigam Limited
STP	:	Sewage Treatment Plant
SWAT	:	Soil Water and Analysis Tools
TA	:	Total Alkalinity
TDS	:	Total Dissolved Solids
TH	:	Total Hardness
TMDLs	:	Total Maximum Daily Loads
TS	:	Total Solids
TSS	:	Total Suspended Solids
UK	:	United Kingdom
US	:	Upstream
USACE	:	US Army Corps of Engineers
USDA - ARS	:	United States Department of Agriculture, Agricultural Research Service
USEPA	:	United States Environmental Protection Agency
VBA	:	Visual Basic Applications
VFs	:	Varifactors
WASP	:	Water Quality Analysis Simulation Program model
WFD	:	Water Framework Directive
WLAs	:	Point Source Loads
WQM	:	Water Quality Model

List of Figures

FIGURE 1.1 DO sag curve 3
FIGURE 1.2 Methodology adopted for the research study 7
FIGURE 2.1 Model selection criteria 13
FIGURE 2.2 Classification of water quality models 14
FIGURE 3.1 Sabarmati River map 38
FIGURE 3.2 Locations of Sabarmati River considered for the study area 40
FIGURE 3.3 Line diagram of Sabarmati river showing selected stretches, monitoring locations, inflows and point sources 41
FIGURE 3.4 Methodology adopted for the data analysis and interpretation 43
FIGURE 3.5 Proposed water quality modelling framework for the river health 47
FIGURE 4.1 Box-whisker plots showing seasonal and temporal variations 54
FIGURE 4.2 Dendrogram based on hierarchical cluster analysis 57
FIGURE 5.1 Application of QUAL2Kw model and grouping of data for model input 68
FIGURE 5.2 Model run for Upstream stretch for Monsoon 2012-2013 (warming up without calibration) 73
FIGURE 5.3 Model output for the middle stream stretch (winter season) 75
FIGURE 5.4 Percentage change in ISS and DO obtained by sensitivity analysis 77
FIGURE 5.5 Percentage change in CBODs and CBODf obtained by sensitivity analysis 78
FIGURE 5.6 Percentage change in NH_3-N and pH obtained by sensitivity analysis 79
FIGURE 5.7 Model output for the middle stream stretch (winter season) 88
FIGURE 5.8 Model output for the middle stream stretch (pre-monsoon season) 89
FIGURE 5.9 Model output for downstream stretch (winter season) 100
FIGURE 5.10 Model output for downstream stretch (pre-monsoon season) 101

List of Tables

TABLE 2.1 Summary of selected water quality models..31
TABLE 3.1 Details of the stretches considered for the study..42
TABLE 3.2 Details of the locations..42
TABLE 4.1 Statistical interpretation of data..50
TABLE 4.2 Independent-Samples Kruskal-Wallis Test (p-value) Summary 56
TABLE 4.3 Load factor matrix for LP sites...60
TABLE 4.4 Load factor matrix for MP sites 60
TABLE 4.5 Load factor matrix for HP sites 60
TABLE 4.6 Significant water quality parameters for spatially distinguished sites 61
TABLE 5.1 Water quality parameters selected for model input 63
TABLE 5.2 Light and Heat parameters 65
TABLE 5.3 Global rate parameters and the auto calibration of the model..........................66
TABLE 5.4 Location Details for Upstream stretch 69
TABLE 5.5 Reach Data - Upstream stretch...69
TABLE 5.6 Head water (HW) data (Monsoon season) for the Upstream stretch 70
TABLE 5.7 Hydraulic data for the Upstream stretch for the Monsoon season 70
TABLE 5.8 Water Quality data for the upstream stretch...71
TABLE 5.9 Meteorological data for upstream stretch (Monsoon season) 72
TABLE 5.10 Solar radiation data for the upstream stretch (Monsoon season) 72
TABLE 5.11 Model fitness and RMSE values for the Upstream stretch (without calibration) 74
TABLE 5.12 Model fitness and RMSE value for upstream stretch (monsoon) 75
TABLE 5.13 A summary of the sensitivity analysis of the model.......................................80
TABLE 5.14 Location details for middle stream stretch 80
TABLE 5.15 Reach Data – Middle stream stretch 81
TABLE 5.16 Headwater (HW) data for the middle stream stretch......................................82
TABLE 5.17 Water level data for the Middle stream stretch...82
TABLE 5.18 Hydraulic data for the middle stream stretch 83
TABLE 5.19 Water quality data for the middle stream stretch..84
TABLE 5.20 Meteorological data for the middle stream stretch...84
TABLE 5.21 Solar radiation data for the Middle stream stretch 85
TABLE 5.22 Pollution load data for the middle stream stretch...86

TABLE 5.23 Model fitness and RMSE values for the middle stream stretch (winter season) 88
TABLE 5.24 Model fitness and RMSE values for the middle stream stretch (Pre-monsoon season) 89
TABLE 5.25 Designated best use water quality criteria 90
TABLE 5.26 Scenario analysis for the middle stream stretch (winter season) 91
TABLE 5.27 Scenario analysis for the middle stream stretch (Pre-monsoon season) 93
TABLE 5.28 Location Details for the downstream stretch 93
TABLE 5.29 Reach Data – downstream stretch 94
TABLE 5.30 Hydraulic data for the downstream stretch 96
TABLE 5.31 Water Quality data for the downstream stretch 96
TABLE 5.32 Pollution load data for the downstream stretch 97
TABLE 5.33 Model fitness and RMSE values for the downstream stretch (winter season) 100
TABLE 5.34 Model fitness and RMSE values for the downstream stretch (pre-monsoon season) 101
TABLE 5.35 General standards for the discharge of effluent into inland surface water ... 102
TABLE 5.36 Scenario analysis for downstream stretch (winter season) 106
TABLE 5.37 Scenario analysis for downstream stretch (pre-monsoon season) 108

List of Appendices

APPENDIX A: Sample water quality data 137
APPENDIX B: Sample meteorological data 141
APPENDIX C: Sample data of river alignment and profile 144
APPENDIX D: Sample data of Dharoi Dam discharge into the river 147
APPENDIX E Sample data of Water level referenced from Derol water gauge station of CWC 148
APPENDIX F : Sample data of the Sabarmati Escape water release (For the year 2016-2017) 153
APPENDIX G: Sample data of water level referenced from hourly water level data (in m) of the Subhas Bridge station of CWC 154
APPENDIX H : Sample data of water discharge from Vasna Barrage 156

CHAPTER 1

Introduction

1.1 Background

The water quality of the river system is a matter of global concern. It is largely influenced by climatic conditions and anthropogenic activities in the catchment area. Rivers are dynamic and hence vulnerable to pollution. They play an important role in transporting municipal and industrial wastewater discharges [1, 2]. The river's water quality is seriously affected by escalating urbanization and industrialization. The discharge of large volumes of wastewater and inadequate infrastructure threaten river health [3, 4]. Declining river water resources and increasing river water pollution are serious issues in many states of India. As a result, many challenges have been encountered in managing river water sources [5].

1.2 Importance of River Water Quality Assessment

Periodic checks on the water quality of the rivers are a prerequisite for the conservation of pristine riverine sources. River water quality assessment provides key information on pollution sources and contributing parameters of pollutants discharged into river water bodies [6, 7].

Water quality monitoring is the foremost step in water resource management. Periodic monitoring of river water quality assesses its condition and provides reliable information on spatial and temporal variations [8]. It serves as a tool to evaluate remedial measures required for the abatement of pollution and conservation of river sources. The data from water quality monitoring serves as the basis of water quality management. It is used to estimate the transport and fate of pollutants for assessing their long-term impacts [9]. The data can also be utilized for predicting future impacts and taking measures required for the restoration and improvement of water quality [10].

1.3 Statistical Analysis of Water Quality Data

Data generated from the river water quality monitoring is quite complex and multidimensional. These data need to be analyzed and interpreted to identify the dominant variables that most clearly define water quality. These variables are best expressed by multivariate statistical methods, also termed chemometric methods [11–13]. Various multivariate statistical analysis techniques, such as cluster analysis (CA), principal component analysis (PCA), factor analysis (FA), discriminant analysis (DA) and analysis of variance (ANOVA), are used to assess spatial and temporal water quality variations [14–19].

1.4 Why to Measure River Health?

Rivers play an important role in assimilating pollution loads due to their dynamic nature and self-purification capacity [20], also termed assimilative capacity. However, the self-purification process allows the river or stream to handle these discharges to a certain extent, reflecting its assimilative capacity. Beyond this, if the pollution load increases, it continues to consume dissolved oxygen to the extent that it leads to an anoxic condition of the receiving water body. This seriously affects the river ecosystem and its existence [21, 22].

1.4.1 Self-Purification Capacity of a River

Self-purification is the natural process by which river water quality recovers to its background state after travelling a certain distance. It is important for the entire ecosystem. It involves different mechanisms, including various physical, chemical, and biological reactions. Physical processes include dilution, sedimentation, adsorption, and volatilization. The self-purification capacity of different rivers depends on river characteristics such as velocity of flow, temperature, depth of flow, and the pollution load discharged into the river [23–25]. The absorption and dissolution of atmospheric oxygen (DO) are key processes in the self-purification, enabling a river to replenish dissolved oxygen. DO is required for microbial respiration and for the growth of bacteria that degrade organic pollutants. Hence, it is a key indicator of the extent of pollution and the level of self-purification of river water [26].

The Streeter–Phelps equation, also known as the DO sag equation, describes how DO decreases in a river or stream due to the degradation of biological oxygen demand (BOD) at a certain distance. This equation is used as a fundamental in water quality modeling tools. The equation states that the total change in oxygen deficit (D) is the difference between the deoxygenation and reaeration rates at any time. Streeter and Phelps derived a first-order reaction equation for DO progress in a river, shown in **Equation (1.1)**. It is also represented schematically as the DO sag curve and is shown in **Figure 1.1**.

$$U\frac{dC}{dx} = -k_d B + k_a (C_s - C) \tag{1.1}$$

Where,

x=distance, U =advection velocity in x direction, C = DO concentration, B = BOD concentration, Cs = saturated DO concentration, kd = deoxygenation rate constant of BOD, and ka = first-order reaeration rate constant of DO

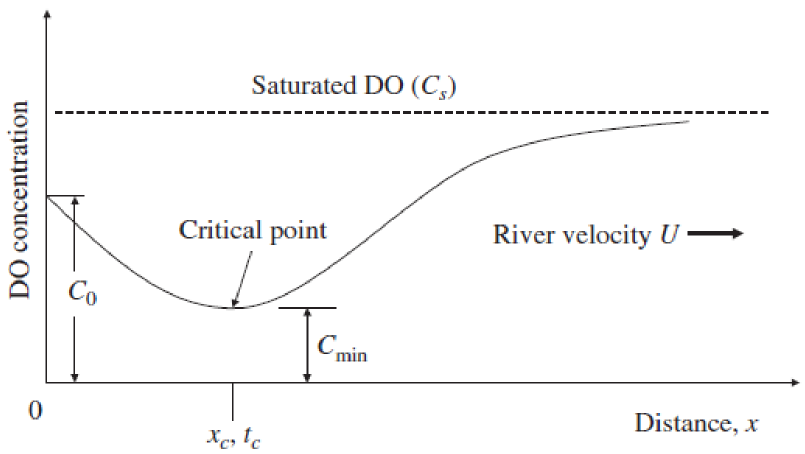


FIGURE 1.1 DO sag curve

DO sag curve describes how DO depletion occurs when the organic load is discharged into the river. At the critical distance xc, DO concentration decreases to a minimum Cmin, which is the critical location where oxidation and reaeration rates become equal, after which DO starts increasing due to reaeration [27].

Many studies utilized the Streeter-Phelps method to determine the pollution load and self-purification capacity of rivers [25, 28, 29].

Complex water quality data can be resolved with DO-BOD modeling effectively. It identifies the extent of dispersion of pollution and serves as a decision-making tool for its abatement

[30–33]. Pollutant loads of fresh water depend on various anthropogenic activities, microbiological reactions, the geo-hydrological background, etc. [34]. The sustainability of different rivers to carry pollution load depends on various temporal and local factors, as well as the type and intensity of the pollutants discharged into the rivers. Various mathematical models are used to define the correlation between pollution load and water quality [35].

EPA has defined a method for determining the assimilative capacity of surface water by total maximum daily loads (TMDLs). The method determines the maximum allowable pollutant load in water bodies. It includes the summation of pollutant loads from point and nonpoint sources, with the accountability of seasonal variation as a margin of safety, as shown in **Equation (1.2)** [36, 37].

$$TMDL = \Sigma WLAs + \Sigma LAs + MOS \tag{1.2}$$

WLAs - point source loads

LAs - nonpoint source loads

MOS - margin of safety

1.4.2 Water Quality Modeling:

Because of continuous development and the need to analyze specific water quality problems more scientifically, many water quality models (WQMs) have been developed. A wide variety of WQMs are now available. However, in all such models, the basis is the assimilative capacity of the river system, which depends on the pollution load and the self-cleansing velocity of the river [38, 39]. The model application requires a thorough understanding of the process, water quality variables, and parameters that influence water quality significantly. The choice of an appropriate model depends on the type and magnitude of the data set, model input requirements, complexity, and limitations. To select a model for a particular water quality problem, it is required to evaluate all existing WQMs [40].

1.5 Definition of the Problem

The Sabarmati River is one of the major rivers of Gujarat. It serves as the lifeline of Ahmedabad city. Different stretches of the Sabarmati River have been utilised for various purposes, substantially affecting water quality. There are very few studies that describe the spatio-temporal variations of the Sabarmati River. Previous research has characterized water quality at limited locations within the city area boundary over specific periods. For instance, the water quality status and classification have been reported, and the spatial variations in phytoplankton diversity have been estimated at only three sites along the river [41–44]. Therefore, this research study was proposed to determine the spatial and temporal variations in the water quality of the Sabarmati River at various locations. This study aimed to identify the most important parameters for establishing pollution mitigation strategies or improving water quality. The study also involves water quality modeling of different river stretches to examine the pollution load and self-purification capacity. This research work provides a basis to ascertain the river's water quality for its intended use. It assists in restoring and maintaining the pristine nature of the water body.

1.6 Objectives of the Study

- To study the Sabarmati River and locate critical stretches for the research.
- Analysis of significant parameters of water quality from collected data sets.
- Modeling of water quality at critical stretches with hypothetical futuristic scenarios.

1.7 Scope of the Work

The research includes a preliminary survey and study of the entire Sabarmati River to identify critical stretches. This requires extensive data collection on river inflow, water quality at various locations, river alignment and hydraulic profile, meteorological data, and pollution sources. The collected data were analyzed statistically using various multivariate methods to identify parameters that significantly affect water quality variations. The selected locations were categorised based on pollution load and similarities among sites. The statistical analysis revealed the critical stretches of the river, which were then subject to water quality simulation. The scope further includes a detailed review of various water quality models and their comparison to select the most suitable model for the study. The selected model was applied for water quality modeling of the identified stretches to determine the carrying capacity of the river and to develop various water quality management scenarios to meet the final objective.

1.8 Significance of the Study

The research study presents spatial and temporal water quality variations of the Sabarmati River for different stretches over 10 years of data. The methods of data treatment and statistical analysis help researchers identify the significant parameters and pollution sources. The thesis provides a comprehensive review of widely used water quality models, facilitating the selection of the most suitable model to meet the study's objectives. It clearly outlines the application of the selected QUAL2Kw model. The requirements for input data, as well as the calibration and validation procedures, sensitivity analysis, scenario analysis, and model outputs, are thoroughly described, providing a clear understanding of the model. The water quality simulations and scenario analysis of critical sections of the Sabarmati River illustrate pollution load capacity. It identifies various scenarios for water quality management for their intended use. Finally, the proposed framework for river water quality can be utilized as a basis and replicated in similar research studies to maintain the river’s health.

1.9 Methodology

The methodology was designed to systematically plan and execute the research work to fulfil defined objectives. **Figure 1.2** shows the methodology of the research study. Before planning the research work, an extensive literature review was conducted to understand existing theories and concepts. Various publications and findings from similar studies were referenced to identify the research gaps and to frame the objectives of the proposed study. Preliminary data and background information about the Sabarmati River were studied in detail to select the study area for the proposed research. The comprehensive literature review helps in selecting the study area, materials, and methods. On finalizing methods, relevant data were collected over 10 years. Various departments were contacted to gather data on water quality, river alignment and profile, water inflow, hydraulic and meteorological data. The collected data were compiled, sorted and treated to standardize and remove outliers. The standardized data were analyzed statistically using SPSS software. To meet the final research objective, existing water quality models, their requirements and applications from various research were thoroughly studied. Based on the comparison of numerous water quality models, collected data and objectives, an appropriate water quality model was selected. The selected model was then applied to different stretches to simulate water quality and develop various scenarios for maintaining self-purification capacity and health of the river.

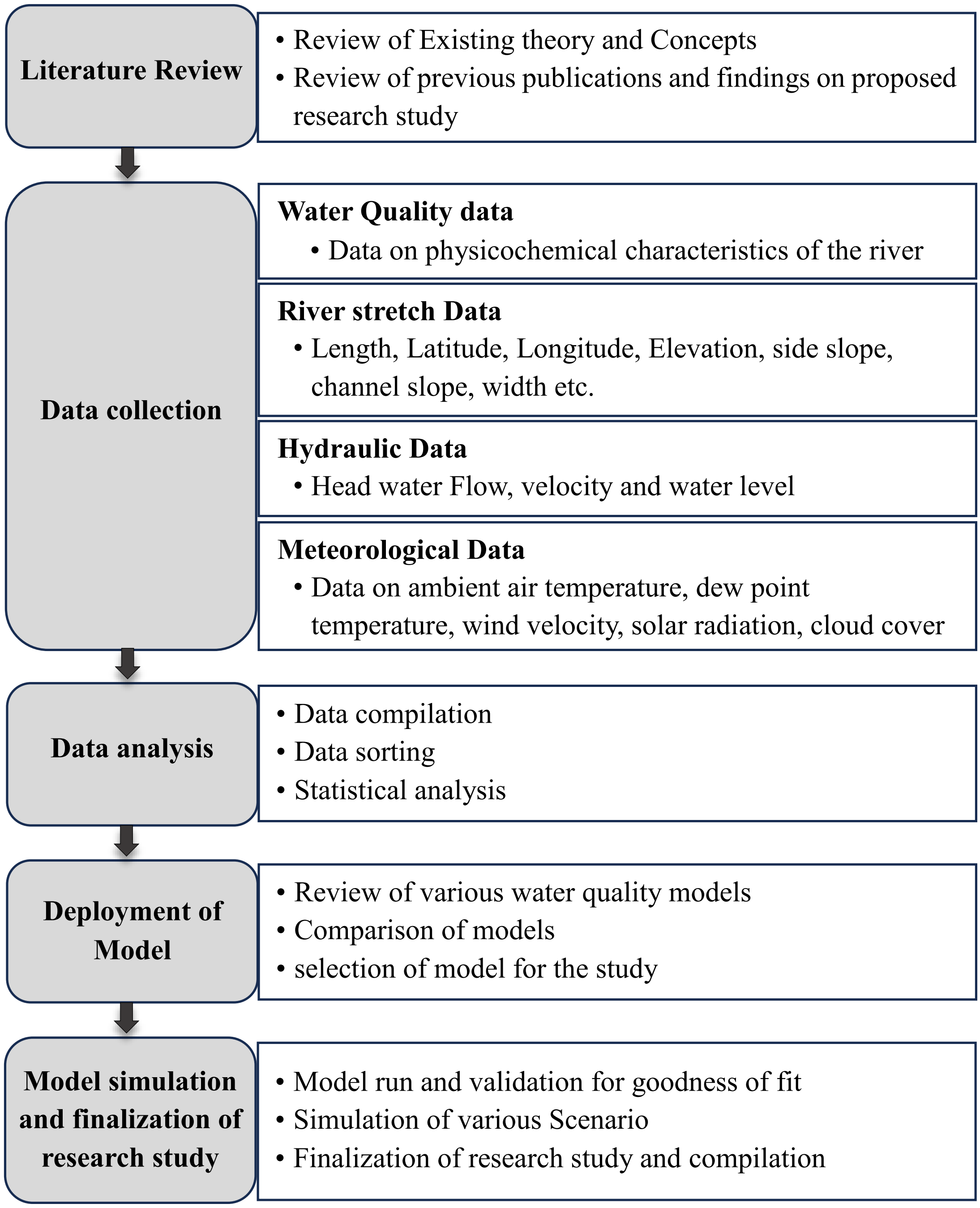


FIGURE 1.2 Methodology adopted for the research study

CHAPTER 2

Literature Review

A detailed literature review was conducted to understand various statistical techniques for assessing river water quality and to determine the most significant variables. Different publications, books, and reports were referenced to identify the suitable method for analyzing and interpreting the datasets. A further literature review was conducted to study water quality modeling and existing water quality models. Widely used water quality models were identified from the review and compared to select the most suitable model for simulating the water quality of the Sabarmati River. This section describes the review of identified multivariate statistical techniques and water quality models that help analyze datasets to fulfil the study's objectives.

2.1 Multivariate Statistical Techniques

Multivariate statistical analysis methods, often referred to as chemometrics, evaluate spatial variations among sites and the temporal changes induced by various natural and/or anthropogenic sources [45, 46]. The most common multivariate statistical techniques utilized in water quality studies include cluster analysis (CA), discriminant analysis (DA), principal component analysis (PCA)/factor analysis (FA), and box-whisker plots. These techniques simplify complex datasets and help interpret multiple constituent parameters, enhancing our understanding of water quality. They also serve as valuable tools for the effective management of water sources and the mitigation of pollution issues. Furthermore, many studies have reported multivariate statistical methods such as ANOVA, PCA, DA, FA, and box-whisker plots etc., effective for assessing river water quality [14, 47].

2.1.1 ANOVA

Analysis of variance (ANOVA) is a statistical method used to compare the means of two or more groups by analyzing variance to determine significant differences between them. It assesses the impact of one or more categorical independent variables (factors) on a continuous dependent variable. One-way ANOVA uses a single independent variable and investigates the differences amongst its various groups, whereas two-way ANOVA examines the effect of two independent variables. Multivariate ANOVA (MANOVA) simultaneously examines multiple dependent variables. Using ANOVA, the variables are assumed to be independent and normally distributed within each group, and the variance is homogeneous across groups. ANOVA uses F-test to compare the variance between the means of groups to the variance within each group. The test reveals the significance of the variables. The hypotheses of an analysis of variance (ANOVA) test are the null hypothesis (H0) and the alternative hypothesis (Ha). The null hypothesis suggests no difference between the means of the groups. The alternative hypothesis states that the mean of at least one group is significantly different from the others. The null hypothesis is rejected if $p<0.05$ and differences are considered significant [48, 49].

Non-Parametric One-Way ANOVA (Kruskal-Wallis Test)

The non-parametric Kruskal-Wallis test is used when data do not meet the assumptions of a parametric one-way ANOVA (normality and homogeneity of variance). When the variable of interest is continuous or discrete. It is analogous to one-way ANOVA. It compares the medians of three or more independent groups based on ranked data instead of means. It is used to test the null hypothesis that ‘k’ independent random samples come from identical groups against the alternative hypothesis that the medians of the groups are not equal [50].

2.1.2 Cluster Analysis:

Cluster analysis is a method for grouping variables based on their similarities and differences. A cluster gathers highly correlated variables. The clusters exhibit internal homogeneity (within the clusters) and external heterogeneity (between the clusters). A dendrogram produced by hierarchical cluster analysis illustrates the relationship among the elements in the dataset. A dendrogram is a tree-like diagram representing the hierarchical grouping of data [13].

Ward's method was employed in the study for the hierarchical cluster analysis of water quality data. This method determines similarity based on the squared Euclidean distance. The Euclidean distance was calculated as the difference between the respective analytical values in datasets. The linkage distance (Dlink/Dmax) is normalized by dividing it by the maximum linkage distance (Dmax) observed in the dataset. The linkage distance quantifies the dissimilarity between the data point clusters. This standardization normalizes linkage distances for easier comparison and visualization across various cases [51].

2.1.3 Principal Component Analysis (PCA)/ Factor Analysis (FA)

Principal component analysis (PCA) is a dimensionality reduction technique mainly used in data analysis and machine learning. It transforms correlated variables into a set of linearly uncorrelated variables called principal components (PCs). The method is applied to a standardized dataset. PCA begins by computing the covariance matrix of the standardized data [52]. The covariance matrix captures the relationships between variables and indicates how they interact. If two variables increase together, they have a positive covariance; if one increases while the other decreases, they exhibit a negative covariance; and if they are independent, the covariance is zero.

PCA calculates the eigenvalues and eigenvectors of the covariance matrix. Eigenvalues represent the amount of variance captured by each principal component and eigenvectors define the direction of these components. The eigenvectors (principal components) are sorted in descending order based on their corresponding eigenvalues. This means that the first principal component explains the most variance in the data, the second principal component explains the second most, and so on.

Finally, the original data are transformed into a new coordinate system defined by the principal components. Each observation in the dataset is projected onto these components, creating a new set of uncorrelated (orthogonal) variables. Not all principal components are retained; instead, a subset that captures most of the variance in the data is selected. This results in dimensionality reduction, because the new dataset contains fewer variables than the original dataset while retaining most of the information [17, 53].

Factor analysis further refines the contribution of less significant variables and extracts a new set of variables called varifactors (VFs) by rotating the axes defined by PCA. While principal components represent a linear combination of the observed variables, VFs can represent unobserved, hypothetical, or latent variables.

2.2 Water Quality Models

The concentration of pollutants entering the river system may increase or decrease as it undergoes mass transfer reactions and kinetic processes. Water quality modeling simulates changes in the concentration of pollutants as they travel from one place to another. Water quality modeling is an effective tool for determining the extent of pollution and its long-term impacts and thereby assists the researcher in assessing associated risks. It provides a basis for environmental managers and decision-makers to take remedial measures to prevent and conserve pristine water sources.

Several reviews on water quality models are available. Cox (2003) reviewed of six WQMs, including QUAL2E, TOMCAT, SIMCAT, QUASAR, ISIS, and MIKE-11. The capability of each model to simulate dissolved oxygen in the lowland river was examined [54]. Sharma & Kansal (2013) compared the AQUATOX, BLTM, EPD-RIV1, QUAL2Kw, WASP, and WQRRS models. Each model was described in detail along with the types of errors that occurred during the simulation [55]. Ranjith et al. (2019) reviewed six models available in the public domain and described six models, WASP7, SIMCAT, QUASAR, TOMCAT, QUAL2KW, and QUAL2EU [56]. Kannel et al. (2011) selected the SIMCAT, TOMCAT, QUAL2Kw, QUAL2EU, WASP7, and QUASAR models based on their suitability for simulating the dissolved oxygen content of rivers and streams [57]. Costa et al. (2021) evaluated five models, AQUATOX, CE-QUAL-W2, SPARROW, SWAT, and WASP7, and verified the particularities of each model along with its applications [58]. Ejigu (2021) described an overview of water quality modeling with model classification and selection and highlighted certain water quality models used at the catchment and for water bodies, including BASINs, MIKE, Streeter-Phelps, QUAL, AQUATOX, CE-QUAL-RIV1, CE-QUAL-W2, DUFLOW, HSPF, TELEMAC, WASP, HEC-5Q, and EFDC [59].

The abovementioned models are physical models and describe the chemical mechanism of water systems. These models compute the linear relationship within the variables. The application of these models becomes limited in the case of missing data and varying environments. Data-driven models work on artificial intelligence. Artificial neural networks (ANNs) are capable of describing more complicated nonlinear relationships within variables. These models employ a deep learning approach based on a machine learning algorithm. ANN model system includes three distinct layers: input, hidden, and output layers. The hidden layer comprises interconnected neurons, where the data introduced through the input layer are processed. A neuron describes a non-linear function. The results are displayed in the output layer [60]. Many studies have used ANNs models in predicting water quality [61–65]. The model output strongly depends on the quantity of data. Relatively small data result in poor prediction. In addition, the selection of the algorithm for model calibration is an important step for computing the complicated relationships between the parameters [31].

2.2.1 Model Selection Criteria

A wide range of water quality models is available in the market. The water quality models use different algorithms and mathematical equations. The input data requirements, capabilities, complexity, and limitations vary with models. The selection of the model requires a thorough understanding of the specific conditions and requirements of a river system. Recognizing the existing models and their effectiveness is necessary to get a reliable output for water quality management of a certain river system.

The foremost step in water quality modeling is selecting a model. The application of an appropriate model that matches the study objectives is a challenging task. Therefore, criteria are needed for selecting a model.

The criteria for selecting a water quality model are summarized in **Figure 2.1**. The model should be selected based on the objectives of the study, data availability, characteristics of the river system, characteristics of the model, and literature review. It needs to be selected such that it addresses all the important aspects of that particular river body. The complexity of a problem leads to the complexity in a model. The selection of a very simple model may result in inaccurate and uncertain output, whereas a complex model may introduce too many parameters with increased resource costs. The selected model should be acceptable to decision-makers for managing water quality based on its intended use. Each model has its own capability to simulate particular variables. The availability of water quality data for the input variables is important for the selection of the model. The model’s flexibility to update and incorporate more variables for future requirements should be considered. A comprehensive model that can simulate present and future needs is more cost effective [40].

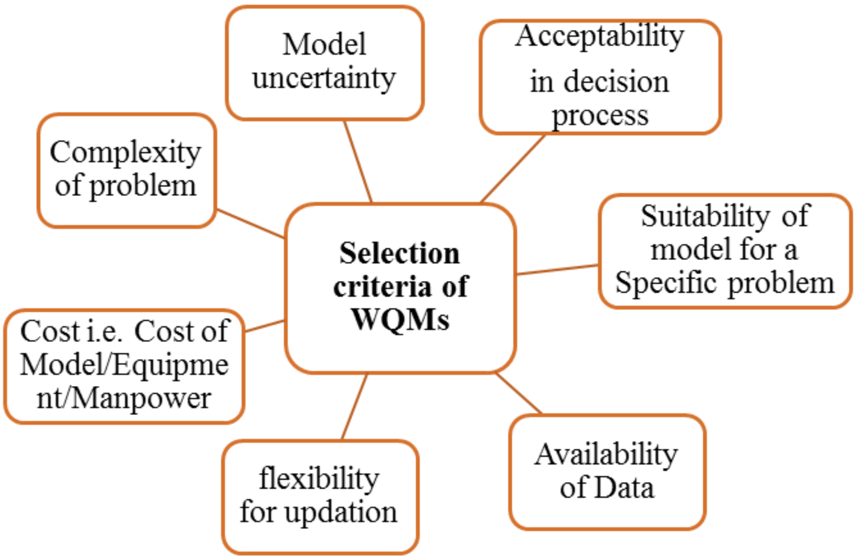


FIGURE 2.1 Model selection criteria

The model should be evaluated based on the defined criteria. The Scope-Record-Experience (ScoRE) method can be used to select a model in which a set of criteria is defined by the end-users and technical team. This method evaluates the models based on the defined criteria, weightage assigned to the criteria, and the final ranking [66].

2.2.2 Classifications of Water Quality Models

Water quality models are broadly classified into two categories: simulation models and optimization models. The optimization model involves a group of mathematical techniques for a particular situation with a cost constraint. Simulation models include a set of equations to represent changes in water quality and describe the functioning of the system [67]. A simulation model can be either a physical or a mathematical model. A physical simulation is a scaled representation of a system, and the obtained results are applied and related to the real system. Mathematical models use computer programs to solve equations to predict changes.

Various mathematical-based water quality models have been developed to determine water quality variations in a water body [55, 68]. Mathematical models can be further classified based on the process, data type, time, and space [69]. **Figure 2.2** illustrates the classifications of the water quality models.

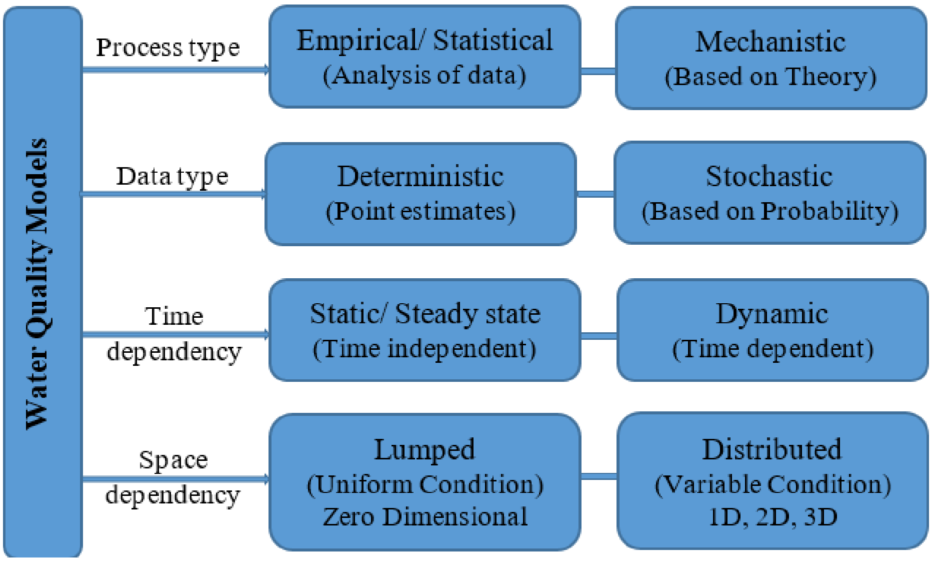


FIGURE 2.2 Classification of water quality models

- Statistical models use mathematical equations to analyse data and establish a fixed relationship between input and output parameters. They are easy to solve. They require an adequate site-specific data set to predict reliable results. Otherwise, it leads to uncertainty in the results and large errors. However, mechanistic models work on theoretical principles. The chemical, mechanical, and biological phenomena of the water system are described through mathematical equations. Extrapolation from mechanistic models is reliable, although such models may be complex.
- The deterministic model contains no random elements. The relationship between the input and output components is determined conclusively and precisely using mathematical equations. The initial condition and parameter values define the model output. Stochastic models include random elements. The model output varies with the same initial condition and parameter value. They are comparatively more complicated.
- Static and dynamic models are classified based on time dependency. Static/steady-state models represent a constant system over time. Dynamic models are time-dependent, and the state of variables changes with time.
- Lumped models are zero-dimensional models that describe homogeneous models and remain uniform in the entire system. Distributed models describe heterogeneous systems that vary with the spatial dimension. The spatial resolution may be one-dimensional, two-dimensional, or three-dimensional based on the spatial characteristic.

2.3 Model Review

The concept of water quality modeling was developed a long time ago. The pioneering work was done by Streeter and Phelps, who developed the first water quality model in 1925 to identify the depletion of DO and the pollution scenario of the Ohio River [27]. Subsequently, various water quality models, including steady-state models, dynamic models, and one-, two-, and three-dimensional models have been developed, and are used for different water quality aspects.

This section describes QUAL2Kw, WASP, SWAT, SIMCAT, MIKE-11, and CE-QUAL-W2, and, widely used river water quality models.

2.3.1 QUAL2Kw/Q2K

2.3.1.1 Model Development

United States Environmental Protection Agency (USEPA) developed various QUAL models for modeling the water quality of dendritic rivers and non-point sources of pollution. These are one-dimensional steady-state or dynamic models. A series of models has been developed from the QUAL models to the QUEL2E series to the QUAL2K series. QUAL2E was amended and established as the QUAL2K model to overcome the limitations of QUAL2E. The modifications include changes in computer code and the addition of new constituents like algal growth, denitrification, and changes in dissolved oxygen by the fixed plant [70, 71]. QUAL2Kw was an updated version of the QUAL2K model, which was initially developed by Chapra and Pelletier in 2003. QUAL2Kw/Q2K is the modified version of the QUAL2E/Q2E model.

2.3.1.2 Model Characteristics

It is a one-dimensional steady-state model but simulations are in dynamic mode for water quality kinetics and heat budget [56, 72, 73].

QUAL2Kw is featured with several new elements: Software is programmed in Microsoft office with macro and visual basic application and excels as a user interface; river reaches of equal or unequal lengths can be simulated in one system with multiple loadings input option; organic carbon is represented by carbonaceous biochemical oxygen demand (CBOD) in two forms (slow and fast); nutrient fluxes and dissolved oxygen are simulated internally resulting from the interactions of sediment and water; the parameters of bottom algae, alkalinity, total inorganic carbon, pathogens can also be simulated; other parameters like a sediment pore water quality, hyporheic exchange, and light extinction are also included.

The model could be evaluated using sensitivity analysis, which helps in the quantification of errors related to the simulated parameters. The reliability of the model can be obtained by Uncertainty analysis. Monte Carlo simulation (A Monte Carlo simulation add-in for Microsoft Excel) calculates the uncertainty of the parameters. Various statistical tests, such as R^2, mean bias error (MBE), root mean square error (RMSE), and standard deviation bias error (SDBE), provide better insights into variations between predicted and observed data [35].

2.3.1.3 Capabilities and Strengths

It can simulate various constituents, including pH, temperature, CBOD, DO, electrical conductivity (EC), organic nitrogen (ON), ammonium nitrogen (NH_4N), nitrate nitrogen (NO_3N), organic phosphorus, inorganic phosphorus, phytoplankton, and periphyton. Such a simulation also includes both point and non-point discharge pollutants [74].

The model has an auto-calibration system [75]. It provides a genetic algorithm to achieve the optimum value of kinetic rate parameters in good agreement with the observed data Pelletier, Chapra, and Tao (2006) provide a framework of QUAL2Kw, including a genetic algorithm for model calibration [76].

The calibrated and validated model provides results with minimum relative and root-mean-square error and is found successful in the simulation of water quality data in the effective implementation of the river water quality restoration plan [77–79].

2.3.1.4 Model Input

The inputs to the model are general information, simulation and output options flow, concentration of headwater and downstream boundary conditions, reach data, system's hydraulics, dispersion, aeration, weir’s height, sediment oxygen demand, flux, reach rate, initial conditions, air temperature, dew point temperature, solar radiation, cloud cover, wind speed, shade, light and heat, model's rate parameters, rate parameters to control genetic algorithm for optional auto-calibration, water quality parameters [75].

2.3.1.5 Governing Equations

The model uses the following mass balance equation for the analysis of constituents that exist in the water column of the respective reach, shown in **Equation (2.1)**.

$$\frac{dC_i}{dt} = \frac{Q_{i-1}}{Vi}C_{i-1} - \frac{Q_i}{V_i}C_i - \frac{Q_{ab,i}}{V_i}C_i + \frac{E'_{i-1}}{V_i}(C_{i-1} - C_i) + \frac{E'_i}{V_i}(C_{i+1} - C_i) + \frac{W_i}{V_i} + S_i \qquad (2.1)$$

Where Q_i is the flow (m^3/d), ab is the abstraction, W_i is the External loading of the constituent to reach i (g/d or mg/d), V_i is the Volume (m^3), E'_i is the Bulk dispersion coefficient between reaches i and i+1 (m^3 /d), and S_i is the sources and sink of the constituent due to reactions and mass transfer mechanisms ($g/m^3/d$ or $mg/m^3/d$).

2.3.1.6 Applications

Ghorbani et al. (2022) simulated water quality of the Dez River (southwest of Iran) by applying the QUAL2Kw model for temperature, discharge, BOD, and EC parameters. The model was calibrated and validated using past data. The critical BOD was simulated for the discharge value. The simulation results indicated a critical BOD at 40 km from Dez Regulating Dam for a discharge of 190 m^3/s. EC value was found to exceed the permissible limit at a discharge of 50 m^3/s. The fitness of the model was checked with RMSE and the per cent Bias (PBIAS) coefficient, which showed the goodness of the model with 95% accuracy [80]. Tran et al. (2022) applied the model to the Lam Takhong River, Thailand, to simulate DO, BOD, nitrate-nitrogen, and ammonia-nitrogen for the critical period and compare it with the designated surface water quality class. The study focused on determining the impairment of DO with other parameters at different stretches of the river. Simulated data of the calibrated and validated model showed that water quality criteria were not met at the downstream location, showing fourth-class water quality with a desired DO value > 2.0 mg/L and BOD value < 4.0 mg/L. The model was found suitable to simulate the future water scenario of the Lam Takhong River and would assist resource managers in taking appropriate policy measures [81]. Pramaningsih et al. (2020) analyzed the pollution load capacity of Karang Mumus River, Samarinda city, and East Kalimantan at four of its different segments using the QUAL2Kw model and land use settlement using Arc GIS. The results showed the exceeding of BOD in all segments and chemical oxygen demand (COD) in three segments. The pollution load was found to have originated due to domestic activities and major land-use settlements [82]. Angello et al. (2021) used the QUAL2Kw model to determine the impacts of rapid urbanization, lack of pollution management, and sanitation infrastructure facility in water quality degradation of the Little Akaki River (LAR), Ethiopia. Different scenarios for pollution reduction and water quality improvements were selected. The study concluded that integration of pollution load control strategy, application of best pollution management practices, and application of instream measures such as wastewater treatment at source, control of diffuse source pollution, and the use of cascaded rock ramps could be the best feasible alternative for sustainable development of river catchment [83]. Moghimi Nezad et al. (2018) utilized the QUAL2Kw model to determine the self-purification of a stretch of the Karun River. The model was calibrated and verified for the past measured data. The results indicated minimum relative and route square error [35]. Park & Lee (2002) applied both QUAL2K and QUAL2E to determine the water quality of Nakdong River, Korea for the parameters including DO, BOD, nitrogen, and phosphorous. The results of these two models showed a significant difference. The author found the results of QUAL2K to be in parity with the field data, which was due to its capability to simulate algal death to BOD, DO, and denitrification [70].

2.3.1.7 Assumptions and Limitations

The limitation of the model is that it can simulate the main stem of the river system but not its branches. The model was found to be highly sensitive to oxidation rate, depth coefficient and moderate to point sources flow, total nitrogen, CBOD, and nitrification rate [84, 85]. Khonok *et al.* (2022) found the model more sensitive for ultimate carbonaceous biochemical oxygen demand (CBODu), EC, and pH compared to dissolved oxygen, total phosphorous, and total nitrogen parameters during both low and high water flow months [86].

2.3.2 WASP

2.3.2.1 Model Development

The Water Quality Analysis Simulation Program model (WASP) was initially developed in 1970 by Hydro Science, Inc. and later adapted by the Large Lakes Research Station (LLRS) of the US Environmental Protection Agency for applications to the great lakes [87]. WASP8 is a modernized version of the earlier 7 versions [88–90]. Wool et al. (2020) have described the detailed framework of the WASP model from its evolution to the release of the model in 2020, marking 50 years of evolution.

2.3.2.2 Model Characteristics

It is a dynamic model and can be used for one-, two-, and three-dimensional systems. It is available in the public domain and can be downloaded freely. It can be utilized to assess water quality problems of different water bodies such as ponds, lakes, reservoirs, rivers, streams, coastal waters, and estuaries [92].

The model can also be coupled with sediment transport and hydrodynamic models that provide temperature, depth, flow, velocity, sediment fluxes, and salinity. The model has two sub-models within the system: the EUTRO model and the TOXI model, which simulate conventional water quality and toxic pollution, respectively.

2.3.2.3 Capabilities and Strengths

The model can simulate various water quality parameters, such as BOD, DO, ammonia, organic nitrogen, nitrate, organic phosphorus, phosphate, phytoplankton, coliform bacteria, and silica [91, 93].

It can be applied to simulate the water quality of 1D, 2D, and 3D systems. It has been used extensively for simulating organic compounds, polychlorinated biphenyls (PCBs), heavy metals, and nutrients in different water bodies and was found to represent accurate and reliable results [94–98].

2.3.2.4 Model input

The inputs to the model are model segmentation, time-series flow, point- and non-point source loads, initial concentrations, boundary limits, output control, kinetic parameters, and constants [99].

2.3.2.5 Governing Equations

The simulation is based on a set of equations of transport and transformation phenomena [99, 100]. The model follows the mass balance equation shown in **Equation (2.2)** for simulation [101, 102].

$$\frac{\partial C}{\partial t} = -\frac{\partial U_x C}{\partial_x} + \frac{\partial}{\partial_x}\left(E_x \frac{\partial C}{\partial_x}\right) - \frac{\partial U_y C}{\partial_y} + \frac{\partial}{\partial_y}\left(E_y \frac{\partial C}{\partial_y}\right) - \frac{\partial U_z C}{\partial_z} + \frac{\partial}{\partial_z}\left(E_z \frac{\partial C}{\partial_z}\right) + S_L + S_B + S_K \quad (2.2)$$

Where C is the concentration of the water quality constituent (M/L^3); t is the time (T); U_x,U_y,U_z are the longitudinal, lateral and vertical advective velocities (L/T); E_x,E_y,E_z are the longitudinal, lateral and vertical diffusion coefficients (L^2/ T); S_L is the direct and diffuse loading rate (M/L^3T); S_B is the boundary loading rate (including upstream, downstream, benthic and atmospheric) (M/L^3T); and S_K is the total kinetic transformation rate, positive is source and negative is sink (M/L^3T).

2.3.2.6 Applications

Shabani et al. (2021) applied the WASP model and linked it to Hydrologic Engineering Center-River Analysis System (HEC-RAS) 2D hydrodynamic model to compute the transportation of arsenic-contaminated sediments due to flood events on Woodbridge Creek, New Jersey. The coupled model was found capable of depicting the transport of surface sediment and arsenic ranging from a net loss of 13.5 cm to a net gain of 11.6 cm, and 16.2 to 2.9 mg/kg, respectively at the end of 48-h flood simulation, per model segment [103]. Obin et al. (2021) used the model for the Lushui river to estimate the pollution load using the flux method. The model was calibrated by sensitivity analysis, orthogonal design, and trial-and-error method. The water quality parameters, including COD, ammonia nitrogen, and total phosphorous parameters were simulated for the normal, wet, and dry seasons. The results were compared with the data given by Zhuzhou Ecological Environment Bureau and found the model quite reliable for water quality prediction and management [104]. Ramos-Ramírez et al. (2020) estimated the dispersion of Chrome III (Cr III) pollutants discharged with the process water in the Bogota River. Simulated results showed eight main zones requiring water treatment. Flow, system geometry, and dispersion coefficient were identified as important factors affecting the simulation results. The model was validated by the Index of Agreement (IOA) parameter, which was derived as 0.853, which indicated a good agreement between observed and simulated data [105]. Mbuh et al. (2019) applied the model successfully to the Shenandoah River basin to evaluate the influence of nutrient loads and non-point sources of pollution on water quality [106]. Yao et al. (2015) utilized the model to evaluate the risks of the point source of pollution in the Taipu River [107]. Hosseini et al. (2017) found the model effective in determining the impacts on river water quality with the increase in water flow and air temperature [108]. Lai et al. (2011) integrated the WASP model with the integrated watershed management model (IWMM). The model was applied in integration with the watershed model for simulating the water quality of the Kaoping River basin, Taiwan, for non-point source (NPS) of pollution. The integration demonstrated significant advances in estimating the impacts of NPS pollutants on water quality, which would be underestimated by applying a water quality model for non-point sources [109].

2.3.2.7 Assumptions and Limitations

The model works with the assumption of a completely mixed regime in the river. The process of sediment transport depends on the user-defined values of temperature and dispersion coefficient. Limitations of the model include the need for extensive training for effective use, along with significant data and time for calibration and validation. Furthermore, it cannot simulate the parameters of microalgae and periphyton. The effects of mixing zones are not accounted for in the model [55, 110].

2.3.3 SWAT

2.3.3.1 Model Development

The Soil Water and Analysis Tools (SWAT) model was established in the early 1990s by the United States Department of Agriculture, Agricultural Research Service (USDA - ARS) in the early 1990s. It was developed to predict long-term impacts on sediment, water, and agricultural chemical yields in large and complex watersheds with varying soil and land use conditions. The model was initially developed with the SWAT94.2 version and upgraded later with the versions of SWAT96.2, SWAT98.1, SWAT99.2, SWAT2000, SWAT2005, SWAT2009, and currently SWAT2012 [111–113]. The algorithm used in SWAT2009 and SWAT2012 is different, and hence, the model system is non-transferable for nutrients between these models [114].

2.3.3.2 Model Characteristics

It is a physical-based model. It can be accessed freely in the public domain. It is used for the simulation of nutrient transport from reservoirs, channels, and groundwater flow transportation. It is a continuous model and helps in understanding long-term impacts [111, 115].

For the simulation process, the model divides the watershed into sub-basins. The sub-basins are further grouped into hydrologic response unit (HRU) and lumped within the sub-basin.

The accuracy of the model depends on the validation and calibration of the model. The fitness of the model can be evaluated depending on the performance rating of the statistics considered for the model evaluation [116, 117]. Arnold, Moriasi, et al., (2012) have established methods for the calibration of the model with uncertainty analysis.

2.3.3.3 Capabilities and Strengths

It is capable of simulating water quality parameters such as carbonaceous BOD, dissolved Oxygen, and algae. The model can simulate physical processes related to the transport of nutrients, bacteria, sediments, water, and crop yield directly. It requires minimum data input and can be utilized for very large and complex basins without extensive cost and time [118].

2.3.3.4 Model Input

The inputs required are watershed general information, temperature, precipitation, wind speed, solar radiation, relative humidity, evapotranspiration, land cover/plant growth, pesticides, nutrient content of fertilizer, water quality, soil characteristics, and point source data [113].

2.3.3.5 Governing Equations

The model simulates the hydrology of a watershed into two divisions. The first division is the land phase, which controls water, nutrients, sediment, and pesticide loadings in each sub-basin of the main channel. The hydrologic cycle is governed by water balance equation shown in **Equation (2.3)**:

$$SW_t = SW_0 + \sum_{i=1}^{t} \left(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw} \right) \tag{2.3}$$

Where SW_t is the final soil water content (mm H_2O), SW_0 is the initial soil water content on day i (mm H_2O), t is the time (days), R_{day} is the amount of precipitation on day i (mm H_2O), Q_{surf} is the amount of surface runoff on day i (mm H_2O), E_a is the amount of evapotranspiration on day i (mm H_2O), w_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm H_2O), and Q_{gw} is the amount of return flow on day i (mm H_2O).

The second phase is the water or routine phase that simulates the movement of water, sediments, nutrients, and organic chemicals flowing through the channel. The simulation is governed by a set of equations for the transport of each parameter [111].

2.3.3.6 Applications

The model has been adopted worldwide for different applications [119]. Chen et al. (2014) utilized the model in one of the main tributaries of the Xiangjiang River and the Zhengshui River to determine the impacts of different watershed management practices on nutrient and sediment transport. The results demonstrated 10% and 30% increases in ammonium and nitrate nitrogen, facilitating the implementation of effective measures to improve water quality [120]. Malik et al. (2021) simulated streamflow for part of the Kashmir valley using SWAT2012 model and achieved good model performance by optimizing parameters through calibration [121]. Epelde et al. (2015) utilized the model in the watershed area of Alegria to estimate the long-term impacts of nitrogen used in agriculture and found trends in Nitrogen concentration in groundwater due to its excessive use [122].

2.3.3.7 Assumptions and limitations

Limitations of the model include difficulty in handling number of input files as a large watershed is divided into a number of hydrological response units. It cannot simulate detailed single-event flood routing. It does not simulate changes in dissolved oxygen and daily flow occurrences, such as storm runoff. The impacts of erosion of the floodplain and snowmelt are difficult to model [123].

2.3.4 SIMCAT:

2.3.4.1 Model Development

The Simulation of catchment (SIMCAT) was developed in the United Kingdom by Anglian water [124]. It was developed to evaluate the potential impact on water quality of the River Dee Special Area of Conservation (SAC) and some of its tributaries due to a proposed road drainage outfall to fulfil the requirement and authorization under Water Environment (Controlled Activities) (Scotland) Regulations, 2005 (CAR).

2.3.4.2 Model Characteristics

SIMCAT is a steady-state, one-dimensional, deterministic and stochastic model. It uses Monte Carlo analysis techniques for simulation. It is ulitized for the simulation of the transport of point source pollutants in the river [54]. The model can also estimate impacts of pollutants of conservative and non-conservative nature [125].

In the model, the river can be divided into user-defined stretches. The river stretches are considered as continuously stirred tank reactors (CSTRs) in series. It considers the complete mixed condition of pollutants for each stretch of the river. It simulates pollutant transport with an assumption of no interactions with sediments [56].

It has been used widely over the years in the United Kingdom and proved as a cost-effective and practical tool for the management of water quality [126, 127].

2.3.4.3 Capabilities and Strengths

The model can simulate parameters like dissolved oxygen, biochemical oxygen demand, ammonia, and other user-defined parameters. The model is used for the river catchment area to ascertain defined water quality targets and identification of the measures for control of water quality within the defined criteria. It has an auto-calibration system and hence provides quick and reliable results (Warn 2010). SIMCAT can model up to 600 reaches and can include about 1400 features such as rivers, weirs, abstractions, discharges, and diffuse pollution [128].

2.3.4.4 Model Input

The model can be operated with limited data. The flow of the main river and water quality data are required to enter. The model requires a statistical summary of water quality as it utilizes Monte Carlo method. The model supports the statistical data in the form of means, standard deviation, and count, Statistical distribution data in the form of constant, normal, log-normal, 3 parameters log-normal, non-parametric distributions, and seasonal (monthly) data [127].

2.3.4.5 Governing Equations

The mass balance of a particular stretch follows the **Equation (2.4)**.

$$C_o = \frac{C_i Q_i + C_t Q_t + C_e Q_e}{Q_r + Q_t + Q_e} \tag{2.4}$$

Where Q is the flow (m^3/min), C is the pollutant concentration (mg/L), O is the outflow, i is the upstream input, t is the tributary input, e is the effluent discharged, and a is the abstractions.

$$v = aQ^b \tag{2.5}$$

$$t = \frac{L}{v} \tag{2.6}$$

Where v is the flow velocity (m/min), Q is the Flow rate (m^3/min), a,b are constants, t is the residence time (min), and L is the length of the reach (m).

The concentration of solute is subjected to first-order decay, which is used to determine the concentration of pollutants moving to the next reach.

2.3.4.6 Applications

Crabtree et al. (2009) used the SIMCAT model to estimate a range of Programmes of Measures (PoMs) to control pollution of phosphate, BOD, and ammonia in the River Ribble catchment, North West of England, to comply with the standards prescribed in the Water Framework Directive (WFD). The results showed that the daily load of phosphate would be required to reduce from the consented load of 744 kg/day to 82 kg/day by 90%. Compliance levels were not achieved for BOD and ammonia. The study suggested reducing the load from wastewater treatment works to achieve compliance. The model has been reported as the best tool to support decision-making in the river water quality management [126]. B. Crabtree et al. (2006) utilized the model for an integrated planning study for river catchments of Ehen, Derwent, Kent, and Eden Rivers, England, that fail to meet prescribed water quality criteria for the ecosystems under candidate Special Areas of Conservation (cSAC). The results recommended providing controls on effluent discharges and pollution from other sources to meet the defined criteria [129]. Jacobs UK Limited (2007) used the model to the Dee River to predict the potential impact on the water quality of the river and its tributaries due to the proposed road drainage [130]. Hankin *et al.*, (2016) mentioned the limited applicability of the model, as a model does not provide a clear mechanism to allow uncertainty parameters [131].

2.3.4.7 Assumptions and Limitations

Limitations of the model include that it cannot simulate a few parameters related with dissolved oxygen. Therefore, it cannot produce reliable results for DO factors. Its application is limited to the parameters of photosynthesis, respiration factor, sediment oxygen demand, and reaeration rate. It cannot simulate temporal changes and is hence not suitable for complex water systems. [56].

2.3.5 MIKE-11:

2.3.5.1 Model Development

It was established by the Danish Hydraulic Institute, Nederland, initially in 1972 [132]. A wide range of models has been developed, including MMIKE 11, MIKE 21, MIKE 3, MIKE SHE, Mouse, and MIKE Basin models [133, 134].

2.3.5.2 Model Characteristics

It is a deterministic type model and can be utilized to simulate unsteady-state flow conditions. It can be used for simple as well as complex river systems. It can be applied as a water quality model to estimate the impacts of discharges on river water quality. Additionally, it can be utilized as a hydraulic model for flood analysis. The model is integrated with a series of modules, including rainfall-runoff, advection-dispersion, and hydrodynamic.

It is widely used in the United Kingdom (UK) for urban pollution management. The Environmental Protection Agency adopted the model to examine the pollution load of receiving water bodies due to the discharge of wastewater [135, 136].

2.3.5.3 Capabilities and Strengths

It can simulate BOD, DO, nitrate, ammonia, heavy metals, and coliform bacteria.

2.3.5.4 Model Input

The inputs to the model are water quality; hydrodynamic, advection and dispersion parameters; Cross-section; boundary conditions specifying tributaries, discharges, and abstractions. The data are linked to a time series of flow and water quality entered in an editor interface [135]

2.3.5.5 Governing Equations

The hydrodynamic model of MIKE-11 uses Saint-Venant equations for the simulation of one-dimensional dynamic flows in rivers, **Equations (2.7) and (2.8)**.

$$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}=q \tag{2.7}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\alpha\frac{Q^2}{A}\right)+gA\frac{\partial h}{\partial x}+\frac{n^2 gQ|Q|}{AR^{\frac{4}{3}}}=0 \tag{2.8}$$

Where Q is the discharge (m^3 /s), A is the cross section (flow) area (m^2), q is the lateral inflow (m^2 /s), h is the water level above a reference datum (m), x is the downstream direction (m), t is the time (s), n is the manning's resistance coefficient (s/$m^{1/3}$), R is the hydraulic or resistance radius (m), g is the acceleration due to gravity (m^2 /s), α is the momentum distribution coefficient introduced to account for the non uniform vertical distribution of velocity in a given section.

2.3.5.6 Applications

Minh et al. (2022) utilized the MIKE-11 model for the complex river network of the Mekong delta area in Vietnam to analyze spatial and temporal variations in BOD, DO, and temperature parameters. The simulated data of the model revealed the pollution scenario, with the need to take adequate measures to reduce the influence of harmful pollutants [137]. Doan et al. (2013) and Kumar et al. (2021) adopted the MIKE BASIN model to determine different scenarios that affect the water availability of the Nhue River of Vietnam and Shipra River respectively [138, 139]. Dehkordi & Kashkuli (2015) applied the MIKE 11 model for control of total dissolved solids (TDS) entering to Hendijan River from the adjoining drain and Zohreh River and Kheirabad River. The simulated data showed that control of TDS to Hendijan River was achieved through constant TDS and discharge from drains and Zohreh River and increase of discharge from Kheirabad River. The simulated results from the model were found important in decision-making in water management [140]. Kamel (2008) applied MIKE 11 HD model for simulation of unsteady flow along the stream reaching in Euphrates River in Iraq. The model provided satisfactory simulated data that assists the decision-making in the prevention of floods in the Euphrates River [141].

2.3.5.7 Assumptions and Limitations

The model requires substantial data for its operation, without which simulation is difficult for some constituents. A skilled person is required for model set-up. The model can be used for complex water systems, but it cannot include the denitrification process. The cross-sections of channels are required to reach boundaries, and hence make the simulation lengthy [54, 142].

2.3.6 CE-QUAL-W2

2.3.6.1 Model Development

The US Army Corps of Engineers (USACE) Waterways Experiment Station (WES) developed the CE-QUAL-W2 (Corps of Engineers-Quality-Width Averaged) model. It is a two-dimensional water quality (longitudinal and vertical) and hydrodynamic model. The model was established originally as LARM (Laterally Averaged Reservoir Model) and utilized for a reservoir without branches [143]. It was amended subsequently with a water quality algorithm [144]. A range of versions has been developed, and version 4.5 is the latest model upgraded with several new features.

2.3.6.2 Model Characteristics

The model is suitable mainly for rivers, lakes, reservoirs, estuaries, and entire river basins with multiple segments. It is freely available and can be downloaded from www.ce.pdx.edu/w2 [145].

2.3.6.3 Capabilities and Strengths

The model is capable of computing hydrodynamic parameters, including water levels, vertical and horizontal velocities, temperature, and 52 water quality parameters, which include pH, dissolved oxygen, nutrients, algae, organic matter, bacteria, and sediment parameters. From the state variables above, 60 variables can be derived internally from the state variables, such as pH, turbidity, organic nitrogen, organic carbon, total phosphorous, total nitrogen, ammonia in unionized form, and Secchi disk depth [146, 147].

2.3.6.4 Model Input

The inputs to the model are a topographic map and/or a sediment range survey; project volume-area-elevation table; initial conditions of time, temp., inflow and outflow, water body type; boundary conditions; hydraulic and kinetic parameters; calibration data [146].

2.3.6.5 Governing Equations

The model works with the concentration change equation, **Equation (2.9)** [110].

$$\frac{\partial BC}{\partial t}+\frac{\partial UBC}{\partial x}+\frac{\partial WBC}{\partial z}-\frac{\partial\left(BD_x\frac{\partial C}{\partial x}\right)}{\partial x}-\frac{\partial\left(BD_z\frac{\partial C}{\partial z}\right)}{\partial x}=C_qB+SB \tag{2.9}$$

Where B is the layer of time-space change, C is the horizontal component of the average concentration, U and W are the lateral average velocities in the x-direction and y-direction, respectively, D_x and D_z are the diffusion coefficients of temperature and composition, respectively, C_q is the components of input and output flow of materialflow rate, and S is the sources and sinks.

2.3.6.6 Applications

Al-Murib & Wells (2019) utilized the CE-QUAL-W2 model to calculate the impacts of total dissolved solids in the downstream stretch of the Tigris River basin by changes in water flow as the TDS level in downstream areas exceeds the standards of drinking and irrigation water quality. The study revealed that increasing river flow by 15% in the upstream stretch resulted in a decrease in TDS content by 5% [148]. Deus et al. (2013) assessed the impact of pisciculture on the water quality of the largest flooded area of Tucurui Reservoir, Brazil, by application of the CE-QUAL-W2 model. The model was calibrated with field data of about 5 years for the parameters of temperature, total suspended solids, dissolved oxygen, ammonia, chlorophyll-*a*, and nitrate. The model was able to reproduce vertical and horizontal gradients with their spatial and temporal variability. The results showed that chlorophyll-*a* is a vital indicator to define the trophic status of the system. The model was found capable of simulating many water quality management scenarios by changes in the reservoir management system [149]. Park et al. (2014) applied the W2 model for estimating nutrient loads discharged from a parallel-connected three reservoirs into the ocean considering the different flow scenarios. The simulated data showed that under an optimal flow scenario and by controlling chlorophyll-*a* content in the reservoir the loading of total nitrogen and total phosphorous could be reduced by 27.2% and 6.6% respectively [150].

2.3.6.7 Assumptions and Limitations

The limitations of the model are that the governing equations are averaged layer and laterally; lateral variations in temperature, velocities, and water quality parameters are not accounted for. It is a complex model, and its operation is time-consuming, which limits the data required for its operation; vertical momentum is not included, which might not provide an accurate outcome in case of significant acceleration [146].

2.4 Comparison of Water Quality Models and Model Selected for the Study

Water quality models are very useful for identifying the extent of pollution contaminants in water quality and forecasting its long-term impacts. Streeter-Phelps model was the first model that described the DO sag over the transport of pollutants along waterways. A wide range of models has been developed and used to simulate different pollution scenarios of river water quality. The water quality models have been widely adopted because of their implementation in projects of river water quality management and restoration. However, choosing a particular model for a specific water quality problem is a challenging task and varies with the different applications. Rivers are complex water systems. Alterations in the water quality of the river depend on its characteristics, seasonal variations, pollutant sources, and the predominance of pollutants. The data requirement of each water quality model varies and each model has some limitations due to its governing mathematical equations and the type of software used. The selection of a water quality model depends on various factors, including the type of water body, the availability of datasets, the objective of the user, and the availability of resources. A set of criteria has been used in the selection of the model. The level of complexity and output from the model are the governing criteria in selecting a water quality model. **Table 2.1** represents the summary of selected water quality models widely used for the simulation of river water quality. Accordingly, an appropriate model can be chosen and applied for a specific water quality problem.

TABLE 2.1 Summary of selected water quality models

Model	Origin and type	Whether in Public domain?	Type of Waterbody	Variables incorporated in the model	Input data requirements	Assumption and Limitation	Strengths and specific characteristics
QUAL2Kw	USEPA; 1D, steady-state	Yes	Rivers, Tributaries, lakes	pH, Temperature, DO, Conductivity, SS, Alkalinity, CBOD, Total carbon (Organic, inorganic), ON, NH_4, NO_2, NO_3, OP, PO_4, Bottom algae, Detritus, Phytoplankton	• Headwater flow and concentration, • Discharges and withdrawals • Reach lengths and elevations • Meteorological data • Hydraulic data • Kinetic rates and constants	• Flow is assumed to be a steady-state • Cannot Simulate branches	• Includes multiple loadings and abstractions • Includes an in-built automatic calibration system • Allows simulation of unequal river spaces • Can simulate even the bottom algae
WASP	USEPA; 1D, 2D, 3D	Yes	Rivers, Streams, Lakes, Ponds, Estuaries, and Coastal waters.	pH, Temperature, DO, NO_2, NO_3, OP, PO_4, Phytoplankton, Periphyton, CBOD, Bottom algae, Detritus, Salinity, Coliform Bacteria, Silica, Sediments, Metals, Toxics	• Output control • Initial concentrations • Boundary limit • Model segmentation • Point and non-point source loads • Kinetic parameters and constants • Time-series flow	• Does not consider mixing zone • Requires extensive data for calibration and verification • Enables simulation of periphyton or microalgae • Dispersion coefficient and temperature are included as a user-defined parameter	• Flexible model and can simulate 1D, 2D, and 3D systems • It addresses the process of the water column and underlying sediments • Used to simulate a wide range of organic compounds, nutrients, heavy metals, PCBs

Model	Origin and type	Whether in Public domain?	Type of Waterbody	Variables incorporated in the model	Input data requirements	Assumption and Limitation	Strengths and specific characteristics
SWAT	USDA - ARS; 1D, Continuous-time work	Yes	Groundwater flow, sediments, and nutrients transported in channels and reservoir	Sediments, NH_3, NO_2, NO_3, OP, PO_4, DO, BOD	• Precipitation • Temperature • Solar radiation • Wind speed • Relative humidity • Evapotranspiration • Land cover/ Plant growth • Pesticides • Nutrient content of fertilizer • Water quality • Soil characteristics • Point source data	• Difficult to handle numbers of input files due to division of large watershed into numbers of units • Cannot simulate storm runoff and changes in dissolved oxygen	• A watershed hydrological model • Used to predict long-term impacts in rural and land management practices and complex watershed • Can be applied for simulation of nutrient transport from reservoirs, channels, and groundwater flow transportation
SIMCAT	United Kingdom (UK); 1D, Steady-state	Yes	Rivers	DO, CBOD, PO_4, NH_3, User-defined parameters	• Discharge and water quality data in the form of statistical distribution	• Changes in reaeration rate and temporal changes are not considered	• Auto calibration, • Can be operated with limited data • No specific training required
MIKE-11	Danish Hydraulic Institute, Nederland; 1D, unsteady flow	No	River, Lakes, Estuaries, and Tidal wetlands	DO, BOD, Nitrate, NH_3, Heavy metals, Coliform bacteria	• Water quality • Hydrodynamic, advection and dispersion parameters • Cross-section • Water quality to enter in an editor interface	• Requires extensive data for its operation • Need expertise for the operation of the model	• Can simulate complex river water systems with branches • Capable of simulating dynamic movements of river water in addition to water quality parameters

Model	Origin and type	Whether in Public domain?	Type of Waterbody	Variables incorporated in the model	Input data requirements	Assumption and Limitation	Strengths and specific characteristics
					• Boundary conditions specifying tributaries, discharges, and abstractions are linked to a time series of flow	• Simulation is lengthy as it requires cross-sections of the channel to reach boundaries • Not freely available and may be costly to use	
CE-QUAL-W2	US Army Corps of Engineers; 2D, longitudinal/ vertical	Yes	Rivers, Lakes, Estuaries	pH, Temperature, DO, Alkalinity ON, NH_3, NO_2, NO_3, OP, PO_4, CBOD, Bottom algae, Detritus, Phytoplankton	• Topographic map and/or sediment range survey • Project volume-area-elevation table • Initial conditions of time • Temperature • Inflow and outflow • Water body type • Boundary conditions • Hydraulic and kinetic parameters • Calibration data	• Assumes a well-mixed condition in the lateral direction. • Lateral variations and vertical momentum are not included • Complex and time-consuming model • Requires a significant amount of data	• Can simulate the eutrophication process and sediment relationship. • Best suited for the long and narrow water body.

2.4.1 Model Summary:

From the review and summary of the selected model, the following can be inferred:

- MIKE-11 is not available in the public domain and also needs substantial training for its operation.
- The requirement of data input is quite extensive in the case of CE-QUAL-W2, WASP and MIKE-11.
- SIMCAT, though a simple model, has a limitation on the simulation of respiration, sediment oxygen demand, and photosynthesis and may be used when modeling using these parameters is not essential.
- Insofar as considering flow and state conditions are concerned, WASP and MIKE-11 can be utilized for the unsteady state flow condition.
- WASP can be applied to simulate one-, two-, and three-dimensional river systems, but it works with an assumption of a completely mixed regime in a water column.
- SWAT is the watershed hydrological model and can be applied for the simulation of nutrient transport from reservoirs, channels, and groundwater flow transportation
- If simulation of maximum numbers of parameters is to be done, QUAL2Kw and WASP may be more useful. WASP is capable of simulating toxicants in addition. QUAL2Kw can also simulate sediment oxygen demand and hyporheic metabolism. It has certain advantages, including easy accessibility, an auto-calibration system, etc.
- CE-QUAL-W2 is widely used in stratified water bodies such as lakes, estuaries, etc.
- For a complex river water quality scenario, a single model may not be capable of simulating all the required parameters. Such models, in combination, can solve the limitation of simulating desired parameters associated with a single model.

2.4.2 A Model Selected for the Study:

From the review and comparison of various water quality models, QUAL2Kw was selected for simulating the water quality of the selected stretches for the following reasons:

- The model is easily accessible and available in the public domain.
- The model simulations are based on the Microsoft Excel interface integrated with visual basic applications (VBA).

- The model is capable of simulating all the selected water quality parameters with the auto calibration option.
- An automatic calibration system helps optimize the rate-specific parameters and model performance to achieve a good fit.
- The model is developed by USEPA and is widely used for simulating water quality of rivers. It was found to be applied in water quality assessment of major Indian rivers, including the Tapi, Yamuna, Godavari, Periyar, and Kshipra [72, 76, 77, 151–154].

Based on the literature review of multivariate statistical analysis and water quality models, the study methodology is finalized for analyzing datasets, which is described in detail in section 3.2.

CHAPTER 3

Study Area and Methodology

3.1 Study Area

The Sabarmati River is one of the major rivers of Gujarat and serves as the lifeline of Ahmedabad city. Different stretches of the Sabarmati River have been utilised for various purposes, substantially affecting water quality. There are very few studies that describe the spatio-temporal variations of the Sabarmati River. Previous research has characterized water quality at limited locations within the city area boundary over specific periods [41–44]. Therefore, the Sabarmati River was selected as the study area to assess water quality variations, simulate water quality, determine the pollution load, and depict various scenarios for restoring and maintaining the health of the river.

3.1.1 About the Sabarmati River

The Sabarmati River is one of the major rivers in India. The basin is surrounded by the Aravalli hills to the north and northeast, the Rann of Kutch to the west, and the Gulf of Khambhat to the south. The river basin is triangular in shape, with the main river forming its base. It begins at a latitude 24° 20'N and a longitude 73° 20'E, at an elevation of 762 m above mean sea level (MSL) in Rajasthan. The catchment area of the river basin is 21,674 km^2, with 18,550 km^2 in Gujarat and the remaining 4124 km^2 in Rajasthan. The river originates from the Aravalli hills in Rajasthan, flows southwest through Gujarat, and ultimately meets the Arabian Sea at the Gulf of Khambhat in the South. The river spans 371 km in length, of which 323 km runs through Gujarat. The drainage network of the river includes five major tributaries, Wakal, Sei, Harnav, Hathmati, and Vatrak rivers [155]. The Sabarmati basin experiences three distinct seasons: summer (March-May), monsoon (June-September), and winter (October-February). It encompasses two climatic zones; the northern part exhibits a subtropical wet climate (primarily in Gujarat area), while the main section is characterized by a tropical wet climate, influenced largely by the presence of the Aravalli and Western Ghats. The climate ranges from semi-arid in northern Gujarat to humid in coastal zones. The average annual rainfall in the basin is reported to be 787.5 mm, predominantly influenced by the southwest monsoon, which begins around mid-June and withdraws in the first week of October. The hydrogeology of the basin is categorized into two distinct formations: consolidated and unconsolidated. The consolidated formation consists of basaltic lava flows, mostly found in the northeastern region of Gujarat. On the other hand, the unconsolidated formation comprises alluvial aquifers formed under confined conditions by groundwater. Discontinuous beds of alluvial aquifers of varying thickness prevail in the hard rock terrain, particularly in the northern and northeastern regions of the basin, where these aquifers exhibit moderate groundwater potential. The basin has a total population of 1,33,07,250, comprising 6,948,046 males (52.21%) and 6,359,204 females (47.78%). Ahmedabad is a densely populated district within the basin. The terrain is hilly in the initial stretches up to the Dharoi dam, after which the river traverses mostly plains. The highest elevation in the basin is reported to be 1,173 meters, with the major area falling under elevation zones of 100-200 m and 10-50 m. Existing data from the soil survey indicate that the basin predominantly consists of black, alluvial, and sandy soils. According to the soil texture classification, fine texture constitutes 60.38% of the area, followed by course texture at 17.60%, while rocky formations and water bodies make up 15.26%. Agricultural land covers 74.68% of the total area, followed by forest area at 11.98%, wasteland at 7.15%, waterbodies at 4.19%, buildup land at 1.95%, and grassland at 0.05%. The economy of the basin is primarily dependent on agriculture, which occupies 57% of the entire basin area. Areas near urban zones predominantly engage in commercial agriculture. Despite the limited surface water availability, the basin is witnessing rapid industrial development, particularly in large and medium-scale sectors such as textiles, chemicals, dairy, and distilleries. Industrial activities are mainly concentrated in the downward side of the basin. The main crops harvested in the basin depend significantly on the seasons and water availability, with the monsoon being the primary season for cultivation [155–157].

The river is an intrinsic part of Ahmedabad city, serving as its lifeline. The riverfront has been developed along the banks, and the river functions as an important source of recreational and cultural activities. However, rapid urbanization and industrialization have led to the pollution of the river, resulting from the discharge of sewage and industrial waste, thereby deteriorating the water quality [43, 158, 159].

The Sabarmati is a non-perennial river with numerous dams along its main course and tributaries. Key structures include the Dharoi Dam, located at the 70 km chainage, which regulates water flow. Additionally, the Narmada Canal crosses the river midstream at about 202.5 km chainage, near Karai village, known as Karai siphon/escape, supplying water from the Narmada canal to maintain river flow. The Vasna Barrage, located at about 222.5 km chainage, retains water for irrigation. **Figure 3.1** shows the map of the Sabarmati River .

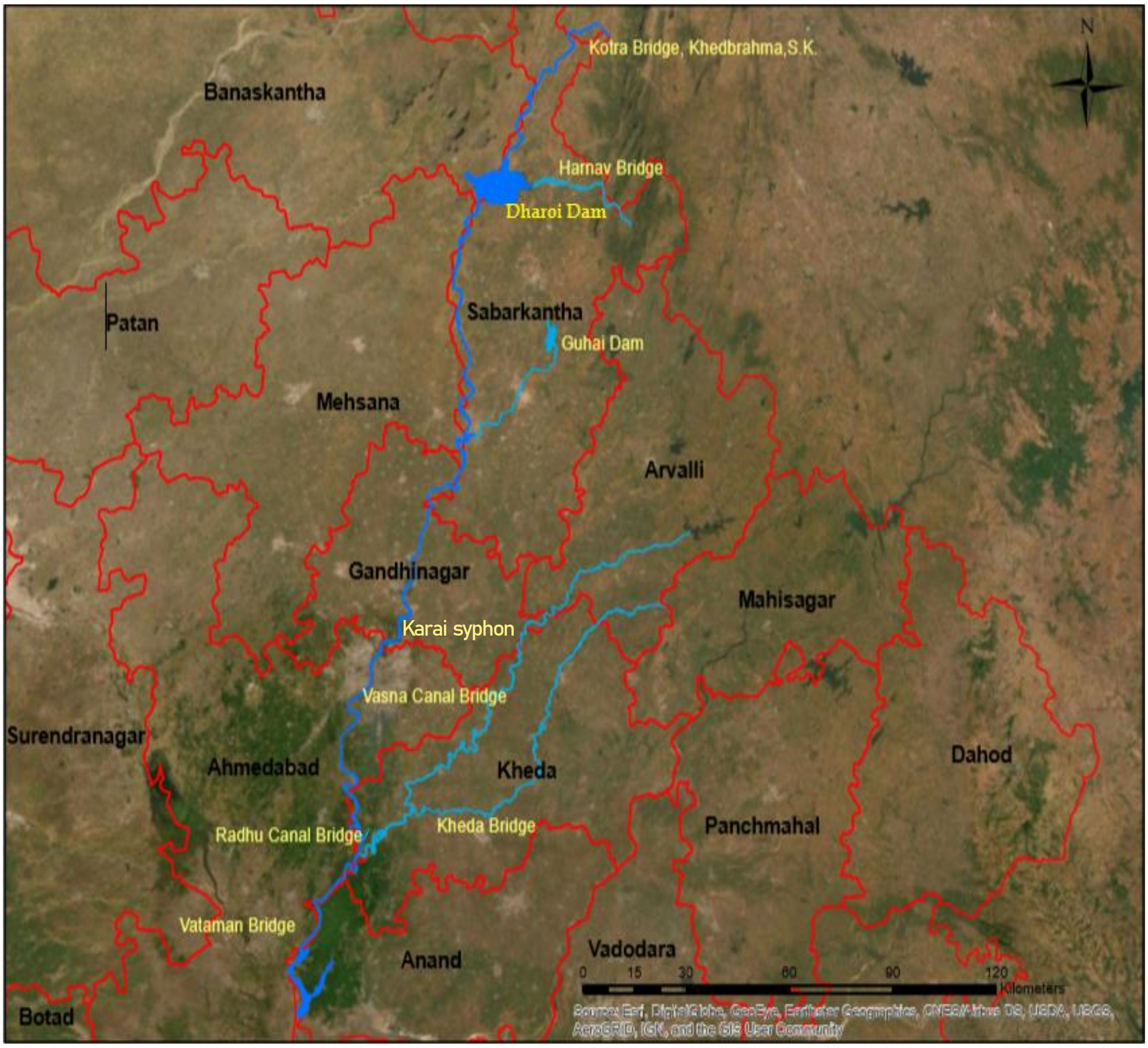


FIGURE 3.1 Sabarmati River map [160]

3.1.2 Stretches of the River Considered for the Study

Based on the collected data and literature, the entire stretch of the Sabarmati River was studied in detail, and critical stretches of the river were identified based on the following.

Inflow to the river:

As described in section 3.1.1, three major structures on the Sabarmati River regulate its water flows: Dharoi Dam located upstream, Karai Syphon/Escape located mid-stream and Vasna Barrage located downstream of the river. These inflows were considered the main headwaters and are critical for maintaining the river flow. Three stretches of the river were considered, with these inflow points as the initial point of stretches. The quantity of flow input to the river was taken from the concerned department and input for simulating water quality as required by the QUAL2Kw model.

Water quality of the river:

Gujarat Environment Management Institute (GEMI) has been carrying out periodic monitoring of the Sabarmati River, dividing the river into upstream, middle stream and downstream locations. As referred from the report and monitoring data, the river starting from Kotra Bridge and flowing through Banaskantha and Sabarkatha districts is taken as upstream, a stretch of the river flowing through Gandhinagar district and a part of the river up to Vasna Bridge of Ahmedabad district is taken as middle stream and the river beyond Vasna Bridge is taken as downstream. The alignment of the river and its reaches flowing through various districts can be referred to in **Figure 3.1**, the Sabarmati River map. The water quality is monitored at different locations with a frequency of about four times a year [160, 161].

Based on the water quality data of the entire stretch monitored by GEMI, the number of critical locations was identified as per this study's objective. It was found for each stretch that there is not much variation in water quality beyond a particular location. Considering these variations for each stretch, the number of critical sites was selected. A total of four sites were considered for the upstream stretch starting from Dharoi Reservoir, three sites for the middle stream stretch starting from Karai Dam/Syphon and four sites for the downstream stretch starting from Vasna Barrage.

Utility of the river water and pollution sources:

The upstream sites are situated outside the main city area and are surrounded by agricultural fields, reflecting a control area with no external pollution sources. The middle stream sites are located within the urban area, and being the riverfront part, famous sightseeing points and tourist places are impacted more by anthropogenic activities. The downstream sites beyond the Vasna Barrage are located at the downstream of the basin and within the urban and rural areas, where sewage and industrial effluent discharges are prevalent.

Considering the inflow, pollution sources, and utility of the river water, three stretches of the Sabarmati River were chosen for the study, as shown in **Figure 3.2**

1) upstream (US-1 to US-4 starting from Dharoi reservoir),
2) middle stream (MS-1 to MS-3 starting from Karai Dam), which includes the riverfront
3) downstream (DS-1 to DS-4 starting from Vasna Barrage)

The selected stretches were analyzed further to identify the most important water quality parameters that significantly affect water quality variations and to simulate water quality scenarios to maintain the river's health. The details of the stretches and locations are shown in **Tables 3.1 and 3.2**, respectively. **Figure 3.3** shows the line diagram of the Sabarmati river along with the selected stretches, monitoring sites, inflows and point sources

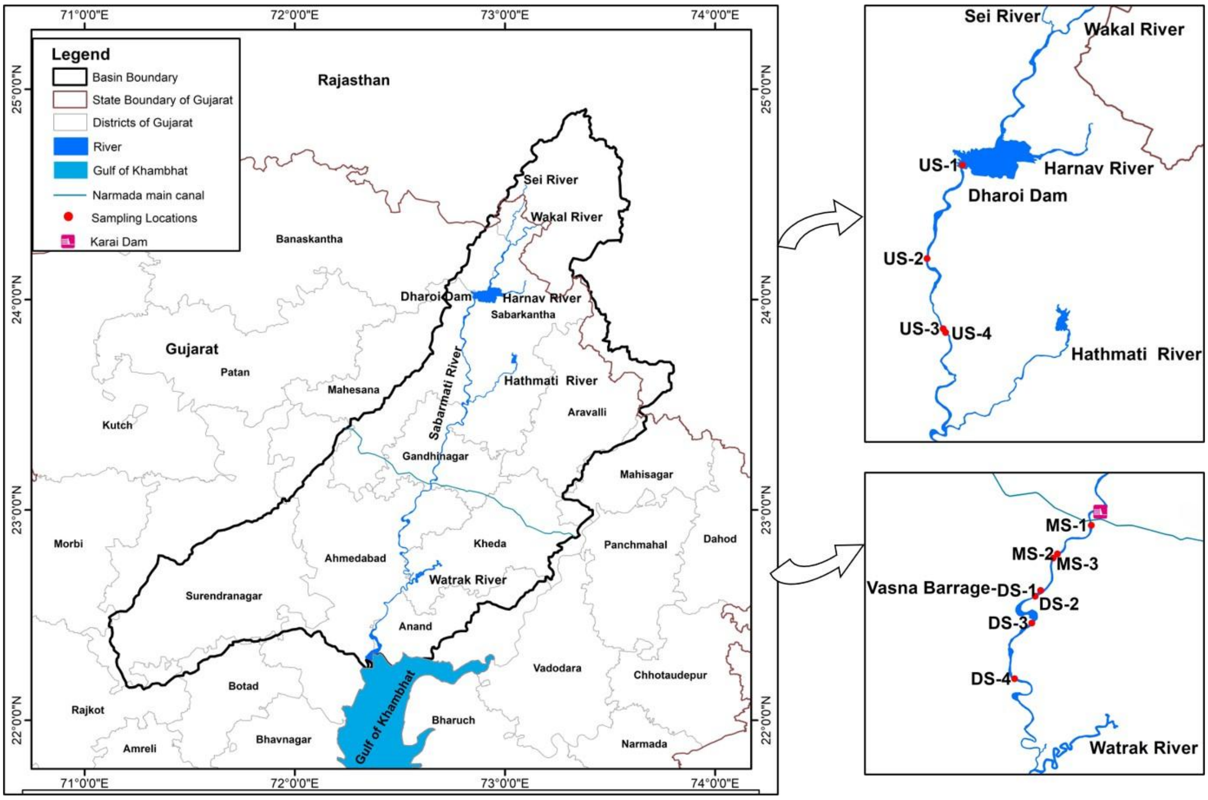


FIGURE 3.2 Locations of Sabarmati River considered for the study area

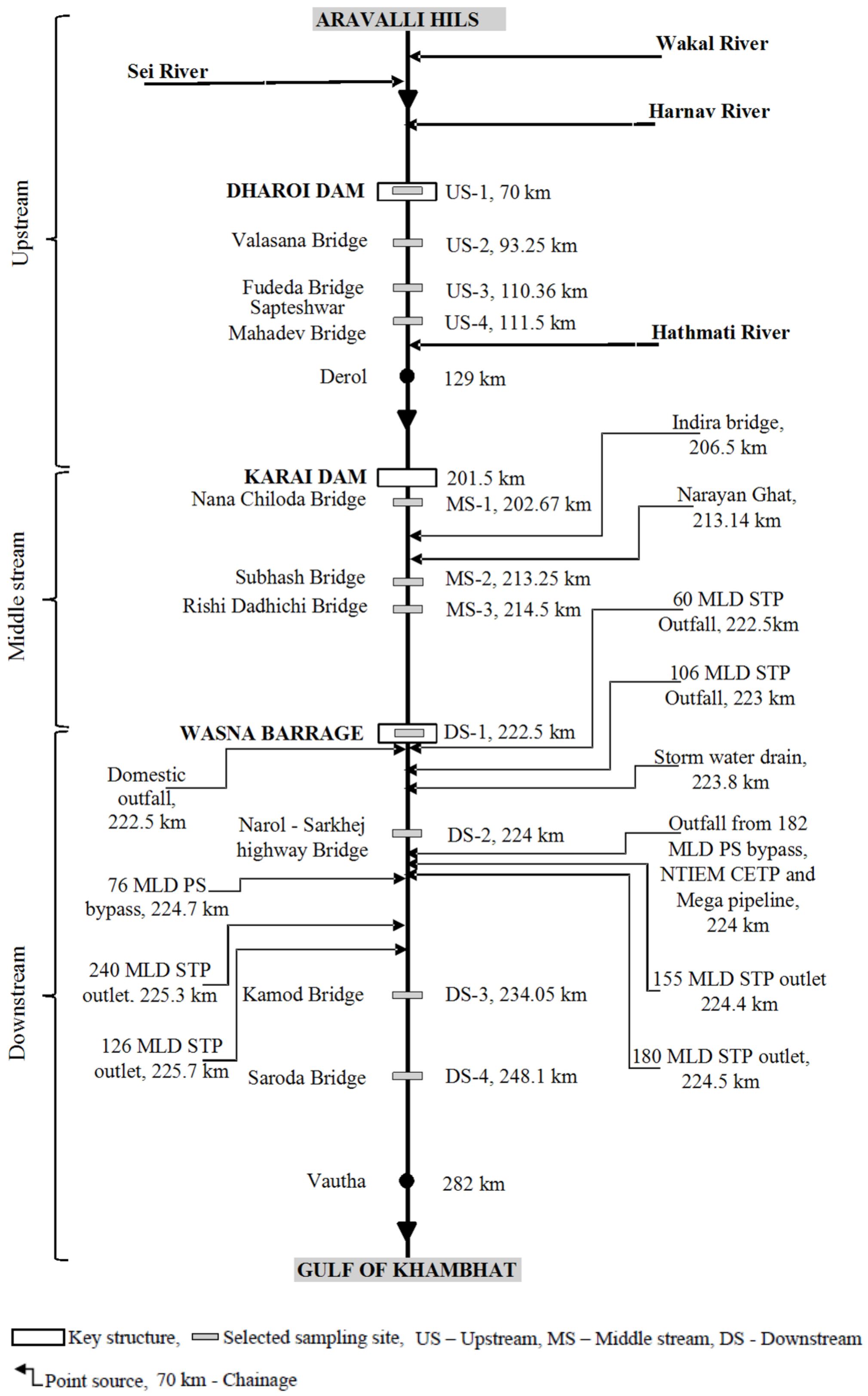


FIGURE 3.3 Line diagram of Sabarmati River showing selected stretches, monitoring locations, inflows and point sources

TABLE 3.1 Details of the stretches considered for the study

Sr. No.	Particular	Up-stream	Middle stream	Downstream
1.	**Location**	Dharoi Reservoir to Sapteshwar Mahadev Bridge US-1 to US-4	Karai Dam to Rishi Dadhichi Bridge MS-1 to MS-3	Vasna Barrage to Saroda DS-1 to DS-4
2.	**Reach Length**	41.5 km	19 km	26 km
3.	**District**	Sabarkantha	Gandhinagar and Ahmedabad	Ahmedabad

TABLE 3.2 Details of the locations

Sr. No.	Notation	Name	Chainage Km	Latitude and longitude
1.	US-1	Dharoi Dam	70	24.010156, 72.85584
2.	US-2	Valasana Bridge	93.25	23.83358, 72.789101
3.	US-3	Fudeda Bridge	110.36	23.701244, 72.819407
4.	US-4	Sapteshwar Mahadev Bridge	111.5	23.694248, 72.823935
5.	MS-1	Nana Chiloda Bridge	202.67	23.115526, 72.649387
6.	MS-2	Subhash Bridge	213.25	23.061471, 72.585662
7.	MS-3	Rishi Dadhichi Bridge	214.5	23.053744, 72.577468
8.	DS-1	Vasna Barrage	222.5	22.992381, 72.553885
9.	DS-2	Narol - Sarkhej Highway Bridge	224	22.981496, 72.54355
10.	DS-3	Kamod Bridge	234.05	22.930805, 72.537107
11.	DS-4	Saroda Bridge	248.1	22.825722, 72.504605

3.2 Materials and Methods

Based on the literature review and research gaps, the methodology is finalized, which includes a step-by-step procedure for analyzing the datasets and interpreting results. It is depicted in **Figure 3.4** and described below.

The collected water quality data were standardized first to remove outliers and prevent their interference with the application and outcome of data analysis. After removing outliers, the data were grouped according to selected stations and seasons. This categorization makes it easier to determine spatial and temporal water quality variations, which facilitates the analysis and modeling of the data to reach effective water quality management scenarios. These data were analyzed using multivariate statistical analysis to identify the critical parameters affecting water quality variations. The analysis was further followed by water quality modeling to ascertain the pollution load capacity of the river and to take measures for improving water quality. The methods used for statistical analysis and water quality modeling are described in detail in the following section.

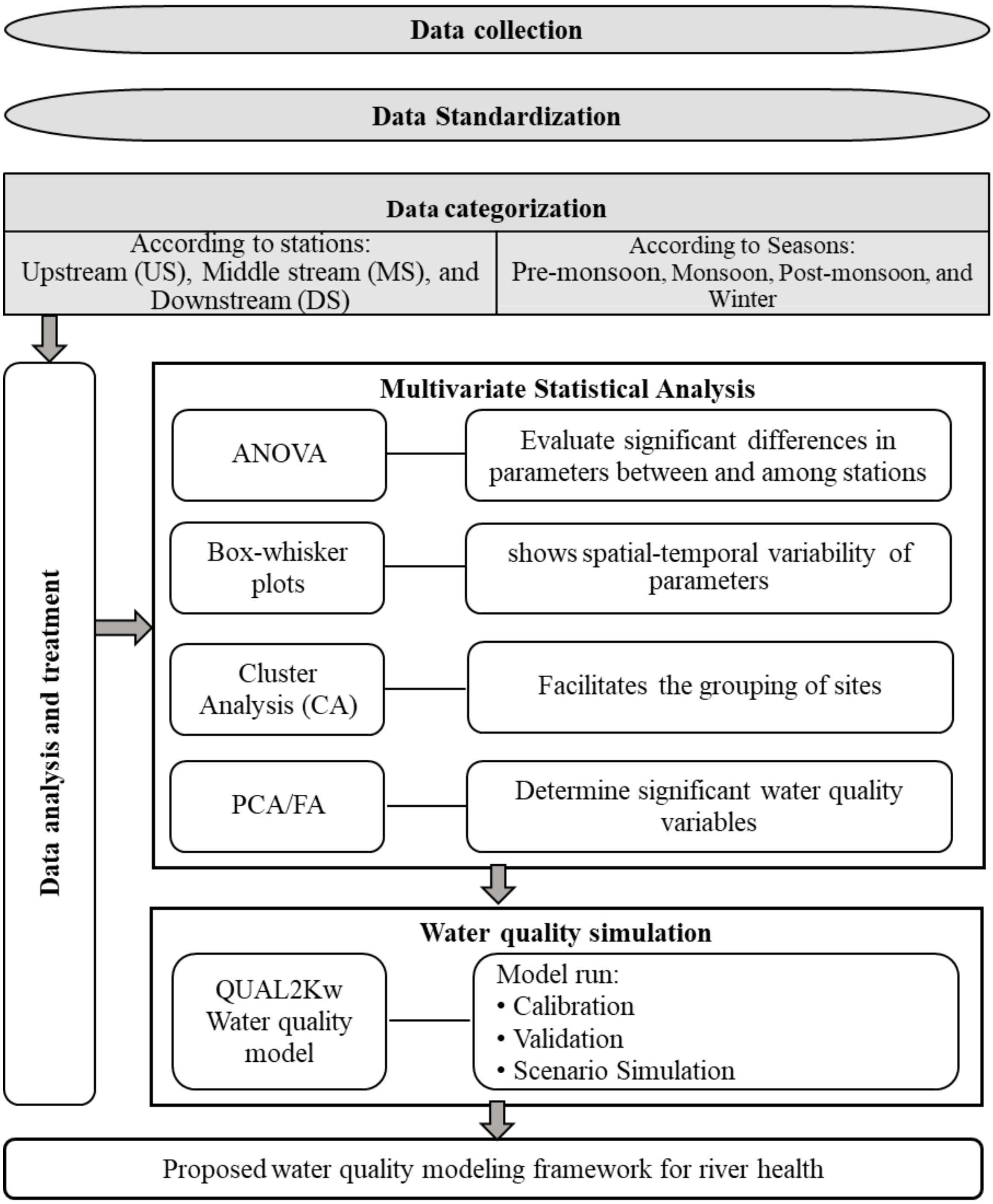


FIGURE 3.4 Methodology adopted for the data analysis and interpretation

3.2.1 Multivariate statistical analysis

Multivariate statistical analysis was conducted to find out the correlation between water quality within the selected stations. It aimed to determine the significant parameters affecting river water quality for its further application to water quality modeling and to develop various scenarios for maintaining the river's water quality and its health. The analysis help identifies most significant parameters affecting water quality variations. Therefore, it reduces number of parameters required to input to water quality models, achieving the reliable output. The following methods were adopted for statistical analysis.

Non-parametric one-way ANOVA (Kruskall-Wallis test):

It was performed to evaluate the significance of water quality parameters between and among stations. Significant differences were found at $p<0.05$ [48, 162]. The method was used to identify the parameters influencing site-specific and season wise and sources of pollution.

Box-whisker plots:

The plots were utilized to visualize the spatial and temporal variations in water quality parameters. These plots display large datasets and highlight differences among the data points [15]. Therefore, water quality parameters were plotted to compare the impact of each parameter on site-specific and seasonal variations.

Cluster analysis:

The water quality at the sites varies depending on site characteristics, purpose of use, and pollution sources. Hierarchical cluster analysis was applied to group sites depending on their similarities and differences, and the correlation of variables [163]. This method was adopted for classifying sites and pollution levels.

Principal component analysis (PCA)/ factor analysis (FA)

Principal component analysis (PCA)/ factor analysis (FA) was used to determine the significant parameters influencing the water quality the most. The method is a dimensionality reduction technique applied to datasets with interrelated variables. This approach retains as much variability in the dataset as possible. A new set of non-correlated variables, known as principal components, is derived by splitting the dataset. The analysis provides eigenvalues and eigenvectors, revealing the dispersion of various measured parameters. The variability in the dataset is summarized through a few principal components, making the information more accessible. Variables are rotated using the varimax method to generate a factor load matrix, which shows the significant water quality variables [52, 164–166]. The principal components analysis was performed on sites, categorized by cluster analysis, to identify most significant parameters affecting the water quality. Thereby, reducing and targeting the parameters for water quality modeling and maintaining the river's health.

SPSS (version 29) software was utilised to run cluster analysis (CA) and principal component analysis (PCA)/ factor analysis (FA).

3.2.2 Water Quality Modeling by QUAL2Kw

From the review of various water quality models and their comparison, QUAL2Kw was utilized for simulating the water quality of the selected stretches as described in section 2.4, due to its easy accessibility, capabilities, Excel interface, auto calibration system and application to the major Indian rivers including the Tapi, Yamuna, Godavari, Periyar, and Kshipra.

The model was applied to the individual stretch of the Sabarmati River to simulate water quality. Each model was calibrated and validated to ensure the model's accuracy. The best-fit model was used to frame various scenarios for maintaining the river's water quality and its health.

3.2.3 Framework for River Health

The study proposes a water quality modeling framework for assessing and maintaining river health, which is generic and can be applied to other river system. The framework outlines a step-by-step process for identifying pollution loads and determining water quality management scenarios to maintain pristine water quality. It has been presented schematically in **Figure 3.5** and described below.

The first step in assessing the river's health is to gather preliminary information about the river, including its profile, inflow, purpose of use, point and non-point sources of discharge, and hydrology. Based on the collected data, critical stretches of the river can be identified and selected for analyzing the pollution load and carrying capacity. The water quality data for these stretches are required to analyze statistically to determine the parameters that significantly affect overall quality. Multivariate statistical analysis helps identify the most critical water quality parameters and their sources. The data needs to be normalized before analysis to prevent interference from unexpected values with the method's application and to obtain a reliable result. The normalized dataset can be utilized further to determine water quality variations, both spatial and temporal. ANOVA and box-whisker plots provide a clear representation of water quality variations and indicate variables responsible for higher variations. Moreover, cluster analysis categorizes the selected sites based on their similarities and helps determine the pollution sources for the identified stretches. Following this analysis, the principal component analysis/factor analysis of grouped sites indicates dominant water quality parameters responsible for pollution and affecting the river's health.

On identifying the dominant water quality parameters, the water quality simulation by QUAL2Kw has been suggested. The model is easily accessible, user-friendly and efficient in simulating water quality and depicting various scenarios for maintaining the river's health. The model input requires reach data, headwater, water quality, hydraulics, meteorological, light and heat parameters, and reach rate parameter for the simulation run. The model also defines rate-specific parameters for light and heat, and selected water quality parameters. The model needs to be calibrated to optimize parameters and to obtain the best-fit model. The auto calibration of the model facilitates optimizing model parameters to minimise the error. The sensitivity of the model should be evaluated, which helps optimize the model between the observed and predicted datasets. The calibrated model should be validated for the selected dataset to ensure the model's performance. On achieving the best-fit model, the calibrated model can be used to determine various scenarios for pollution load reduction and maintaining water quality for the intended use. Thus, the proposed framework helps users and researchers in determining the self-purification capacity and maintaining the river's health for desired use.

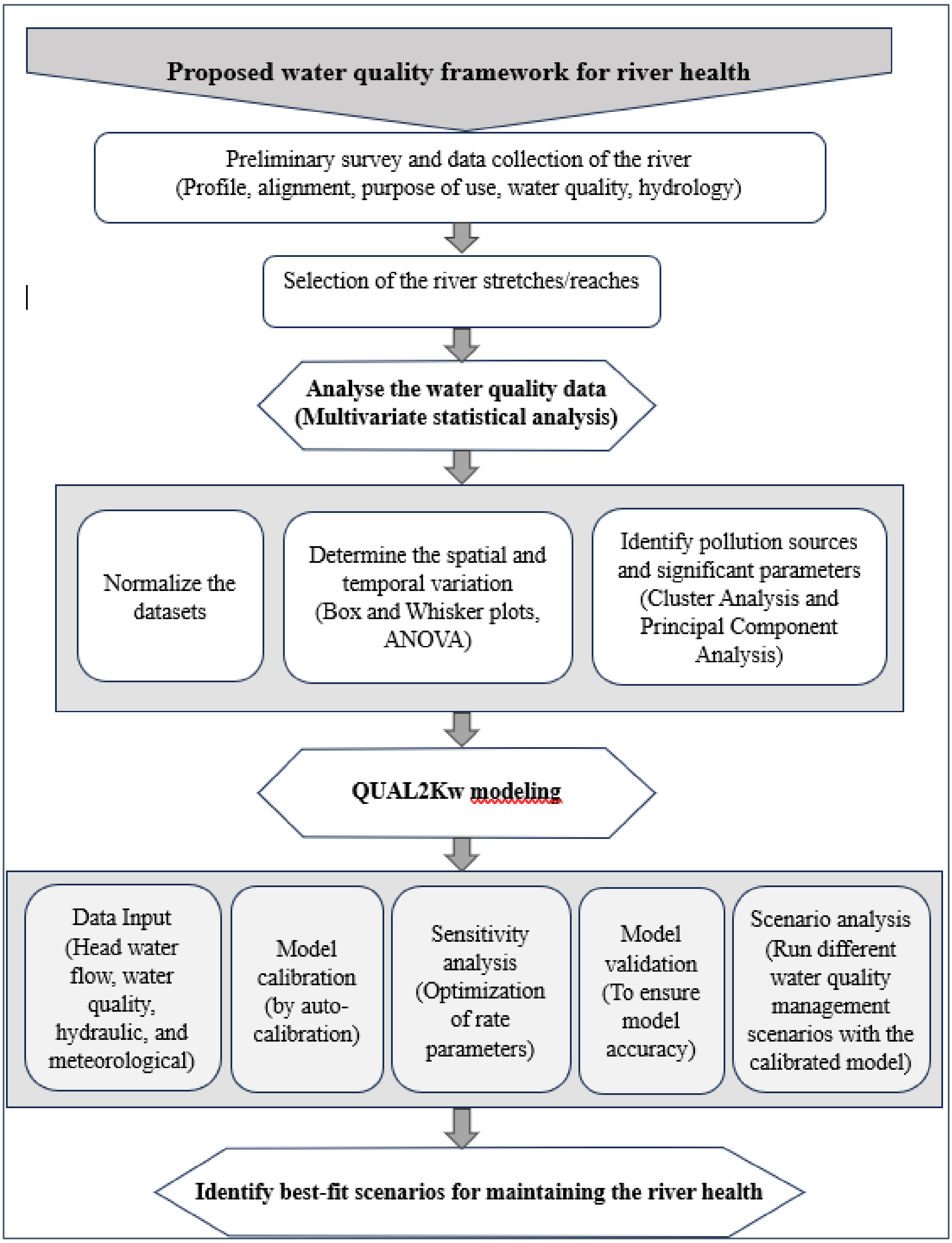


FIGURE 3.5 Proposed water quality modeling framework for the river health

CHAPTER 4

Multivariate Statistical Analysis, Results and Discussions

This chapter describes the application of identified multivariate statistical analysis techniques to the collected water quality datasets. It includes data collection, preparation, analysis, results and discussions of the statistical analysis techniques applied to the collected datasets for the selected stretches, as described in detail in the following sections.

4.1 Data Collection and Preparation:

The water quality data for the selected locations were obtained from the Gujarat Environment Management Institute (GEMI). GEMI's laboratory is accredited by the National Accreditation Board for Testing & Calibration Laboratories (NABL) under the Quality Council of India (QCI). The laboratory has been recognized as the 'State Water Lab' and 'State Air Lab' by the Forest and Environment Department, Govt. of Gujarat under the provisions of the Water (Prevention and Control of Pollution) Act, 1974 and the Air (Prevention and Control of Pollution) Act, 1981. Moreover, it has also been recognized as an 'Environment Laboratory' by the Central Pollution Control Board, New Delhi under the Environment (Protection) Act, 1986. The laboratory operates with standard procedures documented under Integrated Management System (IMS), aligning with international standards ISO 9001:2015 (Quality Management System), ISO 14001:2015 (Environmental Management System), and ISO 45001:2018 (Occupational Health and Safety Management System) [167].

Looking at the data availability and characteristics of the selected sites, 17 water quality parameters were considered: Sample temperature, pH, colour, total solids (TS), total dissolved solids (TDS), total suspended solids (TSS), turbidity, ammonia nitrogen (NH_3- N), chloride, total alkalinity (TA), total hardness (TH), chemical oxygen demand (COD), biological oxygen demand (BOD), dissolved oxygen (DO), electric conductivity (EC), sulphate, and nitrate. The collected data include the samples from the Sabarmati River collected by grab sampling with the standard sampling protocol, with a sampling frequency of about three to four times a year for each location. The Institute has developed its own guideline, 'sampling protocol for water and wastewater', which has been approved by Govt. of Gujarat under the provisions of the Water (Preservation and Control of Pollution) Act 1974. Sample collections were followed only in accordance with the guideline and by skilled staff. The samples were preserved in appropriate air tight sampling bottles and containers with adequate preserving agents to protect samples from probable contamination and to maintain their integrity. Samples were collected separately in accordance with the preservation and analysis requirement for different parameters. Samples were preserved with H_2SO_4 for hardness, ammonia nitrogen and COD, whereas $MnSO_4$ and alkali iodide azide were used for BOD. For all other physicochemical parameters, samples were kept unpreserved. Samples were transported on the same day to GEMI's laboratory for further analysis. The analysis is carried out in accordance with the standard operating procedures (SOPs) and test procedures. The standard methods of the American Public Health Association (APHA), 23rd edition was used for analyzing pH, colour, conductivity, suspended and dissolved solids, turbidity, hardness, chloride, sulphate, nitrate and COD. The Bureau of Indian Standards (BIS), IS 3025, was employed for BOD and DO analysis. The analytical instruments include pH meter, colour comparator, conductivity meter, nephelo turbidity meter, vacuum pump with filtration assembly and oven for solid measurement, titration apparatus for hardness, alkalinity and DO, BOD incubator, COD apparatus, UV-visible spectrophotometer for sulphate and nitrate [160, 161].

The dataset comprises 11 sites monitored at a frequency of about 3 to 4 times a year for 17 parameters from December 2012 to November 2021, totaling 5361 datasets. The parameters of nitrate and sulphate have been monitored since 2015. The sample water quality dataset is included in **Appendix A**.

The data were examined for outliers using the interquartile range (IQR) method. The variables were normalized to have a mean of zero and a standard deviation of one by calculating a standardized z-score [166]. **Table 4.1** presents the statistical interpretation of the data.

TABLE 4.1 Statistical interpretation of data

Location code		Sample Temp. °C	pH	Color (Hazen)	TS mg/L	TDS mg/L	TSS mg/L	Turbidity (NTU)	NH_3N mg/L	Chloride as Cl- mg/L	Total Alkalinity mg/L	Total Hardness mg/L	COD mg/L	BOD mg/L	DO mg/L	Conductivity (µS/cm)	Sulphate mg/L	Nitrate mg/L
US-1	**Mean**	**28.03**	**8.38**	**7.83**	**211.94**	**185.48**	**12.00**	**7.34**	**0.90**	**48.65**	**142.35**	**143.83**	**17.23**	**2.83**	**7.60**	**354.56**	**15.23**	**2.89**
	Range	15 - 38	7.84 - 8.92	5 - 15	76 - 296	68 - 286	2 - 48	1 - 17.2	0.32 - 2.24	18.38 - 100	110.46 -	90 - 190	0 - 44	0.2 - 7	4 - 10.09	267 - 432	9.53 - 19.18	0.16 - 6.1
	S.D.	4.85	0.27	2.79	50.58	55.61	11.09	4.21	0.55	22.55	25.49	22.56	10.19	1.82	1.43	45.07	2.33	1.78
	S.E.	0.86	0.36	0.64	12.65	12.53	2.03	1.06	0.12	4.44	11.46	7.31	1.92	0.34	0.34	44.99	1.89	0.46
US-2	**Mean**	**28.39**	**7.93**	**8.33**	**322.44**	**292.69**	**9.32**	**3.33**	**0.97**	**84.26**	**175.39**	**186.49**	**11.35**	**3.11**	**7.45**	**522.47**	**16.88**	**3.85**
	Range	17 - 36	7.47 - 8.78	5 - 15	172 - 466	50 - 460	1 - 40	0.9 - 7	0.23 - 3	19.26 - 180	23 - 326	70 - 310	0 - 32	0 - 6.06	4 - 10	210 - 830	14.22 -	0.32 - 8.88
	S.D.	4.29	0.32	3.25	89.68	100.50	9.61	1.78	0.74	45.50	72.67	54.88	7.73	1.55	1.45	169.55	2.27	2.59
	S.E.	0.77	0.34	0.71	18.42	19.62	1.79	0.49	0.15	8.32	14.71	11.10	1.51	0.30	0.41	69.87	2.21	0.65
US-3	Mean	28.55	8.04	8.10	341.00	312.63	9.89	5.51	0.96	90.14	176.08	190.62	14.56	2.60	7.11	619.18	18.73	4.30
	Range	17 - 38	7.55 - 8.74	5 - 15	190 - 550	178 - 484	1 - 40	1 - 15	0.34 - 2.24	24.53 - 199.9	23 - 280	120 - 270	0 - 38	0 - 6	4 - 10	317 - 858	9.17 - 28.87	0.21 - 11.74
	S.D.	4.52	0.34	2.76	89.80	83.62	10.13	3.99	0.59	41.12	66.60	36.61	11.85	1.65	1.32	175.21	5.38	3.07
	S.E.	0.81	0.35	0.69	23.76	21.94	1.91	0.92	0.13	9.00	14.83	13.19	2.24	0.34	0.53	81.01	2.46	0.75
US-4	**Mean**	**28.93**	**7.96**	**7.17**	**439.50**	**341.92**	**11.44**	**4.71**	**0.68**	**128.89**	**200.69**	**191.62**	**13.62**	**2.14**	**7.24**	**710.17**	**23.91**	**13.59**
	Range	17 - 38	7.21 - 8.72	5 - 15	170 - 900	156 - 760	1 - 42	0.05 - 16.8	0.23 - 1.12	24.15 - 282	11 - 472.72	100 - 260	0 - 38	0 - 5.4	4 - 10	424 - 1013	1.1 - 49.98	0.14 - 78.4
	S.D.	4.72	0.36	2.79	223.20	132.75	11.32	4.75	0.24	77.21	114.82	45.60	11.22	1.26	1.33	185.60	12.62	21.15
	S.E.	0.83	0.42	0.61	45.19	35.85	2.20	0.94	0.08	14.00	21.76	17.29	2.08	0.24	0.44	103.78	3.41	4.01
MS-1	**Mean**	**26.67**	**8.34**	**8.26**	**189.14**	**162.19**	**11.53**	**4.08**	**0.78**	**40.02**	**140.91**	**120.31**	**15.68**	**3.08**	**7.37**	**292.62**	**15.71**	**5.44**
	Range	15 - 33.5	7.77 - 8.99	5 - 15	62 - 336	60 - 254	1 - 40	1.2 - 7	0.44 - 1	5.84 - 140	112 - 200	100 - 170	1 - 41	0.002 - 13	5 - 9.4	251 - 370	1.22 - 39.3	0.05 - 13.9
	S.D.	3.98	0.24	3.17	64.22	46.89	11.88	1.67	0.20	35.91	22.80	16.56	10.51	3.09	1.10	34.39	12.49	3.83
	S.E.	0.85	0.47	0.79	19.85	16.01	2.63	0.70	0.09	7.70	14.54	11.26	2.28	0.64	0.69	41.13	3.49	1.14
MS-2	**Mean**	**27.73**	**8.04**	**11.41**	**321.13**	**266.63**	**19.91**	**20.89**	**0.99**	**60.83**	**160.46**	**145.89**	**33.85**	**2.93**	**5.91**	**489.14**	**25.45**	**6.06**
	Range	19 - 36	7.05 - 9.66	5 - 30	158 - 698	130 - 575	2 - 68	3.2 - 67.3	0.43 - 3.52	9.68 - 200	14 - 330	79.56 - 240	0 - 111.1	0 - 12	0.82 -	249 - 1023	10.09 -	0.05 - 15
	S.D.	4.50	0.59	6.99	156.77	122.88	16.72	19.27	0.72	47.59	65.86	36.53	30.20	2.97	2.89	225.87	15.34	4.51
	S.E.	0.78	0.25	1.31	30.90	24.61	2.99	3.90	0.15	8.76	14.42	9.50	5.46	0.55	0.54	64.75	3.83	1.00
MS-3	**Mean**	**28.38**	**8.09**	**8.93**	**320.09**	**264.84**	**27.61**	**21.48**	**0.85**	**52.07**	**161.43**	**146.56**	**26.63**	**3.08**	**6.29**	**486.60**	**22.07**	**4.73**
	Range	20 - 36	7.32 - 9.02	5 - 15	154 - 710	148 - 573	2 - 108	3.4 - 77.9	0.43 - 2.16	11.84 - 150	20 - 270.46	79.82 - 230	0 - 90	0 - 8.58	1 - 12.6	265 - 1047	8.3 - 59.65	0.05 - 10.15
	S.D.	4.09	0.44	3.09	149.06	113.68	24.87	20.32	0.48	41.64	50.59	35.77	22.13	2.53	2.50	228.25	12.09	2.94
	S.E.	0.72	0.41	0.85	29.76	23.26	4.49	4.13	0.11	7.64	14.17	9.44	4.11	0.49	0.49	66.24	3.25	0.71

Location code		Sample Temp. °C	pH	Color (Hazen)	TS mg/L	TDS mg/L	TSS mg/L	Turbidity (NTU)	NH_3N mg/L	Chloride as Cl- mg/L	Total Alkalinity mg/L	Total Hardness mg/L	COD mg/L	BOD mg/L	DO mg/L	Conductivity (µS/cm)	Sulphate mg/L	Nitrate mg/L
DS-1	**Mean**	**28.53**	**8.24**	**9.46**	**303.21**	**243.76**	**20.65**	**34.91**	**0.89**	**77.65**	**163.97**	**152.29**	**35.29**	**3.71**	**6.71**	**419.94**	**23.31**	**6.69**
	Range	20 - 38.1	7.44 - 9.04	5 - 25	68 - 661	64 - 578	1 - 68	1.1 - 127	0.24 - 3	13.7 - 219.92	19 - 300	110 - 250	0 - 100	0 - 12	1.21 -	282 - 816	3.83 - 59.63	0.05 - 17.55
	S.D.	4.28	0.36	5.56	138.78	117.08	15.53	36.87	0.60	67.61	68.02	34.91	27.41	2.74	2.40	148.86	14.65	4.51
	S.E.	0.77	0.58	1.18	31.63	26.13	3.17	7.26	0.13	12.46	15.55	9.57	5.25	0.53	0.56	55.50	3.76	1.08
DS-2	**Mean**	**29.01**	**7.51**	**133.50**	**1811.33**	**1429.57**	**254.06**	**130.93**	**26.09**	**351.57**	**518.07**	**233.72**	**353.25**	**35.34**	**0.50**	**3451.39**	**128.89**	**28.62**
	Range	19 - 37	6.82 - 8.82	10 - 590	340 - 4810	230 - 4196	44 - 700	17.6 - 270	0.47 - 74	28 - 629.8	51 - 1050	120 - 320	9 - 980	0 - 271	0.5 - 0.5	317 - 12460	14 - 224.2	0.05 - 65.3
	S.D.	4.35	0.57	160.53	1023.57	963.94	153.85	68.24	19.49	159.60	255.53	50.16	240.20	69.16	0.00	3383.35	51.16	19.39
	S.E.	0.76	0.32	28.44	226.63	195.52	29.78	16.94	3.62	41.68	52.36	19.60	45.34	12.28	0.06	701.69	17.47	4.48
DS-3	**Mean**	**29.03**	**7.42**	**80.17**	**1464.13**	**1267.21**	**102.90**	**80.30**	**17.69**	**450.25**	**450.56**	**253.66**	**219.34**	**28.27**	**0.79**	**2335.70**	**155.47**	**29.86**
	Range	19 - 38.1	7.16 - 7.99	5 - 300	336 - 2340	100 - 2294	14 - 252	20 - 172	0.58 - 42	27 - 740	65 - 767	140 - 350	30 - 490	0 - 167	0 - 3.8	320 - 3350	20 - 237.02	0.05 - 57.05
	S.D.	4.47	0.19	71.73	521.10	562.50	62.11	41.81	12.41	182.14	211.84	62.66	121.78	48.04	1.07	973.59	60.90	17.79
	S.E.	0.78	0.54	13.18	108.15	103.42	11.87	10.62	2.25	36.42	38.67	18.39	21.86	8.69	0.20	306.51	19.52	4.40
DS-4	**Mean**	**29.34**	**7.61**	**56.33**	**1282.56**	**1125.82**	**77.68**	**67.27**	**16.85**	**409.20**	**446.65**	**247.08**	**168.34**	**31.82**	**0.39**	**2055.00**	**122.99**	**26.46**
	Range	20 - 38	7.27 - 8.49	5 - 200	268 - 2338	180 - 2290	8 - 220	21.1 - 145	0.41 - 39	60 - 805.06	43 - 700.08	100 - 360	20 - 400	0 - 138	0 - 1	313 - 3150	16 - 204.1	0.05 - 54.1
	S.D.	4.57	0.30	44.96	456.00	502.79	59.43	31.51	11.63	184.31	208.08	63.24	90.63	46.59	0.26	878.64	47.24	16.61
	S.E.	0.80	0.44	8.41	99.85	96.40	10.98	8.53	2.14	37.16	39.53	14.63	16.76	8.33	0.06	271.60	15.38	3.99

4.2 Data Analysis and Interpretation

For the statistical analysis of the data, the water quality data were categorized according to the sampling stations: upstream (US), middle stream (MS), and downstream (DS), and according to the seasons: pre-monsoon (March-May), monsoon (June -August), post-monsoon (September– November), and winter (December – February). The results of the analysis are described in the following section.

4.2.1 Box and Whisker Plots

Box-whisker plots **Figure 4.1** illustrate the temporal and spatial variation in the water quality parameters. Seasonal changes in water quality parameters are evident through temporal variations. The temperature was highest during the pre-monsoon season and lowest in the winter. A clear inverse relationship between temperature and dissolved oxygen (DO) is apparent; DO levels were highest in winter and lowest during the pre-monsoon season, highlighting a distinct seasonal effect. The dissolution of oxygen occurs naturally. In warmer water, oxygen is more easily saturated, resulting in lower dissolved oxygen levels compared to colder water. This inverse relationship between temperature and DO was reported in the study on the Fuji River, Japan [15]. Parameters including pH, colour, TS, TDS, NH_3-N, Chloride, EC, and COD were higher in the pre-monsoon season than in other seasons. These parameters exhibited a decreasing trend during the monsoon season, indicating the effect of dilution. The average values of solid concentration parameters, such as TS, TDS, TSS, and turbidity were lower in the post-monsoon season compared to the monsoon season due to reduced runoff. Higher concentration of pollution indicating parameters, TDS, chlorinde, NH_3-N, COD sulphate and nitrate during winter and premonsoon season, indicates the criticality of pollution load in these seasons.

At all sampling sites, the average pH ranged from 7.5-8.5, with higher pH variations observed at the downstream sites. The upstream stretch showed the highest average DO, followed by the middle and downstream stretches. DO levels below 2.3 mg/L were detected downstream of the Vasna Barrage site. Parameters, such as nitrate and sulphate, TDC, chloride, EC, total alkalinity and total hardness were higher at upstream sites compared to middle stream sites. This may be attributed to surface runoff as the upstream sites are surrounded by agricultural fields. Whereas, parameters such as BOD, COD, NH_3-N, TSS and turbitidy content were lower at the upstream locations and the Karai Dam site in the middle stream. Beyond these sites, these parameters showed a gradual increasing trend going towards downstream. These shows that the water quality is comparatively good at the upstream sites. Middle stream sites are located within urban areas and are developed as the riverfront area. Therefore, these sites are affected by the recreational activities prevalent in that area. Upstream sites, beyond the Vasna Barrage site, showed elevated levels of all parameters, including colour, TS, TDS, chloride, total alkalinity, COD, BOD, conductivity, sulphate, and nitrate, indicating chemical pollution resulting from effluent and sewage discharges. The pollution from effluent discharges beyond the Vasna Barrage has been reported in a previous study [168].

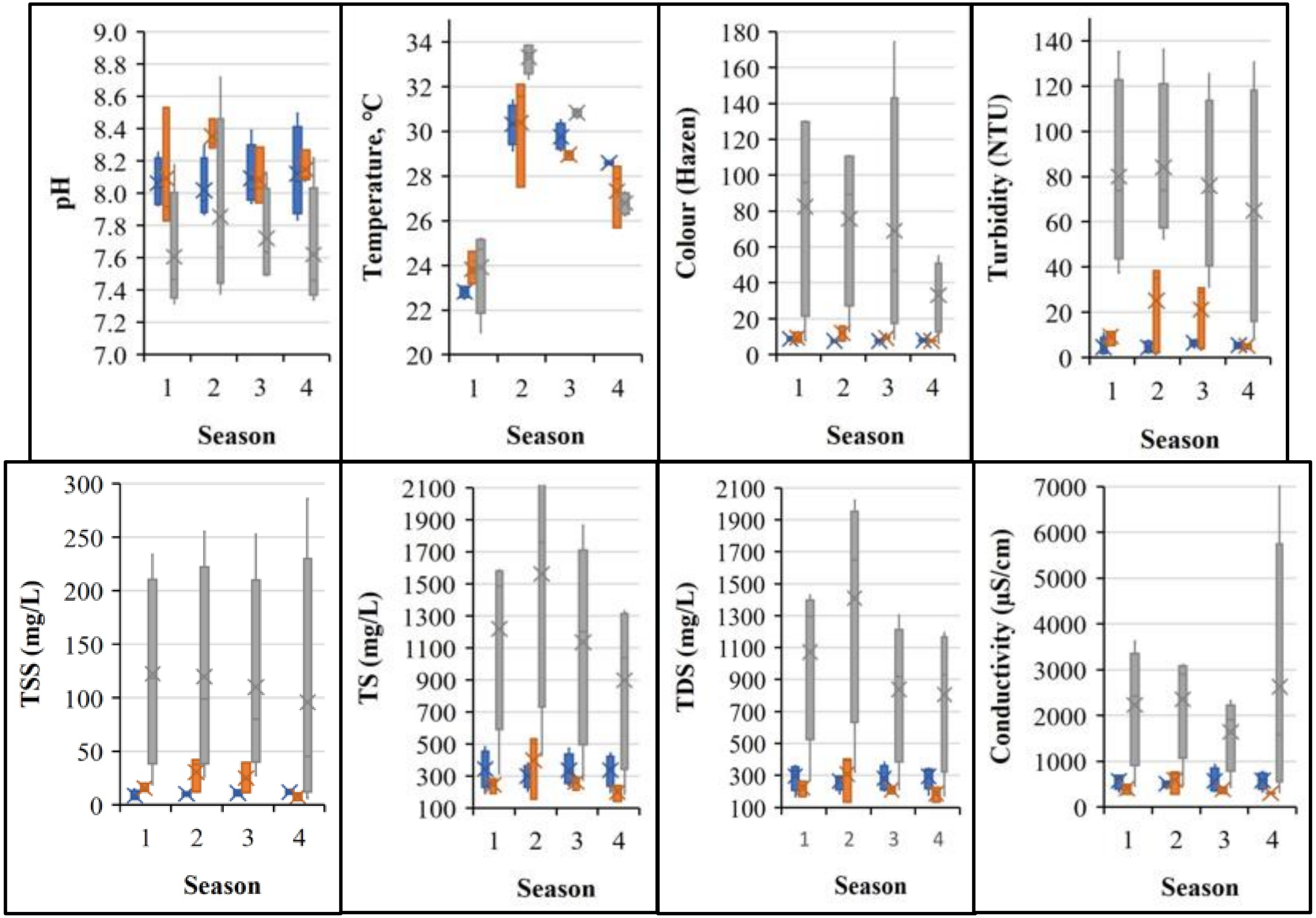


FIGURE 4.1 Box-whisker plots showing seasonal and temporal variations

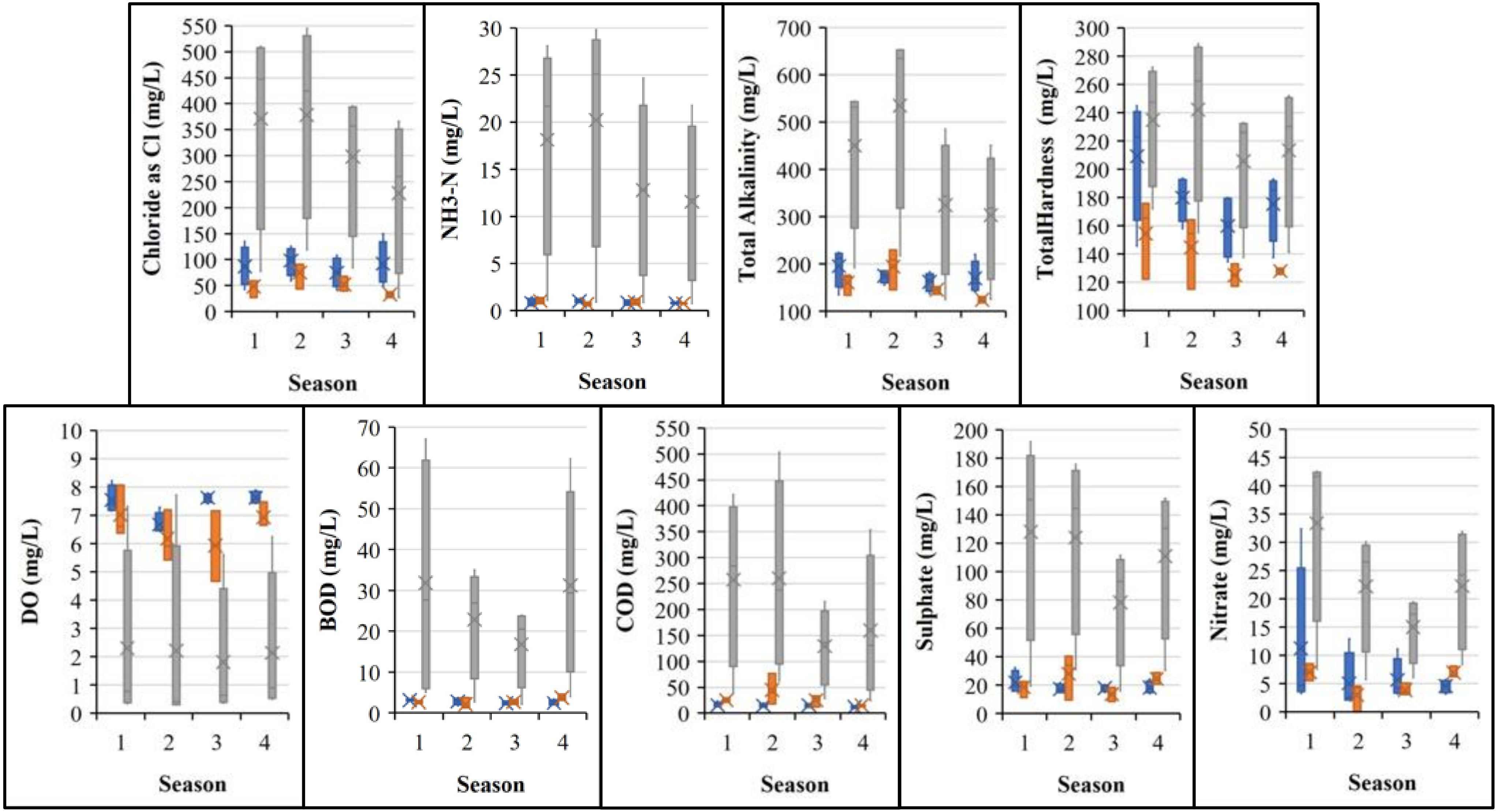


FIGURE 4.1 Box-whisker plots showing seasonal and temporal variations (Contd.)

4.2.2 ANOVA Analysis

The non-parametric Kruskal-Wallis test was used to determine the significance of water quality parameters across sampling points and seasons [50]. **Table 4.2** presents a summary of the independent samples from the Kruskal-Wallis test with two different grouping variables. The test results revealed significant differences in water quality parameters among the sampling sites ($p<0.05$), except temperature. However, when grouped by seasons, temperature, colour, NH_3N, chloride, and nitrate exhibited significant variations ($p<0.05$). The correlation of these variables indicates the influence of seasonal temperature, dilution, and runoff. The non-significance of other variables with the season ($p>0.05$) indicates the anthropogenic influence in the study area. This finding aligns with the conclusion drawn from a study on the Fuji River, which indicated a non-significance correlation of TSS, EC, COD, and PO_4-P with the seasons, signifying the contribution from anthropogenic sources [15].

TABLE 4.2 Independent-Samples Kruskal-Wallis Test (p-value) Summary

Asymptotic Sig. (2-sided test)	**Sample Temp.**	**pH**	**Color (Hazen)**	**TS mg/L**	**TDS mg/L**	**TSS mg/L**	**Turbidity NTU**	**NH_3N mg/L**	**Cl^- mg/L**
Among stations	0.058	000	000	000	000	000	000	000	000
Among seasons	000	0.079	0.011	0.052	0.519	0.103	0.715	0.004	0.024
Asymptotic Sig. (2-sided test)	**TA mg/L**	**TH mg/L**	**COD mg/L**	**BOD mg/L**	**DO mg/L**	**EC (µS/cm)**	**Sulphate mg/L**	**Nitrate mg/L**	
Among stations	000	000	000	.001	000	000	000	000	
Among seasons	0.001	0.577	0.141	0.116	0.468	0.136	0.694	000	

4.2.3 Cluster Analysis

The spatial variations in the water quality parameters were assessed through cluster analysis. This analysis produced a dendrogram, **Figure 4.2**, that grouped the sampling sites into three significant clusters, with a (Dlink/Dmax) X 100 ratio below 60. [19, 169].

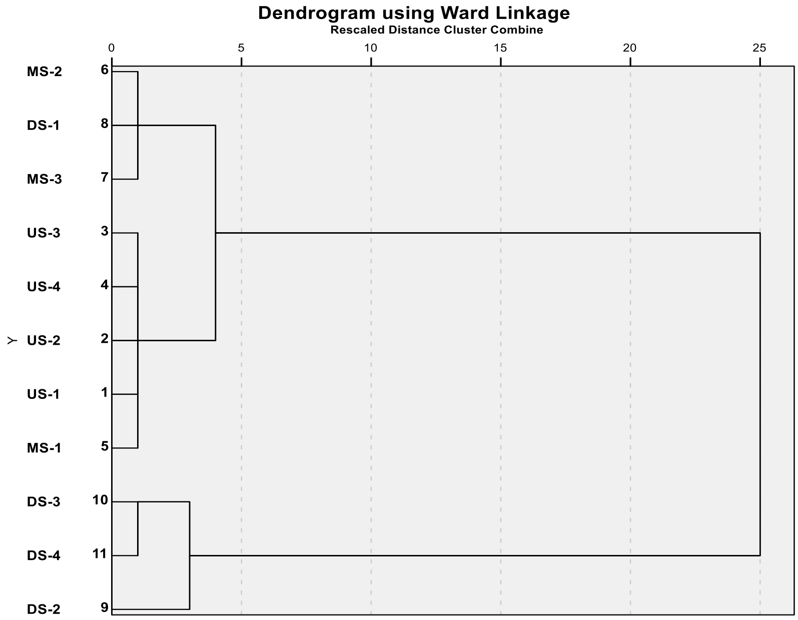


FIGURE 4.2 Dendrogram based on hierarchical cluster analysis

Upstream sites US-1 to US-4 and middle stream site MS-1 form a single cluster. These sites exhibited higher DO values, indicating good water quality with minimal anthropogenic impact. These sites are classified as less polluted (LP). The middle stream downstream of Karai Dam i.e. MS-2, MS-3, and downstream site DS-1 at Vasna Barrage formed another cluster. These sites are significantly affected by recreational and anthropogenic activities. The previous study also reported the deterioration in the water quality at the sites located within the Ahmedabad city area [44], thus classified as moderately polluted (MP). Sites DS-2 to DS-4, located downstream of the Vasna Barrage, face pollution from various discharges, which is consistent with findings from a previous study [168]. Therefore, these sites are categorized as highly polluted (HP). This method is effective for classifying surface water across the entire region, facilitating the design of an optimal future sampling network.

4.2.4 Principal Component Analysis (PCA) / Factor Analysis (FA)

Principal component analysis (PCA) / factor analysis (FA) was performed on the three distinct spatial sites identified through cluster analysis i.e. LP, MP, and HP sites. A large number of variables were reduced by eliminating highly correlated and dependent variables. As highlighted in previous studies on river water quality assessment, the application of FA requires the removal of highly correlated variables to prevent interference with the identification of unique contributing variables. Eliminating overlapping variables or those representing similar water quality dimensions is also beneficial for reducing monitoring costs. This is a crucial step, as it relies on site-specific requirements [2, 166]. In the present study, parameters such as colour, TS, TSS, turbidity, conductivity, total hardness, and total alkalinity were removed due to their high correlation. Although some parameters like BOD and DO, as well as COD and BOD, are correlated, they were retained in the analysis as they are important indicators of pollution load and the river's carrying capacity. The normalized raw data, including sample temp., pH, TDS, NH_3N, chloride, COD, BOD, DO, sulphate, and nitrate was grouped for LP, MP, and HP sites and subjected to principal component analysis. This approach aimed to compare the water quality variables and to determine the key parameters influencing each grouped site.

Kaiser–Meyer–Olkin (KMO) and Bartlett's sphericity were conducted to assess the suitability of the dataset for PCA [45, 49, 164]. A KMO value closer to 1 indicates a more suitable dataset, while a value below 0.5 suggests unsuitability of the data for PCA. Bartlett's test assesses the equality of variance among multiple variables, indicating whether the correlation matrix is an identity matrix. A significance level of $p<0.05$ suggests that the variance is unequal and that substantial correlations exist among the samples. For all three spatial sites, the estimated KMO values were greater than 0.6, and Bartlett's test returned a significance level of 0 for all three regions. This indicates a significant relationship among the variables and confirms the suitability of the data for PCA.

The scree plot identifies the number of principal components (PCs) based on their eigenvalue [49]. The components with an eigenvalue greater than 1 are retained for further analysis. The load factor matrix for LP, MP, and HP sites is summarized in **Tables 4.3 to TABLE** 4.5 with eigenvalue, percentage variance, and cumulative variance percentage. The analysis revealed four PCs for LP and HP sites and three PCs for MP sites, all with eigenvalues greater than 1, contributing the maximum to the overall variance. These PCs account for 62.38%, 60.32%, and 67.18 % of the total variance in the datasets for the LP, MP, and HP sites, respectively. The parameters contributing the most were identified from the component loading.

Component loadings indicate the correlation between the variables and the newly formed components through load factors. The load factor values substantially polarized after rotation. The coefficients determined from the varimax rotation method were utilized to identify the dominant water quality parameters, as evidenced by previous studies. The absolute value of the load factor indicates the significance of the variables [17, 19, 52, 165]. Previous studies have considered different thresholds for load factors to identify significant water quality variables. According to a study conducted on the Bagmati River of Nepal, the load factors with an absolute value >=0.8 were categorized as ‘strong’, indicating a high proportion of variance in the principal component; values between >=0.6 and < 0.8 were categorized as ‘moderate’ factor loading; and values from >=0.4 and <0.6 were categorized as ‘weak’ factor loading, suggesting lesser importance in explaining the variance [12]. Another study on the Karoon River in Iran identified significant water quality parameters with an absolute factor value > 0.6 [17].

As shown in **Table 4.3**, PC1 explained 18.26% of the total variance for LP sites, exhibiting strong positive loading on the nutrient parameters (sulfate and nitrate). This component indicates that these parameters are primarily influenced by non-point sources, such as agricultural runoff [19]. PC2 accounted for 17.82% of the total variance and was associated with moderate loading on COD and DO, suggesting the influence of both anthropogenic and natural sources. Bathing and cattle grazing activities were observed near these sites, particularly at the US-1 Dharoi Dam site and US-4 Sapteshwar temple, which are well-known tourist destinations and bathing locations, contributing significantly to anthropogenic input. The third principal component, PC3, demonstrated moderate loading on salt groups, TDS and Cl, accounting for 15.67% of the total variance. PC4 explained 10.62% of the total variance, showing strong loading solely on sample temperature, reflecting seasonal impacts.

In the datasets of MP sites presented in **Table 4.4**, PC1 described the highest proportion of the total variance at 28.11% among the three PCs, with strong positive loading on TDS and Cl, and moderate loading on COD and sulphate. PC2 explained 18.64% of the total variance, exhibiting strong positive loading on pH, moderate negative loading on NH_3N, and moderate positive loading on DO. PC3 accounted for 13.57% of the total variance, characterized by strong positive factor loading on nitrate only. These sites, located along the riverfront and within the city, are predominantly influenced by recreational activities, with religious activities also present nearby.

TABLE 4.3 Load factor matrix for LP sites

LP sites				
Rotated Component Matrix				
	Component			
	1	2	3	4
T Sample	-0.13	0.07	0.18	0.88
pH	-0.18	0.6	-0.34	0.07
TDS	-0.03	-0.14	0.78	0.19
NH_3N	-0.23	0.37	0.45	-0.49
Cl	0.48	0.06	0.74	-0.06
COD	-0.01	0.62	0.07	-0.05
BOD	0.17	0.58	0.13	-0.03
DO	0.06	0.73	-0.15	0.01
Sulphate	0.87	-0.02	0.12	-0.04
Nitrate	0.84	0.1	0.01	-0.03
Eigenvalues	2.11	1.83	1.28	1.02
% Variance	18.26	17.82	15.67	10.62
Cumulative variance %	18.26	36.08	51.75	62.38

TABLE 4.4 Load factor matrix for MP sites

MP sites			
Rotated Component Matrix			
	Component		
	1	2	3
T Sample	0.43	0.41	0.30
pH	0.28	0.81	0.04
TDS	0.89	-0.03	0.12
NH_3N	0.01	-0.65	0.32
Cl	0.84	0.15	0.26
COD	0.63	-0.07	-0.36
BOD	-0.36	0.04	-0.49
DO	-0.18	0.76	0.08
Sulphate	0.70	0.06	0.20
Nitrate	0.05	-0.04	0.82
Eigenvalues	3.1	1.79	1.14
% Variance	28.11	18.64	13.57
Cumulative variance %	28.11	46.76	60.32

TABLE 4.5 Load factor matrix for HP sites

HP sites				
Rotated Component Matrix				
	Component			
	1	2	3	4
T Sample	0.09	-0.02	-0.33	0.75
pH	0.23	-0.24	-0.72	0.11
TDS	0.85	0.13	0.14	0.15
NH_3N	0.85	-0.06	-0.10	0.06
Cl	0.60	0.49	0.00	-0.05
COD	0.45	0.16	0.63	0.07
BOD	0.12	-0.56	0.55	0.06
DO	-0.06	-0.19	-0.26	-0.75
Sulphate	0.33	0.70	0.22	0.13
Nitrate	0.02	0.81	0.15	0.12
Eigenvalues	2.86	1.51	1.33	1.03
% Variance	21.96	18.34	14.95	11.94
Cumulative variance %	21.96	40.29	55.24	67.18

For the dataset of HP sites shown in **Table 4.5**, PC1 accounted for 21.96% of the total variance, demonstrating strong positive loading on TDS and NH_3N, along with moderate positive loading on Chloride. PC2 contributed 18.34% of the total variance, with positive loading on nutrient parameters, strong loading on nitrate, and moderate loading on sulphate. This reflects the impact of surface runoff from nearby agricultural fields, as noted in previous studies [170]. PC3, which explained 14.95% of the total variance, correlated moderately with pH (negative) and COD (positive). The component loadings of PC1 and PC3 indicate contamination of river water by both organic and inorganic constituents, with the influence of wastewater discharges evident in these parameters. PC4 showed moderate factor loading on sample temperature (positive) and DO (negative), indicating a seasonal impact of temperature, consistent with findings from a study of the Fuji River in Japan [15].

For this study, water quality parameters with an absolute value of the factor loading >=0.6 were deemed significant for their contribution to water quality variation. Using this criterion, the parameters that affect water quality variability at the spatially distinguished sites were identified from the load factor matrices and summarized in **Table 4.6**.

TABLE 4.6 Significant water quality parameters for spatially distinguished sites

LP sites	:	Sample temp., TDS, Cl, COD, DO, Sulphate, Nitrate
MP sites	:	pH, TDS, NH_3N, Cl, COD, DO, Sulphate, Nitrate
HP sites	:	Sample temp., pH, TDS, NH_3N, Cl, COD, DO, Sulphate, Nitrate

CHAPTER 5

QUAL2Kw Modeling, Results and Discussions

This chapter presents water quality simulations of the identified significant water quality variables for selected stretches using the QUAL2Kw model. It details the model's input data requirements, data sources, calibration and validation requirements, application to the selected stretches, model sensitivity, simulation results, scenario analysis and discussions. The details are provided in the following subsections.

5.1 Input Data Requirements and Data Source

5.1.1 Water Quality Data

From the significance of water quality parameters determined from principal component analysis section 4.2.4 and standard requirements of water quality, seven water quality parameters, including dissolved oxygen (DO), temperature, COD, BOD, NH_3-N, inorganic suspended solids (ISS), and pH, were selected for water quality simulations, which are important for the carrying capacity and health of the river.

- BOD, COD, and NH_3-N are important pollution load indicators and negatively impact the DO content. Temperature also has a direct correlation with the DO.
- ISS and pH are important indicators of the survival of the aquatic plant and the river ecosystem.
- Temperature is required for the model for an accurate simulation, as it significantly influences water quality parameters.

The parameters were considered based on the input requirements of the QUAL2Kw model. **Table 5.1** shows the water quality parameters required for model input and those considered from the collected datasets.

TABLE 5.1 Water quality parameters selected for model input

Parameter name as per QUAL2Kw	**Parameters considered** [152, 171, 172]
Temperature	Temperature
Inorganic suspended solids (ISS),	Inorganic suspended solids – 50% of TSS
Dissolved Oxygen (DO),	Dissolved oxygen (DO),
CBODslow,	CBODfast - BOD
CBODfast,	CBODslow - COD-CODf
NH_4 - Nitrogen	NH_4-N– NH_3-N
pH	pH

COD is assumed to represent the total oxygen demand, including ultimate carbonaceous BOD, i.e. CBODu. CBODf represents the portion of the total oxygen demand that reacts quickly. Therefore, BOD is considered as CBODf. The remaining oxygen demand represents slower-reacting oxygen demand, i.e. CBODs. It is computed by deducting CBODf from COD. Inorganic suspended solids were considered to be 50% of the total suspended solids [77, 152]. The water quality data sourced from the Gujarat Environment Management Institute, as discussed in section 4.1 above, were grouped based on the input requirements of the simulation run. The sample water quality dataset is included in **Appendix A**

5.1.2 Meteorological Data

Meteorological data, including ambient air temperature, dew point temperature, wind velocity, and solar radiation, were obtained from the Indian Meteorological Department (IMD) for the monthly period from 2012-2021 for Idar, Gandhinagar, and Ahmedabad stations. **Appendix B** shows the sample meteorological data. The data were compiled statistically and averaged by seasons and locations for model input.

5.1.3 Reach Data

Reach length, chainage, elevation, latitude, and longitude were determined from the alignment data of the selected locations obtained from the Gujarat Environment Management Institute (GEMI). The sample data are shown in **Appendix C**. According to Chapra (2008) , sediment oxygen demand (SOD) for organic river sediments ranges 1–2 $g/m^2/day$ [173]. Therefore, the bottom SOD coverage was assumed to be 100 % and the prescribed SOD (g $O_2/m^2/day$) was taken as 1.0. The sediment/hyporheic zone thickness of 10 cm, sediment porosity of 0.4, and hyporheic exchange flow of 0% were considered for the model run [77, 174].

5.1.4 Headwater Data

For the upstream stretch, the discharge from the Dharoi Dam into the Sabarmati River was adopted as headwater flow. Daily discharge data of the Dharoi Dam (2012-2021) were obtained from the Dharoi division. Sample data of Dharoi Dam discharge into the river are shown in **Appendix D**. For the water level data in the river upstream stretch, the river gauge data (Daily data) of the hydro-meteorological station of the Central Water Commission (CWC) located on the Sabarmati River at Derol Bridge, Vijapur were referenced. The data for the Derol station were collected from the CWC division for 2012-2021. It includes the gauge, water level, discharge, top width, wetted perimeter, hydraulic radius, manning coefficient, area, slope, velocity, and method of velocity observation. **Appendix E** shows sample data of the water level from the CWC Derol station.

The water released from the Sabarmati escape near Karai village (Karai Syphon) served as headwater for the middle stream stretch. The data were collected from the Narmada System Control Room, Sardar Sarovar Narmada Nigam Limited (SSNNL), Gandhinagar. The data includes monthly water release data from 2016-202. Sample data of water release from the Karai Syphon are shown in **Appendix F**. The water level in the middle stream stretch was considered based on the Hourly water level data (2012-2021) for the Subhas Bridge station of the Central Water Commission. **Appendix G** shows sample data of water level from the Subhas Bridge Station of CWC.

For the downstream stretch, the discharge released from the Vasna Barrage into the river was taken as headwater flow. The data was collected from the Vasna Division, Ahmedabad. It includes the daily and monthly water release data from the Vasna Barrage for 2012-2021. Sample data of the Vasna Barrage are shown in **Appendix H**.

5.1.5 Hydraulic Data

The hydraulic characteristics, channel slope, side slope, cross-sectional area, and velocity were calculated for each site depending on the collected river alignment data. Velocity and depth coefficients were computed depending on the rating area curve method as below [75, 77].

$V = aQ^b$,

$h = cQ^d$,

$b + d \leq 1$

where V =velocity, Q= discharge; h = depth, a = velocity coefficient, c =depth coefficient; b = velocity exponent, d = depth exponent.

5.1.6 Light and Heat Rate Parameters

Table 5.2 shows the light and heat parameters adopted for the study [72]. These parameters were from the global rate values and kept constant for the study.

TABLE 5.2 Light and Heat parameters

Parameter	*Value*	*Unit*	
Photosynthetically Available Radiation	**0.47**		
Background light extinction	**0.2**	*/m*	k_{eb}
Linear chlorophyll light extinction	**0.0088**	*1/m-(ugA/L)*	a_p
Nonlinear chlorophyll light extinction	**0.054**	*1/m-(ugA/L)$^{2/3}$*	a_{pn}
ISS light extinction	**0.052**	*1/m-(mgD/L)*	a_i
Detritus light extinction	**0.174**	*1/m-(mgD/L)*	a_o
Macrophyte light extinction	**0.015**	*1/m-(gD/m^3)*	a_{mac}
Solar shortwave radiation			
Atmospheric attenuation model for solar	**Bras**		
Bras solar parameter (used if Bras solar model is selected)			
atmospheric turbidity coefficient (2=clear, 5=smoggy, default=2)	**3**		n_{fac}
Ryan-Stolzenbach solar parameter (used if Ryan-Stolzenbach solar model is selected)			
atmospheric transmission coefficient (0.70-0.91, default 0.8)	**0.8**		a_{tc}
Downwelling atmospheric longwave IR radiation			
atmospheric longwave emissivity model	**Brunt**		
Brutsaert longwave emissivity parameter (used if Brutsaert longwave model is selected)			
parameter for emissivity using the Brutsaert equation	**1.24**		k_{brut}
Evaporation and air convection/conduction			
wind speed function for evaporation and air convection/conduction	**Brady-Graves-Geyer**		
Parameter for attenuation of solar radiation by cloud cover			
parameter for attenuation of solar radiation by cloud cover	**0.65**		*KCL1*
Parameter for cloud cover adjustment of sky emissivity of longwave radiation			
parameter for cloud cover adjustment of sky emissivity	**0.17**		*KCL2*

5.2 Model Calibration

A model was run for a population size of 100 with 50 generations for better performance and goodness of fit. The calculation time of 5.625 min was set to avoid model instability. The Euler method for numerical integration and the Brent method for pH modeling were applied. Phytoplankton were not considered for the study. O'Connor and Dobbins' equation was selected for the reaeration model. **Table 5.3** shows the Global rate parameters used for the model calibration. The rate parameters were considered based on the selected parameters, which are: CBODs - hydrolysis rate and oxidation rate, CBODf- oxidation rate, Inorganic suspended solids - settling velocity, and ammonium – nitrification. The values with the 'Yes' option in auto calibration inputs were calibrated by the QUAL2Kw model using the genetic algorithm (GA) [72, 76, 84].

TABLE 5.3 Global rate parameters and the auto calibration of the model

QUAL2Kw
Stream Water Quality Model
Sabarmati river Upstream
Global rate parameters

Open File | Run VBA | Run Fortran | Run Auto-cal | Fitness: 6.286

Parameter	Value	Units	Symbol	Auto-calibration inputs: Auto-cal	Min value	Max value
Stoichiometry:						
Carbon	40	gC	gC	No	30	50
Nitrogen	7.2	gN	gN	No	3	9
Phosphorus	1	gP	gP	No	0.4	2
Dry weight	100	gD	gD	No	100	100
Chlorophyll	1	gA	gA	No	0.4	2
Inorganic suspended solids:						
Settling velocity	0.00328	m/d	v_i	Yes	0	2
Oxygen:						
Reaeration model	O'Connor-Dobbins			f(u h)		
Temp correction	1.024		θ_a			
Reaeration wind effect	None					
O2 for carbon oxidation	2.67	gO_2/gC	r_{oc}			
O2 for NH4 nitrification	4.57	gO_2/gN	r_{on}			
Oxygen inhib model CBOD oxidation	Exponential					
Oxygen inhib parameter CBOD oxidation	0.60	L/mgO2	K_{socf}	No	0.60	0.60
Oxygen inhib model nitrification	Exponential					
Oxygen inhib parameter nitrification	0.60	L/mgO2	K_{sona}	No	0.60	0.60
Oxygen enhance model denitrification	Exponential					
Oxygen enhance parameter denitrification	0.60	L/mgO2	K_{sodn}	No	0.60	0.60
Oxygen inhib model phyto resp	Exponential					
Oxygen inhib parameter phyto resp	0.60	L/mgO2	K_{sop}	No	0.60	0.60
Oxygen enhance model bot alg resp	Exponential					
Oxygen enhance parameter bot alg resp	0.60	L/mgO2	K_{sob}	No	0.60	0.60
Slow CBOD:						
Hydrolysis rate	0.11425	/d	k_{hc}	Yes	0	5
Temp correction	1.047		θ_{hc}	No	1	1.07
Oxidation rate	0.000745	/d	k_{dcs}	Yes	0	0.5
Temp correction	1.047		θ_{dcs}	No	1	1.07
Fast CBOD:						
Oxidation rate	0.43725	/d	k_{dc}	Yes	0	5
Temp correction	1.047		θ_{dc}	No	1	1.07
Ammonium:						
Nitrification	0.02	/d	k_{na}	Yes	0	10
Temp correction	1.07		θ_{na}	No	1	1.07
pH:						
Partial pressure of carbon dioxide	347	ppm	p_{CO2}			

5.3 Model Validation

The fitness of the calibrated model was measured as the reciprocal of the weighted average of the normalized root mean square error (RMSE) of the difference between the predicted and observed/input data of water quality, shown in **Equation (5.1)** [76].

$$f(x) = \left[\sum_{i=1}^{n} w_i\right] \left[\sum_{i=1}^{n} \frac{1}{w_i} \left[\frac{\frac{\sum_{j=1}^{m} O_{ij}}{m}}{\left[\frac{\sum (P_{ij}-O_{ij})^2}{m}\right]^{1/2}}\right]\right] \tag{5.1}$$

where Oi,j: observed values, Pi,j: predicted values, m: number of pairs of predicted and observed values, wi : weighting factors, and n: number of different state variables included in the reciprocal of the weighted normalized RMSE.

The weighting factors of the parameter can be selected arbitrarily. Weights for the water quality parameters were determined to reduce the error between measured and model-predicted parameters. The relative weights of each parameter indicate the leverage of a particular parameter on the model fitness. Considering this strategy, a higher weight was assigned to the most influencing parameter. With trials, the weight for DO was taken as 10 and justified as it is the most influencing parameter. The weight of 2 was considered for CBODs and CBODf, and 1 for ISS, NH_3-N, and pH. [84, 175].

5.4 Model Application

Water quality models were simulated for all three selected stretches: upstream (US-1 to US-4), middle stream (MS-1 to MS-3), and downstream (DS-1 to DS-4). The upstream stretch, characterized by good water quality and identified as a less polluted site based on multivariate statistical analysis, served as the control. The input data requirements of the QUAL2Kw model and sensitivity analysis were assessed with this stretch. The water quality during the monsoon was reasonable compared to the other seasons. Therefore, the monsoon dataset (2012-2021) was used for model calibration, and the model's fitness was checked through validation.

Based on the upstream water quality simulation run with the QUAL2Kw model, the water quality was simulated for the middle and downstream stretches for the 2012-2021 dataset. From the assessment of water quality variations and multivariate statistical analysis, pre-monsoon and winter seasons were found to be critical due to higher chemical loads. Therefore, the water quality models were simulated for the pre-monsoon and winter seasons to determine the carrying capacity and self-purification requirements. The model was calibrated with the 2012-2017 dataset and validated with the 2018-2021 dataset. Various scenarios were run to determine the requirements for water quality standards. **Figure 5.1** shows the application of the model, with grouping of data input to the model for each stretch.

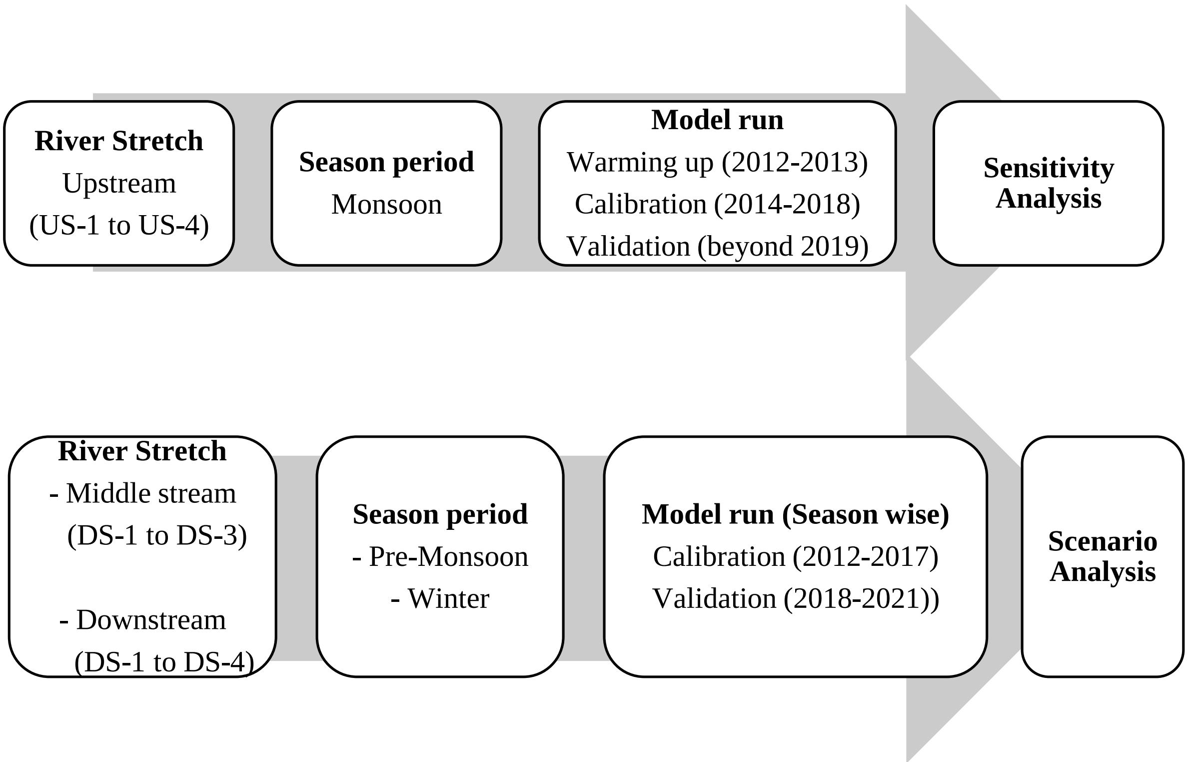


FIGURE 5.1 Application of QUAL2Kw model and grouping of data for model input

5.5 Upstream Stretch Simulation Run

To understand the model's application requirements and output, the model was run using monsoon season data from 2012-2013 without a calibration run, i.e. warming up the model. The model was calibrated for the monsoon season data 2014-2018 with the auto calibration method for the selected rate parameters. The calibrated model's performance was evaluated by considering 2018-2021 for validation.

5.5.1 Data Input to the Model

- **Location details**

The location details for the upstream stretch are shown in **Table 5.4**.

TABLE 5.4 Location Details for Upstream stretch

Location	Name	Chainage km
US-1	Dharoi Dam	70
US-2	Valasana Bridge	93.25
US-3	Fudeda Bridge	110.36
US-4	Sapteshwar Mahadev Bridge	111.5

- **Reach data**

Table 5.5 shows the river reach data for the upstream stretch, including their length, elevation, latitude, and longitude.

TABLE 5.5 Reach Data - Upstream stretch

Reach Label	Downstream end of reach label	Number	Reach Length	Downstream		Downstream location	Elevation		Downstream					
							Upstream	Downstream	Latitude			Longitude		
			(km)	Latitude	Longitude	(km)	(m)	(m)	Degrees	Minutes	Seconds	Degrees	Minutes	Seconds
	Headwater	0		24.01	72.86	0.000		162.094	24.00	0	37	72.00	51	21
US-1 to US-2	Valasana Bridge	1	23.25	23.83	72.79	23.250	162.094	161.000	23.00	50	1	72.00	47	21
US-1 to US-2	Fudeda Bridge	2	17.11	23.70	72.82	40.356	161.000	119.000	23.00	42	4	72.00	49	10
US-1 to US-2	Sapteshwar Mahadev Bridge	3	1.14	23.69	72.82	41.500	119.000	107.674	23.00	41	39	72.00	49	26

- **Headwater data**

Dharoi Dam data collected from the dharoi division were taken as a headwater input. Water level data was referenced from the derol station of the CWC division. The data are summarized in Error! Reference source not found..

TABLE 5.6 Head water (HW) data (Monsoon season) for the Upstream stretch

	2012-2013	2014-2018	2018-2021
Flow (m^3/s)	1.119	33.321	44.045
Water Level (m)	0.37	0.66	0.661

- **Hydraulic data**

The hydraulics were calculated based on water level and flow data. **Table 5.7** shows the calculated hydraulics for the upstream stretch simulation run.

TABLE 5.7 Hydraulic data for the Upstream stretch for the Monsoon season

Reach Label	Downstream end of reach label	Area m^2	Velocity m/s	Velocity coefficient, a	Velocity Exponent, b	Depth coefficient, c	Depth exponent, d
Monsoon season							
For warming up (2012-2013)							
	Headwater	59.60	0.136	0.0876	0.2100	0.238	0.21
US-1 to US-2	Valasana Bridge	50.91	0.159	0.0886	0.2800	0.210	0.27
US-2 to US-3	Fudeda Bridge	66.88	0.121	0.0718	0.2500	0.224	0.24
US-3 to US-4	Sapteshwar Mahadev Bridge	41.67	0.194	0.1153	0.2500	0.229	0.23
For Calibration (2014-2018)							
	Headwater	107.15	0.311	0.139	0.23	0.66	0.303
US-1 to US-2	Valasana Bridge	118.09	0.282	0.106	0.28	0.66	0.254
US-2 to US-3	Fudeda Bridge	124.64	0.267	0.111	0.25	0.66	0.282
US-3 to US-4	Sapteshwar Mahadev Bridge	76.09	0.438	0.182	0.25	0.66	0.292

Reach Label	Downstream end of reach label	Area m^2	Velocity m/s	Velocity coefficient, a	Velocity Exponent, b	Depth coefficient, c	Depth exponent, d
For Validation (2019- 2021)							
	Headwater	126.54	0.348	0.157	0.21	0.298	0.21
US-1 to US-2	Valasana Bridge	119.09	0.370	0.128	0.28	0.238	0.27
US-2 to US-3	Fudeda Bridge	125.70	0.350	0.136	0.25	0.266	0.24
US-3 to US-4	Sapteshwar Mahadev Bridge	76.73	0.574	0.223	0.25	0.277	0.23

❑ **Water quality data**

The water quality data grouped for simulating the upstream stretch for the monsoon season are presented in **Table 5.8**.

TABLE 5.8 Water Quality data for the upstream stretch

Location	Temperature (°C)	ISS (mg/L)	DO (mg/L)	CBODslow (mg/L)	CBODfast (mg/L)	NH_3-N (ug/L)	pH
Monsoon season							
For warming up (2012-2013)							
US-1 / HW	29.10	5	8.50	19.00	3.50	2000.00	8.54
US-2	30.95	3	9.50	15.00	4.00	2500.00	8.37
US-3	31.80	3	8.00	31.50	2.00	2000.00	8.56
US-4	32.70	3	8.00	22.00	2.50	1000.00	8.57
For Calibration (2014-2018)							
US-1 / HW	28.33	4.5	7.52	8.32	2.33	546.17	8.31
US-2	28.17	5.8	7.31	3.69	2.33	565.33	7.75
US-3	29.33	7	7.16	10.29	2.12	994	7.83
US-4	29.17	7.7	7.61	10.89	2.00	547.5	7.89
For Validation (2019- 2021)							
US-1 / HW	34.00	1	6.50	17.90	1.90	340	8.54
US-2	34.00	1	6.80	17.90	4.40	330	8.22
US-3	33.00	1	6.84	6.10	1.96	580	7.90
US-4	34.00	1	7.30	27.80	1.70	340	7.79

❑ Meteorological data

Table 5.9 shows the averaged meteorological data for the monsoon season, grouped for the upstream stretch simulation run.

TABLE 5.9 Meteorological data for upstream stretch (Monsoon season)

	Air temp. (°C)	Dew point temp. (°C)	Wind speed (m/s)
Monsoon 2012-2013	30.02	24.74	2.11
Monsoon 2014-2018	30.72	24.53	2.28
Monsoon 2019-2021	30.76	25.61	2.32

❑ Solar radiation data

The solar radiation data input to the model for the upstream stretch simulation is presented in the **Table 5.10**.

TABLE 5.10 Solar radiation data for the upstream stretch (Monsoon season)

	12:00 AM	1:00 AM	2:00 AM	3:00 AM	4:00 AM	5:00 AM	6:00 AM	7:00 AM	8:00 AM	9:00 AM	10:00 AM	11:00 AM
Winter season (December-February)												
Monsoon 2012-2013	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.21	0.56	0.95	1.30	1.59
Monsoon 2014-2018	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.28	0.68	1.12	1.54	1.84
Monsoon 2019-2021	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.35	0.84	1.34	1.81	2.13
	12:00 PM	**1:00 PM**	**2:00 PM**	**3:00 PM**	**4:00 PM**	**5:00 PM**	**6:00 PM**	**7:00 PM**	**8:00 PM**	**9:00 PM**	**10:00 PM**	**11:00 PM**
Monsoon 2012-2013	1.74	1.71	1.58	1.35	1.07	0.66	0.27	0.01	0.00	0.00	0.00	0.00
Monsoon 2014-2018	2.02	2.03	1.94	1.63	1.21	0.72	0.29	0.04	0.00	0.00	0.00	0.00
Monsoon 2019-2021	2.23	2.23	2.10	1.76	1.32	0.82	0.34	0.04	0.00	0.00	0.00	0.00

5.5.2 Warming up the Model

The simulated output of the model run for the monsoon season 2012-2013 datasets without a calibration run is shown in **Figure 5.2** and **Table 5.11**. The results indicated a vast variation between the observed and simulated data of DO, CBODf, CBODs, and NH_3N, resulting in an inconsistent model with a fitness value of 2.80. This shows that the performance of the model depends on the rate parameters of selected water quality parameters, which need to be calibrated to improve the accuracy of the model [78].

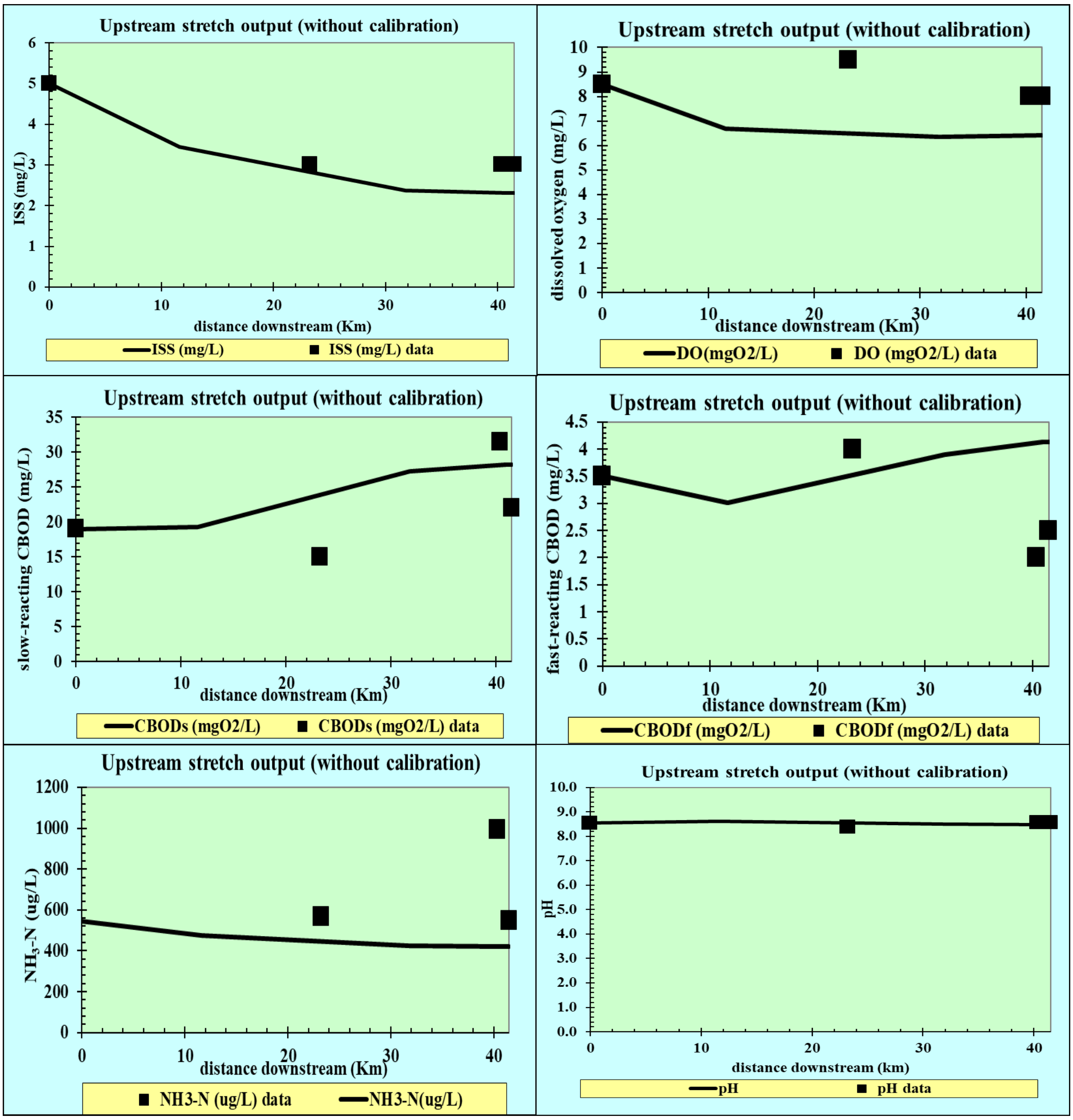


FIGURE 5.2 Model run for Upstream stretch for Monsoon 2012-2013 (warming up without calibration)

TABLE 5.11 Model fitness and RMSE values for the Upstream stretch (without calibration)

Parameters	ISS	DO	CBODs	CBODf	NH_3-N	pH	Model fitness
Root Mean Squared Error (RMSE) %	53.9%	31.2%	37.0%	34.8%	97.2%	28.6%	**2.80**

5.5.3 Calibration and Validation of the Model

The results of the calibration and validation are shown in **Figure 5.3**. The simulated results of the calibrations show that CBODs, CBODf, and NH_3-N decrease linearly with the distance downstream. Whereas there is a small difference between the simulated and observed ISS values. There was no point load input for this stretch, as it is characterized by less polluted stretches having no external pollution sources. As a result, the simulated calibrated DO is in good agreement with the observed value. The performance of the model was evaluated using validated data and its corresponding fitness value.

Table 5.12 shows the normalized RMSE values of the simulated calibrated and validated outputs. The results indicate the RMSE values in good parity between the calibrated and validated data for DO (3.3% & 4.5%), BODs (52.4% & 60.6%), and NH_3-N (61.7% & 59.4%). Whereas the difference was large for ISS (44% & 0.6%), CBODf (9.6% & 44.4%), and pH (14.5% & 65.6%). There is a small difference between the initial value at the headwork and the simulated values of ISS and pH at the end point of 41.5 km. The differences in the observed data in ISS, CBODf, CBODs, NH_3-N, and pH indicate the impact of surface runoff during the monsoon season. However, the overall performance of the calibrated model with a fitness value of 6.29 is found satisfactory, compared to the validated model with a fitness value of 5.65.

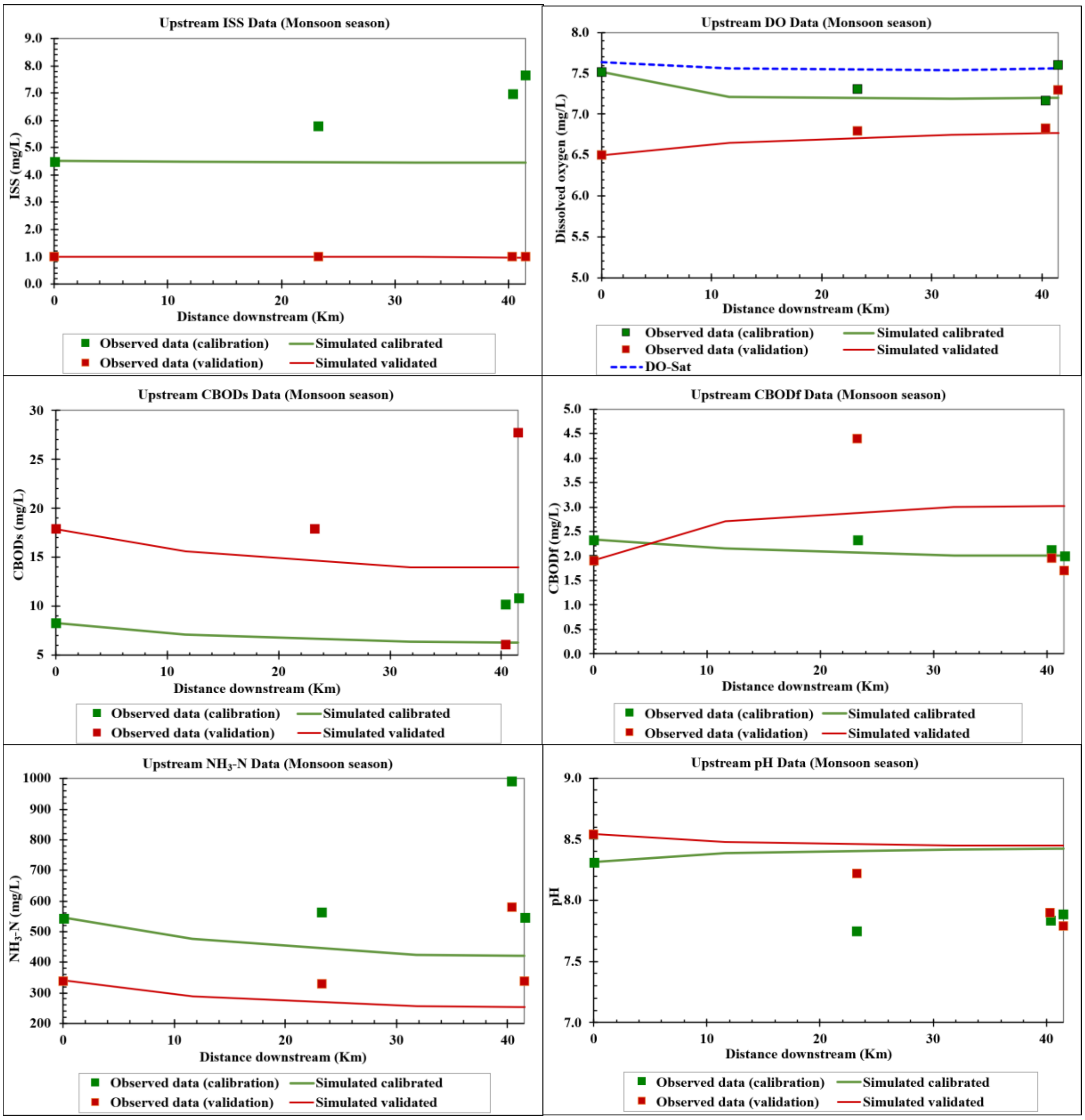


FIGURE 5.3 Model output for the middle stream stretch (winter season)

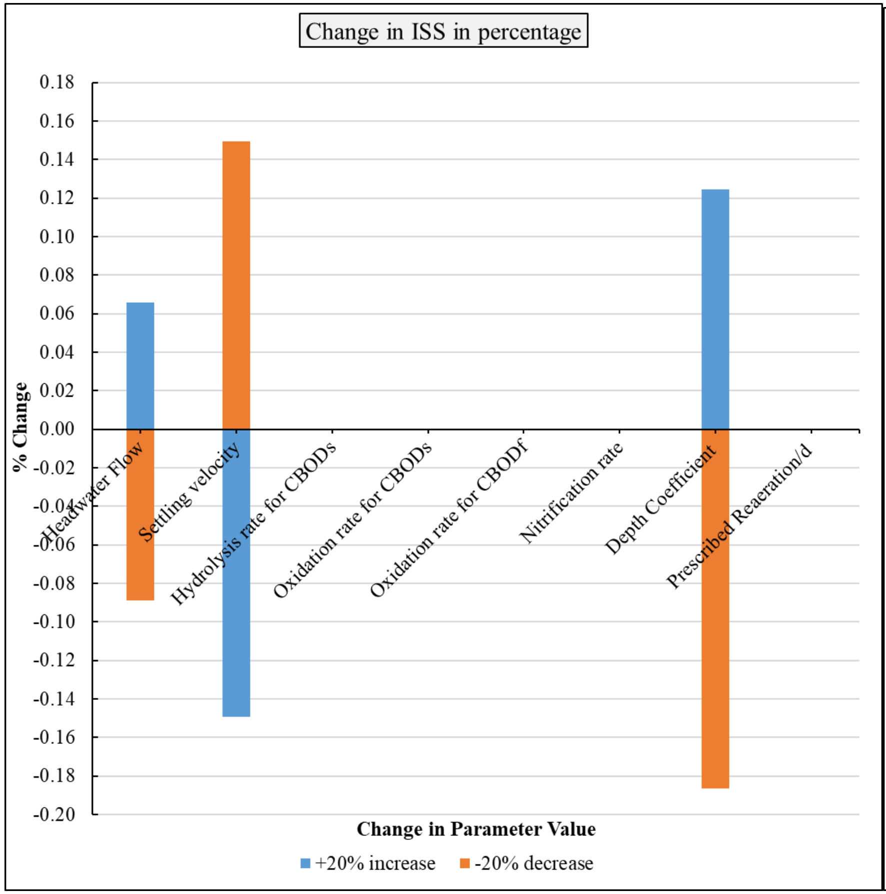
TABLE 5.12 Model fitness and RMSE value for upstream stretch (monsoon)

	ISS	DO	CBODs	CBODf	NH_3-N	pH	Model fitness
Calibration	44.0%	3.3%	52.4%	9.6%	61.7%	14.5%	6.29
Validation	0.6%	4.5%	60.6%	44.4%	59.4%	65.6%	5.29

5.5.4 Sensitivity Analysis

A sensitivity analysis was conducted to quantify errors between observed and simulated water quality parameters. It also helps optimize the model's performance. The parameters having maximum influence on selected water quality parameters were determined through sensitivity analysis [85, 86, 176]. The water quality of the river is affected mainly by the flow, reaeration rate, and constituents present. Therefore, for sensitivity analysis, the variations in the headwater flow, reaeration rate, depth coefficient, and the specific rate parameters, including settling velocity, hydrolysis and oxidation rate for CBODs, oxidation rate for CBODf, and nitrification rate. The calibrated model was used for sensitivity analysis, and the impact of each parameter was examined by increasing and decreasing its value by 20% while keeping all other parameters constant [174, 177]. The impact on the simulated output was checked for changes in each parameter. **Figures 5.4 to 5.6** show the percentage change in simulated water quality parameters by a 20% increase and decrease in the input variable. A summary of the sensitivity analysis is presented in **Table 5.13**.

The results of the sensitivity analysis show that a change in headwater flow has an impact on DO, CBODs, CBODf, and NH_3-N. The depth coefficient has a considerable impact on DO and NH_3N and has a slight impact on ISS, CBODs, and CBODf. Settling velocity influences only the ISS parameter. The change in the prescribed reaeration rate influences mainly DO, NH_3-N, and pH. The nitrification rate primarily affects NH_3-N and affects the DO value slightly. It was found that the hydrolysis rate of CBODs influences not only CBODs but also CBODf. Additionally, a slight change in DO, NH_3-N, and pH was also noted. While the oxidation rate of CBODs has little influence on the CBODs and CBODf value. The Oxidation rate of CBODf impacts CBODf majorly and also influences DO, NH_3-N, and pH results. The conductivity and alkalinity were not influenced by a change in any parameters.



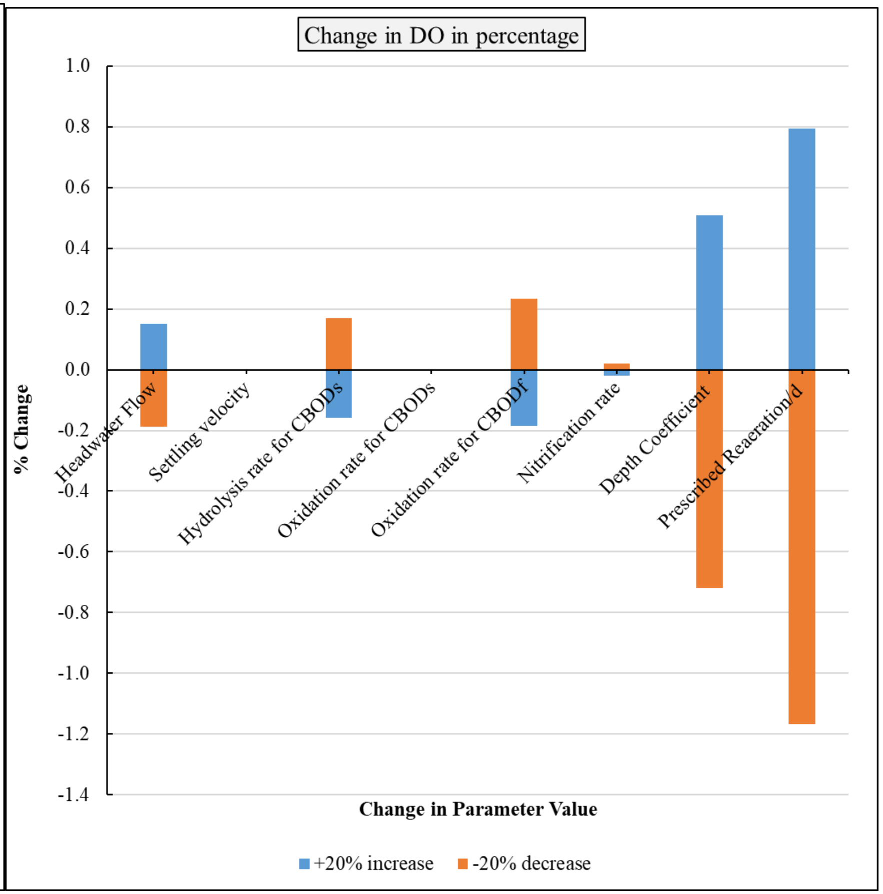


FIGURE 5.4 Percentage change in ISS and DO obtained by sensitivity analysis

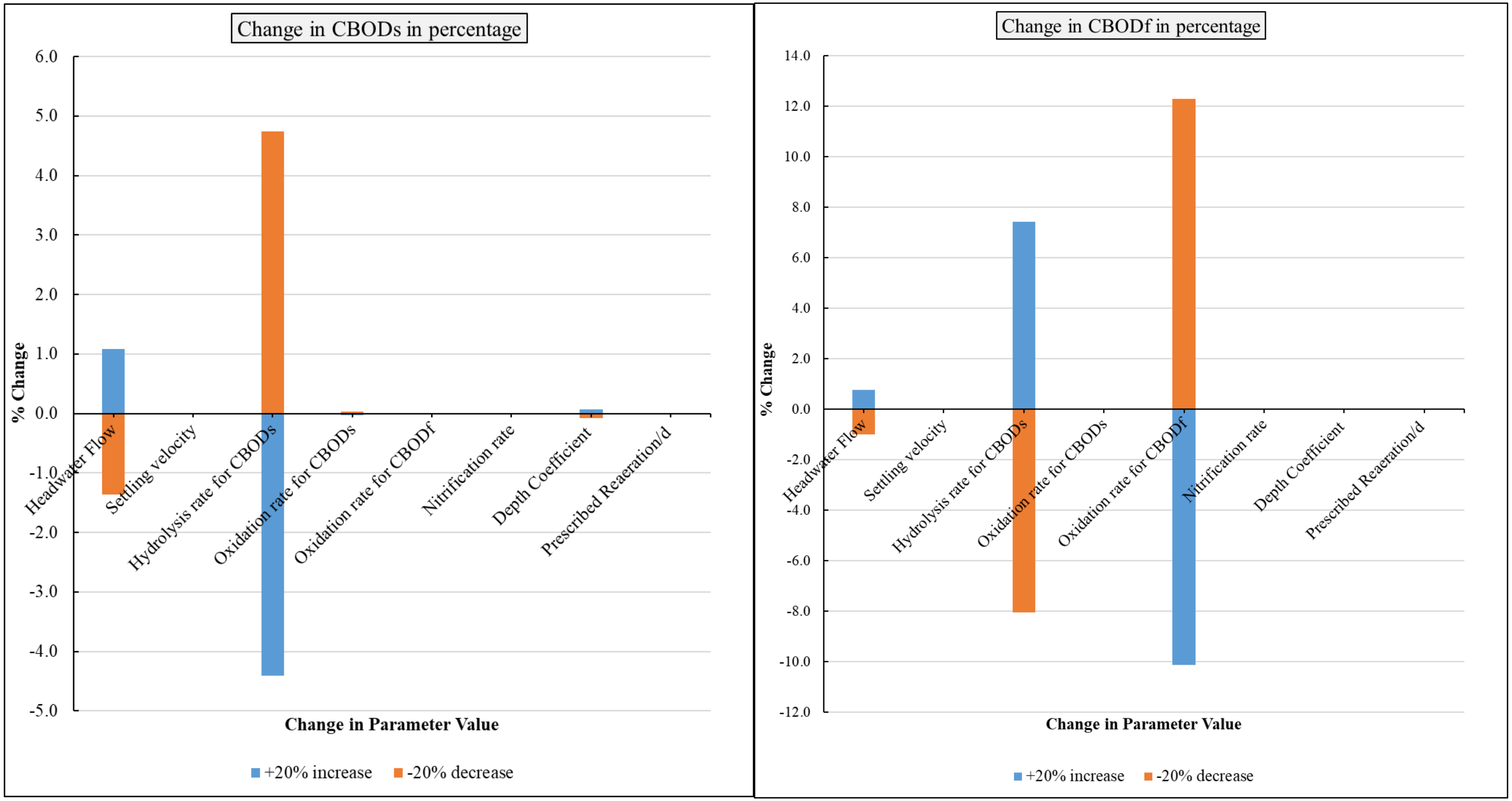
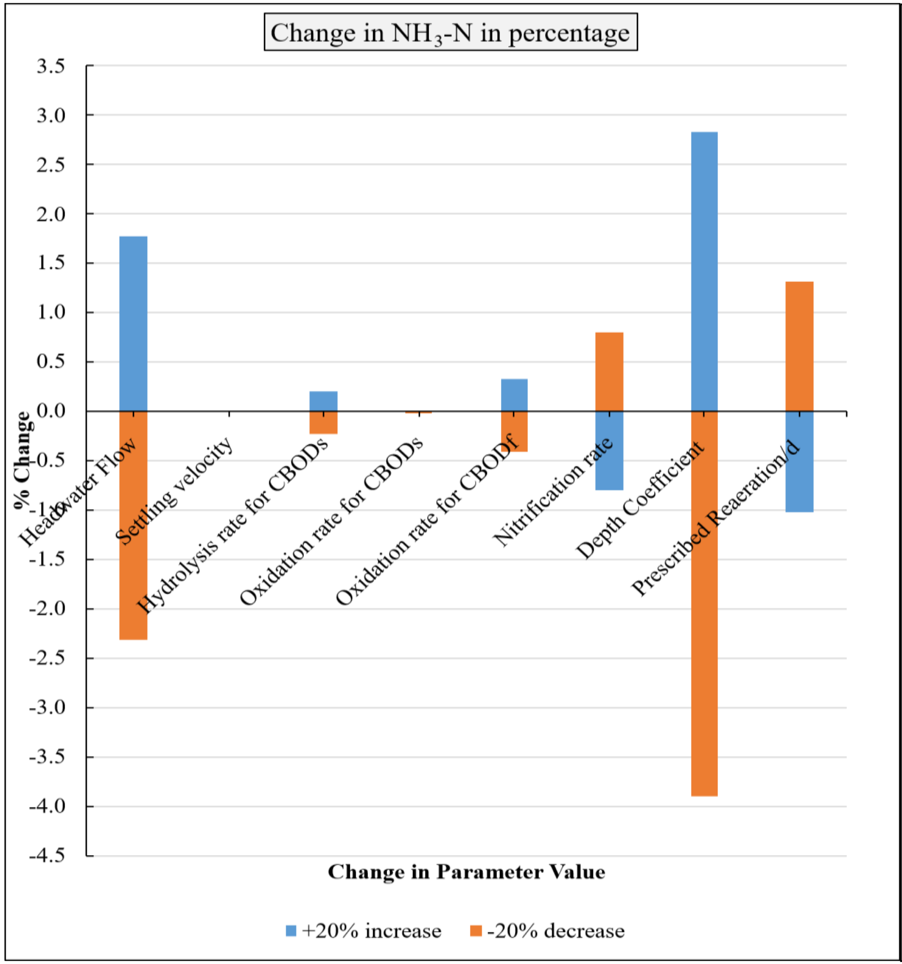


FIGURE 5.5 Percentage change in CBODs and CBODf obtained by sensitivity analysis



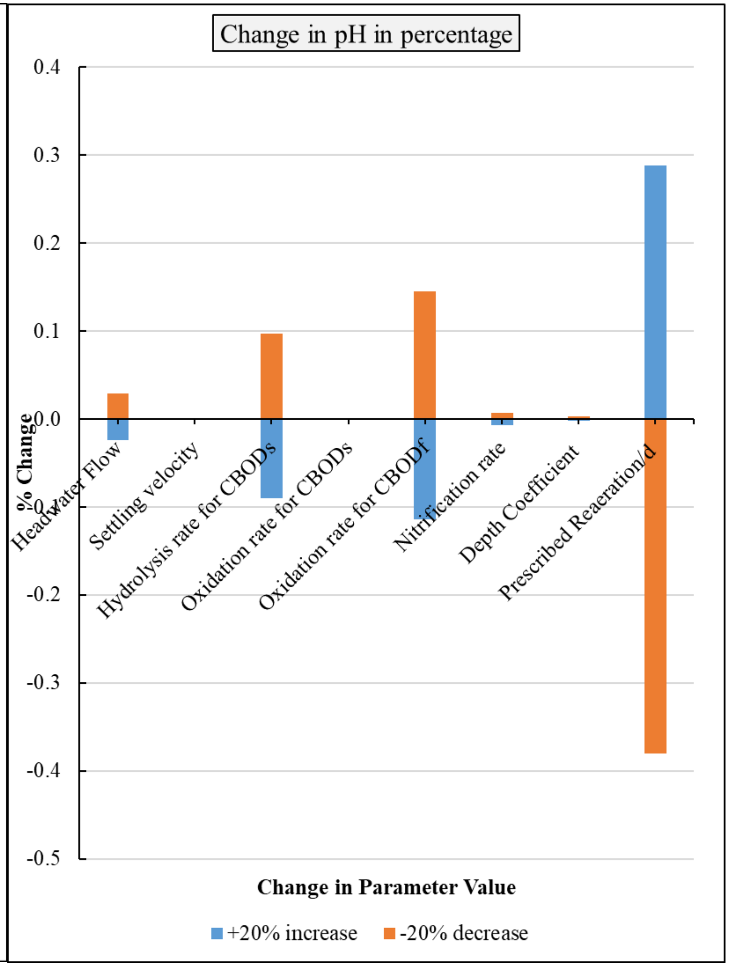


FIGURE 5.6 Percentage change in NH_3-N and pH obtained by sensitivity analysis

TABLE 5.13 A summary of the sensitivity analysis of the model

Parameter	ISS	DO	CBODs	CBODf	NH_3-N	pH
+20% increase						
Headwater Flow	0.07	0.15	1.08	0.77	1.78	-0.02
Settling velocity	-0.15	0.00	0.00	0.00	0.00	0.00
Hydrolysis rate for CBODs	0.00	-0.16	-4.41	7.44	0.21	-0.09
Oxidation rate for CBODs	0.00	0.00	-0.03	-0.01	0.00	0.00
Oxidation rate for CBODf	0.00	-0.18	0.00	-10.12	0.33	-0.11
Nitrification rate	0.00	-0.02	0.00	0.00	-0.79	-0.01
Depth Coefficient	0.12	0.51	0.07	0.03	2.83	0.00
Prescribed Reaeration/d	0.00	0.79	0.00	-0.02	-1.03	0.29
-20% decrease						
Headwater Flow	-0.09	-0.19	-1.36	-0.98	-2.31	0.03
Settling velocity	0.15	0.00	0.00	0.00	0.00	0.00
Hydrolysis rate for CBODs	0.00	0.17	4.74	-8.04	-0.22	0.10
Oxidation rate for CBODs	0.00	0.00	0.03	-0.01	0.00	0.00
Oxidation rate for CBODf	0.00	0.23	0.00	12.29	-0.41	0.15
Nitrification rate	0.00	0.02	0.00	0.00	0.80	0.01
Depth Coefficient	-0.19	-0.72	-0.08	-0.03	-3.90	0.00
Prescribed Reaeration/d	0.00	-1.17	0.00	0.03	1.31	-0.38

5.6 Middle Stream Stretch Simulation Run Output

The model was run for the critical identified periods, pre-monsoon and winter. The model was simulated individually for both seasons. The model was calibrated with the 2012-2017 dataset and validated with the 2018-2021 dataset. The data input to the model was grouped accordingly and presented in the following section.

5.6.1 Data Input to the Model

❑ **Location details**

The details of the selected locations for the middle stream stretch are shown in **Table 5.14**.

TABLE 5.14 Location details for middle stream stretch

Location	Name	Chainage km
MS-1	Nana chiloda Bridge	202.67
MS-2	Subhash Bridge	213.25
MS-3	Rishi Dadhichi Bridge	214.5

❑ Reach data

The reach data for the middle stream stretch, including the length, elevation, latitude, and longitude for each reach, are shown in **Table 5.15**.

TABLE 5.15 Reach Data – Middle stream stretch

Reach Label	Downstream end of reach label	Number	Reach Length	Downstream		Downstream location	Elevation		Downstream					
							Upstream	Downstream	Latitude			Longitude		
			(km)	Latitude	Longitude	(km)	(m)	(m)	Degrees	Minutes	Seconds	Degrees	Minutes	Seconds
	Headwater	0		23.12	72.65	0.000		54.389	23.00	6.00	55.89	72.00	38.00	57.79
MS-1 to MS-2	Subhash Bridge	1	10.58	23.06	72.59	10.580	54.389	45.055	23.00	3.00	41.30	72.00	35.00	8.38
MS-2 to MS-3	Rishi Dadhichi Bridge	2	1.25	23.05	72.58	11.830	45.055	44.563	23.00	3.00	13.48	72.00	34.00	38.89

❑ **Headwater flow**

The flow released from the Karai Dam was taken as a headwater flow for the middle stream stretch. The monthly data received from the SSNNL were sorted for the winter and pre-monsoon season for the model calibration and validation, and presented in **Table 5.16**. The water level data was referenced from the Subhas Bridge station, collected from the CWC division. The water level data grouped for the model input are shown in **Table 5.17**.

TABLE 5.16 Headwater (HW) data for the middle stream stretch

Winter season				
Headwater Flow	**For Calibration (Dec. 2016- Feb. 2018)**		**For Validation (Dec. 2018- Feb. 2021)**	
	Cusec	**Cumec**	**Cusec**	**Cumec**
Maximum	1706.0	48.31	1188.0	33.64
Minimum	71.7	2.03	51.8	1.47
Mean	**702.7**	**19.90**	**692.9**	**19.62**
Range	71.67 - 1705.96	2.03 - 48.31	51.83 - 1188	1.47 – 33.64
Pre-monsoon season				
Headwater Flow	**For Calibration (2016-2017)**		**For Validation (2018-2021)**	
	Cusec	**Cumec**	**Cusec**	**Cumec**
Maximum	1181.0	33.44	1720.5	48.72
Minimum	192.6	5.45	50.8	1.44
Mean	**661.6**	**18.73**	**593.5**	**16.81**
Range	192.58 - 1181	5.45 - 33.44	50.83 - 1720.5	1.44 - 48.72

TABLE 5.17 Water level data for the Middle stream stretch

Winter season				
	For Calibration (Dec. 2016- Feb. 2018)		**For Validation (Dec. 2018- Feb. 2021)**	
	Discharge in Cumecs	**WL in m**	**Discharge in Cumecs**	**WL in m**
Maximum	48.31	40.24	33.64	40.06
Minimum	2.03	39.31	1.47	39.27
Mean	19.90	39.84	19.62	39.84
Pre-monsoon season				
Headwater Flow	**For Calibration (2016-2017)**		**For Validation (2018-2021)**	
	Discharge in Cumecs	**WL in m**	**Discharge in Cumecs**	**WL in m**
Maximum	33.44	40.06	48.72	40.25
Minimum	5.45	39.48	1.44	39.26
Mean	18.73	39.82	16.81	39.78

WL as per stage-discharge of Derol, CWC,
Q=c*(h+a)^b
b= 2.275, c=29.552,
a = min. WL at taken from Subhash Bridge data = -39.0

- **Hydraulic data**

The hydraulic data calculated for the input to the model for the middle stream simulation run are shown in **Table 5.18**.

TABLE 5.18 Hydraulic data for the middle stream stretch

Reach Label	Downstream end of reach label	Area m^2	Velocity m/s	Velocity coefficient, a	Velocity Exponent, b	Depth coefficient, c	Depth exponent, d
Winter season							
For calibration (Dec. 2012- Feb. 2018)							
	Headwater	60.42	0.33	0.18	0.20	0.42	0.14
MS-1 to MS-2	Subhash Bridge	130.98	0.15	0.05	0.35	0.26	0.30
MS-2 to MS-3	Rishi Dadhichi Bridge	106.16	0.19	0.09	0.25	0.31	0.24
For validation (Dec. 2018- Feb. 2021)							
	Headwater	60.42	0.32	0.18	0.20	0.42	0.14
MS-1 to MS-2	Subhash Bridge	130.98	0.15	0.05	0.35	0.26	0.30
MS-2 to MS-3	Rishi Dadhichi Bridge	106.16	0.18	0.09	0.25	0.31	0.24
Pre-monsoon season							
For calibration (2012- 2017)							
	Headwater	57.92	0.32	0.18	0.20	0.41	0.14
MS-1 to MS-2	Subhash Bridge	126.81	0.15	0.05	0.35	0.26	0.30
MS-2 to MS-3	Rishi Dadhichi Bridge	102.73	0.18	0.09	0.25	0.31	0.24
For validation (2018- 2021)							
	Headwater	53.04	0.32	0.18	0.20	0.39	0.14
MS-1 to MS-2	Subhash Bridge	118.49	0.14	0.05	0.35	0.25	0.30
MS-2 to MS-3	Rishi Dadhichi Bridge	95.89	0.18	0.09	0.25	0.29	0.24

- **Water quality data**

The input data of water quality for the middle stream stretch are shown in **Table 5.19**.

TABLE 5.19 Water quality data for the middle stream stretch

Location	Temperature (°C)	ISS (mg/L)	DO (mg/L)	CBODslow (mg/L)	CBODfast (mg/L)	NH_3-N (ug/L)	pH
Winter season							
For calibration (Dec. 2012- Feb. 2018)							
MS-1	23.56	6.8	7.93	17.55	1.80	768.55	8.44
MS-2	22.79	6.38	6.48	30.55	2.76	1036.00	7.72
MS-3	23.36	11.5	6.37	30.20	3.05	1442.09	7.76
For validation (Dec. 2018- Feb. 2021)							
MS-1	27.32	6.92	7.60	22.71	4.02	776.85	8.76
MS-2	24.50	6.50	7.16	25.69	3.91	540.00	8.28
MS-3	24.34	6.56	5.19	32.54	2.29	1056.58	7.83
Pre-monsoon season							
For calibration (2012- 2017)							
MS-1	27.50	5.88	7.20	19.15	3.69	746.39	8.31
MS-2	29.50	14.50	4.73	65.50	2.00	1115.89	7.97
MS-3	30.43	18.67	4.03	38.25	2.00	465.00	8.03
For validation (2018- 2021)							
MS-1	26.67	5.76	7.37	12.59	3.08	782.77	8.34
MS-2	34.33	23.33	7.49	58.22	1.38	701.18	9.12
MS-3	34.33	23.67	7.27	25.33	1.31	555.00	8.79

- **Meteorological data**

Table 5.20 shows the meteorological data grouped for model input for the middle stream stretch.

TABLE 5.20 Meteorological data for the middle stream stretch

	Air temp. (°C)	Dew point temp. (°C)	Wind speed (m/s)
Winter season (December-February)			
For Calibration (Dec. 2012- Feb. 2018)	21.48	10.60	1.42
For Validation (Dec. 2018- Feb. 2021)	20.93	10.45	1.81

	Air temp. (°C)	Dew point temp. (°C)	Wind speed (m/s)
Pre-monsoon season (March-May)			
For Calibration (2012- 2017)	31.16	15.83	1.75
For Validation (2018- 2021)	31.69	15.99	1.84

❑ **Solar radiation data**

Table 5.21 shows the solar radiation data input to the model for the middle stream stretch.

TABLE 5.21 Solar radiation data for the Middle stream stretch

	12:00 AM	1:00 AM	2:00 AM	3:00 AM	4:00 AM	5:00 AM	6:00 AM	7:00 AM	8:00 AM	9:00 AM	10:00 AM	11:00 AM
Winter season (December-February)												
For Calibration (Dec. 2012- Feb. 2018)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.36	0.96	1.55	2.02
For Validation (Dec. 2018- Feb. 2021)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.38	0.98	1.58	2.05
	12:00 PM	**1:00 PM**	**2:00 PM**	**3:00 PM**	**4:00 PM**	**5:00 PM**	**6:00 PM**	**7:00 PM**	**8:00 PM**	**9:00 PM**	**10:00 PM**	**11:00 PM**
For Calibration (Dec. 2012- Feb. 2018)	2.25	2.26	2.05	1.62	1.00	0.43	0.05	0.00	0.00	0.00	0.00	0.00
For Validation (Dec. 2018- Feb. 2021)	2.30	2.30	2.08	1.64	1.06	0.45	0.05	0.00	0.00	0.00	0.00	0.00
Pre-monsoon season (March-May)												
	12:00 AM	**1:00 AM**	**2:00 AM**	**3:00 AM**	**4:00 AM**	**5:00 AM**	**6:00 AM**	**7:00 AM**	**8:00 AM**	**9:00 AM**	**10:00 AM**	**11:00 AM**
For Calibration (2012- 2017)	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.28	0.93	1.64	2.27	2.74
For Validation (2018- 2021)	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.33	1.01	1.75	2.39	2.85
	12:00 PM	**1:00 PM**	**2:00 PM**	**3:00 PM**	**4:00 PM**	**5:00 PM**	**6:00 PM**	**7:00 PM**	**8:00 PM**	**9:00 PM**	**10:00 PM**	**11:00 PM**
For Calibration (2012- 2017)	2.97	2.99	2.77	2.30	1.66	0.95	0.29	0.01	0.00	0.00	0.00	0.00
For Validation (2018- 2021)	3.08	3.13	2.84	2.35	1.69	0.94	0.28	0.01	0.00	0.00	0.00	0.00

- **Point source data – middle stream stretch**

The middle stream stretch receives the pollution load from the Indira Bridge (Ch. 206.5 mt) and Naran Ghat (213.135 mt.) locations. At the Indira Bridge location, people from the surrounding area used to throw offerings into the river. The idol immersion activities also take place at this location. A temple is located at Naran Ghat near Subhash Bridge, where various religious activities take place. It is also a source of point load because of the disposal of offerings into the river. There is no data available for the pollution load from these point sources. Hence, the pollution loads have been estimated as below.

Inflow from pollution load = 10% of the headwater flow, contribution of 50% flow from Indira Bridge and 50% from Naran Ghat

	Chainage	Flow m^3/s
Indira Bridge	206.5	0.988
Narayan Ghat	213.14	0.988

The pollution load for each parameter is calculated from the trend of increase in the parameters from MS-1 to MS-3. The contribution to the pollution load is considered to be 60% from Indira Bridge and 40% from Naran Ghat, as shown in **Table 5.22**.

TABLE 5.22 Pollution load data for the middle stream stretch

The trend of increase in pollution load parameters	ISS mg/L	CBODs mg/L	CBODf mg/L	NH_3-N ugN/L	Contribution to the pollution load
Winter season	1.07	11.41	1.17	463.84	60% from Indira Bridge and 40% from Naran Ghat
Pre-monsoon season	15.34	45.99	-	262.70	

5.6.2 Calibration and Validation

Winter season:

The simulation run output for the winter is presented in **Figure 5.7**, and RMSE values are shown in **Table 5.23**. The graphs indicate that CBODs, CBODf, and NH_3-N increase with distance downstream due to point sources within the stretch. As a result, the DO value decreased steadily as distance increased, but remained constant beyond 10 km, at about 6.5 mg/L, indicating good water quality. There is little difference between the simulated and observed inorganic suspended solids. The predicted pH values also closely match the observed data.

Normalized root mean squared error (RMSE) values between simulated and observed data for calibration and validation are 42.6% & 5.2% for ISS, 6.5% & 16.2% for DO, 27.1% & 14.6% for CBODs, 27.9% & 26.4% for CBODf, 21.5% & 41.6% for NH_3-N, and 1.6% & 3.6% for pH. Significant differences were observed for ISS, DO, CBODs, and NH_3-N due to variations in the observed water quality data during calibration and validation. The data reflect the impact of point source loads on water quality at the MS2 and MS3 locations. However, the calibrated model with a fitness of 7.06 explains the relationship between simulated and observed data, with a fitness of 5.77 during validation, indicating satisfactory performance.

Pre-monsoon season:

The simulation run output for the pre-monsoon is presented in **Figure 5.8**, and RMSE values are shown in **Table 5.24**. Graphs show that the concentrations of ISS and CBODs increase with distance downstream from the headwater flow, indicating input from point sources. CBODf decreases continuously as the distance from the headwater increases, representing the oxidation of organic compounds. NH_3-N decreases up to 5.3 km and rises again downstream. DO shows a depleting trend and goes below 6.0 mg/L beyond 4.0 km, but still fulfils the minimum DO requirement of 4.0 mg/L.

The simulated data for calibration and validation yielded RMSE values for ISS, DO, CBODs, CBODf, NH_3-N, and pH as follows: 16.6% & 17% for ISS, 16.6% & 11.9% for DO, 26.1% & 40.9% for CBODs, 26.3% & 2.6% for CBODf, 49.9% & 13% for NH_3-N, and 3.5% & 14.7% for pH. The differences in RMSE values for CBODs, CBODf, NH_3-N, and pH between calibration and validation can be attributed to changes in water quality caused by anthropogenic activities during the two periods.

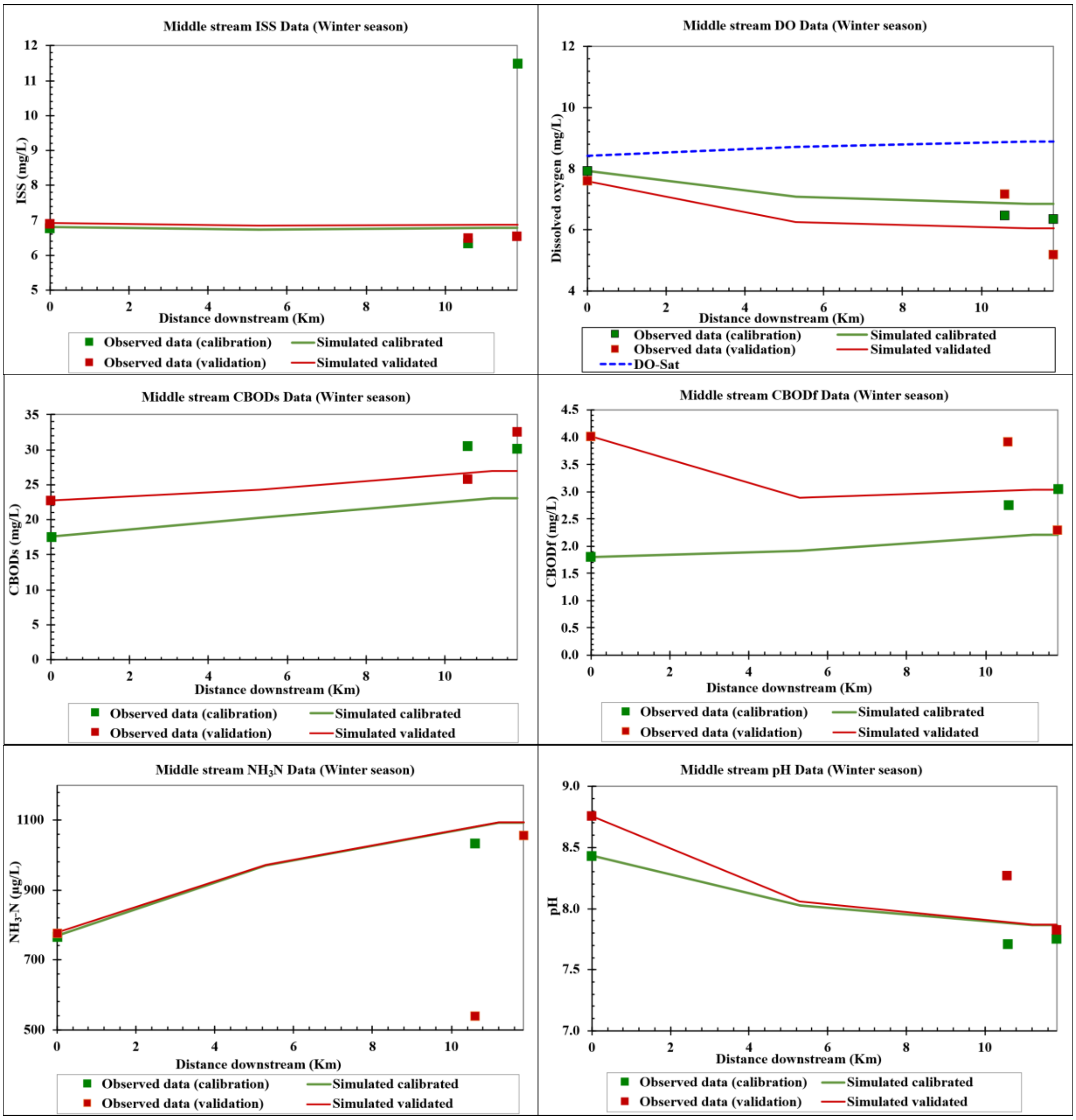


FIGURE 5.7 Model output for the middle stream stretch (winter season)

TABLE 5.23 Model fitness and RMSE values for the middle stream stretch (winter season)

Parameters	ISS	DO	CBODs	CBODf	NH_3-N	pH	Model fitness
Calibration	42.6%	6.5%	27.1%	27.9%	21.5%	1.6%	7.06
Validation	5.2%	16.2%	14.6%	26.4%	41.6%	3.6%	5.77

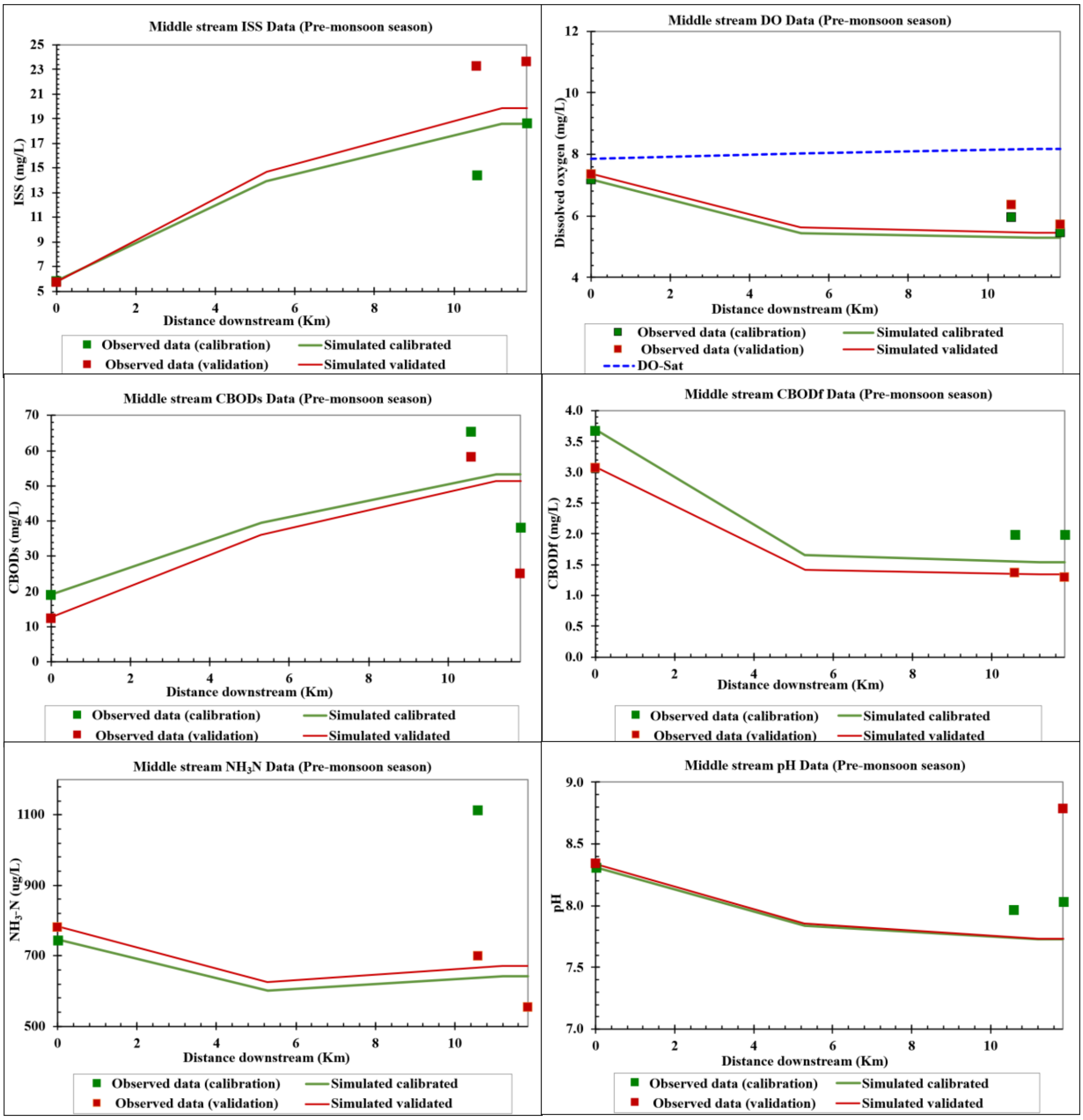


FIGURE 5.8 Model output for the middle stream stretch (pre-monsoon season)

TABLE 5.24 Model fitness and RMSE values for the middle stream stretch (Pre-monsoon season)

Parameters	ISS	DO	CBODs	CBODf	NH_3-N	pH	Model fitness
Calibration	16.6%	16.6%	26.1%	26.3%	49.9%	3.5%	6.43
Validation	17.0%	11.9%	40.9%	2.6%	13.0%	14.7%	6.78

5.6.3 Scenario Analysis

The middle stream stretch, being a riverfront location, is used for recreational activities. Hence, various water quality scenarios were simulated to ascertain the water quality as per the IS 2296 and CPCB's designated best use water quality classification shown in **Table 5.25**.

TABLE 5.25 Designated best use water quality criteria

Designated-Best-Use	Class of water	Criteria
Drinking Water Source without conventional treatment but after disinfection	**A**	Total coliforms organism MPN/100ml shall be 50 or less pH between 6.5 and 8.5 Dissolved oxygen 6mg/l or more Biochemical oxygen demand 5 days 20°C 2mg/l or less
Outdoor bathing (Organised)	**B**	Total coliforms organism MPN/100ml shall be 500 or less pH between 6.5 and 8.5 Dissolved oxygen 5mg/l or more Biochemical oxygen demand 5 days 20°C 3mg/l or less
Drinking water source after conventional treatment and disinfection	**C**	Total coliforms organism MPN/100ml shall be 5000 or less pH between 6 to 9 Dissolved oxygen 4mg/l or more Biochemical oxygen demand 5 days 20°C 3mg/l or less
Propagation of Wild life and Fisheries	**D**	pH between 6.5 to 8.5 Dissolved Oxygen 4mg/l or more Free Ammonia (as N) 1.2 mg/l or less
Irrigation, Industrial Cooling, Controlled Waste disposal	**E**	pH between 6.0 to 8.5 Electrical conductivity at 25C micro mhos/cm Max.2250 Sodium absorption Ratio Max. 26 Boron Max. 2mg/l
	A	Total coliforms organism MPN/100ml shall be 50 or less pH between 6.5 and 8.5 Dissolved oxygen 6mg/l or more Biochemical oxygen demand 5 days 20C 2mg/l or less

Source: Indian standard IS2296:1992, CPCB's water quality criteria [178, 179]

The scenario analysis also helps understand the pollution load capacity and the river's health [35, 82, 85, 172, 180]. The scenarios were simulated considering the following criteria.

1.) Modifications in river inflow
2.) Modifications in pollution load

The results of the various scenarios run and the data comparison for the water quality at the endpoint of the middle stream are tabulated in **Tables 5.26 and 5.27** for the winter and pre-monsoon seasons, respectively.

Middle stream (winter):

Simulated data of calibration with an average flow of 19.90 m^3/s during the winter season showed the DO value of 6.85 mg/l (>6.0 mg/L), pH of 7.86 (between 6.5 and 8.5), but the BOD value reached 2.21 mg/L, which is slightly above 2.0 mg/L, requiring Class A water quality criteria.

Scenario 1, an increase in the headwater flow by 50%, i.e. 29.85 m^3/s of headwater flow, an increase in the DO value of 7.01 mg/L (> 6.0 mg/L) and a decrease in CBODf value to 2.0 mg/L (equal to or less than 2.0 mg/L) with the pH value of 7.95 (between 6.5 and 8.5), which meets the CPCB Class A water quality criteria.

The pollution load capacity was checked with the reduction in the headwater flow by every 10% in scenario 2. The results show that the decrease in headwater flow by 50%, i.e. from 19.90 m^3/s to 9.95 m^3/s, CBODs remain below 3.0 mg/L required for the outdoor bathing water quality Class B. Further reduction in the headwater flow will increase in CBODs value above 3.0 mg/L. During lean flow i.e. 2.0 m^3/s condition, the water quality was found to deteriorate, resulting in DO below 5.0 mg/L required to meet Class B water quality criteria. Therefore, it can be said from the scenario that a minimum flow of 10 m^3/s is required to maintain the minimum water quality criterion of outdoor bathing Class B for the middle stream stretch with the existing pollution load during the winter season.

Scenario 3 depicts that the reduction in point source load by 20% and 50% will be able to improve water quality conditions, with a BOD value below 2.0 mg/L, satisfying Class A water quality criteria.

TABLE 5.26 Scenario analysis for the middle stream stretch (winter season)

Scenario No.	Criteria	Sr. No.	Particular	Flow, m^3/s	ISS mg/L	DO mg/L	CBODs mg/L	CBODf mg/L	NH_3-N µg/L	pH
	Calibrated model		**Avg. flow**	**19.90**	**6.78**	**6.85**	**23.12**	**2.21**	**1092.55**	**7.864**
	CPCB water quality criteria				**Class A**	**≥ 6.0**	**-**	**≤ 2.0**	**-**	**6.5-8.5**
					Class B	**≥ 5.0**	**-**	**≤ 3.0**	**-**	**6.5-8.5**
SC1	Increase in flow	1	50% increase in inflow	29.85	6.75	7.01	20.90	1.99	987.28	7.947

Scenario No.	Criteria	Sr. No.	Particular	Flow, m^3/s	ISS mg/L	DO mg/L	CBODs mg/L	CBODf mg/L	NH_3-N µg/L	pH
SC2	Reduction in flow condition	2.1	10% reduction in flow	17.91	6.79	6.80	23.84	2.27	1126.29	7.840
		2.2	20% reduction in flow	15.92	6.81	6.74	24.72	2.36	1167.55	7.814
		2.3	30% reduction in flow	13.93	6.83	6.66	25.82	2.47	1219.11	7.783
		2.4	40% reduction in flow	11.94	6.86	6.57	27.25	2.60	1285.35	7.747
		2.5	50% reduction in flow	9.95	6.90	6.44	29.15	2.79	1373.54	7.703
		2.6	60% reduction in flow	7.96	6.96	6.27	31.81	3.05	1496.65	7.650
		2.7	70% reduction in flow	5.97	7.06	6.01	35.79	3.44	1680.31	7.582
SC2a	Lean flow condition	2a	Lean flow	2.03	7.76	4.49	61.16	5.98	2838.32	7.313
SC3	Reduction in pollution load	3.1	20% reduction	19.90	6.56	6.99	20.08	1.91	960.06	7.923
		3.2	50% reduction	19.90	6.37	7.16	16.79	1.59	816.92	8.017

Middle stream (pre-monsoon):

For the pre-monsoon season, the water quality simulated by calibration with 18.73 m^3/s headwater flow showed the DO value > 5.0 (5.28 mg/L), BOD value of <3.0 mg/L (1.54 mg/L), and pH value of between 6.5 and 8.8 (7.73), satisfying the Class B water quality criteria.

Scenario 1, an increase in headwater flow by 50% i.e. 28.10 m^3/s, simulates the water quality with slightly higher values of DO (5.48 mg/L) and pH (7.79) and little lower value of BOD (1.46 mg/L), which remains within the Class B water quality criteria.

As shown in Scenario 2, for a subsequent reduction in the headwater flow by 10%, the DO value is depleting with an increase in CBODs, CBODf, and NH_3-N. For the reduction in headwater flow beyond 30% i.e. 13.11 m^3/s, DO value decreases below 5.0 mg/L, degrading the water quality from Class B to Class C. The water quality remains within Class C criteria up to 70% reduction in the headwater flow i.e. 5.62 m^3/s. Simulation with the lean flow of 1.44 m^3/s during the season showed the worst water quality with a DO value of 2.24 mg/L, less than the minimum DO requirement of 4.0 mg/L required for the survival of the river ecological system.

Scenario 3 indicates that the reduction in the point source load by 20% and 50%, improves the DO of the water to 5.5 mg/L and 5.75 mg/L, with the BOD value remaining below 2.0 mg/L, aligning with the Class B water quality criteria.

TABLE 5.27 Scenario analysis for the middle stream stretch (Pre-monsoon season)

Scenario No.	Criteria	Sr. No.	Particular	Flow, m^3/s	ISS mg/L	DO mg/L	CBODs mg/L	CBODf mg/L	NH_3-N µg/L	pH
	Calibrated model		**Avg. flow**	**18.73**	**18.62**	**5.28**	**53.14**	**1.54**	**642.02**	**7.73**
	CPCB water quality criteria				**Class A**	**≥ 6.0**	**-**	**≤ 2.0**	**-**	**6.5-8.5**
					Class B	**≥ 5.0**	**-**	**≤ 3.0**	**-**	**6.5-8.5**
SC1	Increase in flow	1	50% increase in inflow	28.10	14.64	5.48	42.27	1.46	619.28	7.79
SC2	Reduction in flow condition	2.1	10% reduction in flow	16.86	19.89	5.22	56.61	1.57	650.45	7.71
		2.2	20% reduction in flow	14.99	21.45	5.14	60.84	1.61	661.28	7.69
		2.3	30% reduction in flow	13.11	23.39	5.03	66.13	1.67	675.50	7.66
		2.4	40% reduction in flow	11.24	25.88	4.90	72.92	1.74	694.69	7.63
		2.5	50% reduction in flow	9.37	29.20	4.73	81.94	1.85	721.55	7.59
		2.6	60% reduction in flow	7.49	33.83	4.48	94.53	2.02	761.04	7.55
		2.7	70% reduction in flow	5.62	40.74	4.12	113.33	2.28	823.50	7.48
SC2a	Lean flow condition	2a	Lean flow	1.44	83.39	2.24	229.96	4.61	1289.89	7.23
SC3	Reduction in pollution load	3.1	20% reduction	18.73	14.09	5.50	40.36	1.36	583.97	7.78
		3.2	50% reduction	18.73	9.08	5.75	26.21	1.16	522.13	7.86

5.7 Downstream Stretch Simulation Run

Similar to the middle stream stretch, the model for the downstream stretch was simulated for the critical identified periods, pre-monsoon and winter, calibrated with the 2012-2017 dataset and validated with the 2018-2021 dataset. The data grouped for model input are presented in the following section.

5.7.1 Data Input to the Model

❑ **Location details:**

Table 5.28 shows the details of the location for the downstream stretch.

TABLE 5.28 Location Details for the downstream stretch

Location	Name	Chainage km
DS-1	Vasna Barrage	222.5
DS-2	Narol - Sarkhej Highway Bridge	224
DS-3	Kamod Bridge	234.05
DS-4	Saroda Bridge	248.1

❑ **Reach data**

Table 5.29 shows the details of the segments of the downstream stretch, including length, elevation, latitude, and longitude for each segment.

TABLE 5.29 Reach Data – downstream stretch

Reach Label	Downstream end of reach label	Number	Reach Length	Downstream		Downstream location	Elevation		Downstream					
							Upstream	Downstream	Latitude			Longitude		
			(km)	Latitude	Longitude	(km)	(m)	(m)	Degrees	Minutes	Seconds	Degrees	Minutes	Seconds
	Headwater	0		22.99	72.55	0.00		45.95	22.00	59.00	32.57	72.00	33.00	13.98
DS-1 to DS-2	Narol - Sarkhej Highway Bridge	1	1.50	22.98	72.54	1.50	45.95	40.99	22.00	58.00	53.39	72.00	32.00	36.78
DS-2 to DS-3	Kamod Bridge	2	10.05	22.93	72.54	11.55	40.99	36.56	22.00	55.00	50.90	72.00	32.00	13.59
DS-3 to DS-4	Saroda Bridge	3	14.05	22.83	72.50	25.60	36.56	28.06	22.00	49.00	32.60	72.00	30.00	16.58

- **Headwater flow**

The Vasna Barrage, taken as a head point of the downstream stretch, holds water coming from upstream of Ahmedabad. This helps maintain the river's water level and supports irrigation. The overflow from the barrage is discharged into the Fatehwadi Canal located on the right bank and used for irrigation. The surplus water is released into the Sabarmati River downstream of the Vasna Barrage. Hence, the river runs dry downstream of the barrage. The river receives the discharge from the STPs and CETPs in the surroundings.

Therefore, it is essential to maintain minimal water flow downstream of the barrage to maintain the riverine ecological system. The average bed level of the river downstream of the Vasna Barrage is reported to be 125 ft. Hence, a minimum water level of 129 ft. is considered for the river downstream of the barrage. Therefore, the flow in the river is calculated as 236 m^3/s as below. The model was simulated considering the minimum calculated flow for the winter and pre-monsoon seasons.

Min. water level considered for the river	= 129.00	ft
	=39.32	mt
Bed level of the river	= 38.56	mt. taken from CS
Hence, water level	0.76	mt.
Considering velocity of flow	0.32	m/s
bottom width	580.00	m taken from CS
Hence, side slope 1,	0.04	taken from CS
Side slope 2,	0.03	taken from CS
Hence, Top width	622.84	m
Calculated area for given WL		
Area of trapezoid = (a+b)Xh/2	737.28	m^2
Hence flow	236	m^3/s

- **Hydraulic data**

Hydraulics were calculated based on the flow of 236 m^3/s and the minimum water level of 129 ft and are presented in **Table 5.30**.

TABLE 5.30 Hydraulic data for the downstream stretch

Reach Label	Downstream end of reach label	Area m^2	Velocity m/s	Velocity coefficient, a	Velocity Exponent, b	Depth coefficient, c	Depth exponent, d
	Headwater	737.28	0.32	0.08	0.26	0.15	0.30
DS-1 to DS-2	Narol - Sarkhej Highway Bridge	123.68	1.18	0.28	0.26	0.17	0.27
DS-2 to DS-3	Kamod Bridge	450.82	0.32	0.08	0.26	0.17	0.27
DS-3 to DS-4	Saroda Bridge	442.77	0.33	0.08	0.26	0.17	0.27

❑ **Water quality data**

Table 5.31 shows the water quality data grouped season-wise for the downstream stretch simulation run.

TABLE 5.31 Water Quality data for the downstream stretch

Location	Temperature (°C)	ISS (mg/L)	DO (mg/L)	CBODslow (mg/L)	CBODfast (mg/L)	NH_3-N (ug/L)	pH
Winter season							
For calibration (Dec. 2012- Feb. 2018)							
DS-1	21.14	9.42	7.53	29.03	5.19	1110.00	8.15
DS-2	24.73	92.43	0.50	315.99	79.60	28970.00	7.55
DS-3	24.83	78.71	0.50	332.48	13.67	23448.57	7.25
DS-4	25.58	55.17	0.50	193.78	58.25	20436.67	7.42
For validation (Dec. 2018- Feb. 2021)							
DS-1	20.51	9.94	6.49	49.01	4.54	988.75	8.26
DS-2	23.50	202.50	0.50	510.00	4.03	21950.00	7.26
DS-3	25.50	39.50	0.50	245.60	2.23	19200.00	7.49
DS-4	24.11	28.79	0.50	196.56	23.45	18389.82	7.51
Pre-monsoon season							
For calibration (2012- 2017)							
DS-1	32.37	12.00	5.86	51.50	4.84	621.50	8.92
DS-2	34.00	116.67	0.50	381.22	53.78	38280.00	8.21
DS-3	32.70	59.33	0.50	176.91	56.42	32556.67	7.33
DS-4	30.88	47.50	0.50	99.50	61.00	30100.00	7.63
For validation (2018- 2021)							
DS-1	32.33	14.00	6.99	48.79	1.40	1155.00	8.12
DS-2	33.67	138.33	0.50	548.31	23.89	29763.44	7.16
DS-3	35.00	63.00	0.69	310.19	19.18	22279.38	7.41
DS-4	36.33	24.33	0.43	218.05	21.55	24961.56	7.65

❑ Meteorological data

Meteorological data shown in the **Table 5.20** were adopted for the simulation run for the downstream stretch.

❑ Solar radiation data

The data grouped in **Table 5.21** were used as input to the downstream stretch.

❑ Point source data

The Sabarmati River downstream of the Vasna Barrage receives discharges from sewage treatment plants (STPs) and common effluent treatment plants (CETPs) located in the surroundings. The outfalls beyond Vasna Barrage into the river have been taken from the Gujarat Pollution Control Board (GPCB) action taken report 2023 [181]. The pollution load data for the selected dataset is not available. Therefore, the pollution load for model calibration has been calculated based on the trend of increase in the parameters from DS-1 to DS-4, with the pollution load contribution based on the GPCB report and shown in **Table 5.32**.

TABLE 5.32 Pollution load data for the downstream stretch

The trend of increase in pollution load parameters downstream	ISS mg/L	CBODs mg/L	CBODf mg/L	NH_3-N ug/L
Winter season	137.79	312.00	47.82	24471.25
Pre-Monsoon season	61.86	238.89	36.18	33400.22

Discharges into the Sabarmati River (GPCB report)			Calculated data	
Outfall name	**discharge in MLD**	**discharge in m^3/s**	**Chainge in km**	**% contribution to the pollution load**
Domestic outfall near Vasna Barrage, Vasna Side	27.85	0.32	222.50	1.50
Outfall of 106 MLD STP	57.59	0.67	223.00	3.00
Outfall of storm water drain V. N. Bridge	22.63	0.26	223.80	3.00
Bypass of 76 MLD pumping station	284.18	3.29	224.70	28.00
Final outlet of 240 MLD STP	248	2.87	225.30	12.00
Final outlet of 126 MLD STP	68	0.79	225.70	3.00
Bypass from 182 MLD pumping	163.95	1.90	224.00	20.00
Final outlet of 155 MLD STP	126.11	1.46	224.40	6.00

Discharges into the Sabarmati River (GPCB report)			Calculated data	
Outfall name	**discharge in MLD**	**discharge in m^3/s**	**Chainge in km**	**% contribution to the pollution load**
Final outlet of 180 MLD STP	134.78	1.56	224.50	6.00
Outfall of 60 MLD STP	32.43	0.38	222.50	1.50
From outlet of MEGA pipeline into River Sabarmati at V. N. Bridge, Narol	46.57	0.54	224.00	5.00
From outlet of NTIEM pipeline into River Sabarmati at V. N. Bridge, Narol	80.58	0.93	224.00	11.00

5.7.2 Calibration and Validation

The model for the downstream stretch was simulated with the minimum calculated flow of 235.93 m^3/s for winter and pre-monsoon seasons, and the results are shown in **Figures 5.9 and 5.10**. Therefore, the simulated data for both seasons showed a similar trend for water quality parameters, following the same system hydraulics. The simulated data from the calibrated model shows a sudden increase in ISS, CBODs, CBODf and NH_3-N concentrations downstream of the Headwater up to 6.5 km, indicating high pollution load input within the stretch. The trend line follows the pattern according to the water quality characteristics downstream of the stretch beyond 6.5 km and is described below.

For the winter season, CBODs, CBODf and NH_3-N follow only a slight decreasing trend from 6.5 to 25.6 km. ISS concentration increases from the headwater concentration 9.4 mg/L to 102.88 mg/L at 6.5 km, decreases to 69.97 mg/L and remains constant beyond 18.6 km. As a result, DO from headwater 7.4 mg/L decreases drastically to 1.0 mg/L at 6.5 km, which further reduces to 0.5 mg/L as the distance increases downstream. pH reduces from 8.1 to 7.5 mg/L downstream of the headwater because of the pollution load input.

Whereas for the pre-monsoon season, CBODf increases from 49.0 mg/L to 58.5 mg/L, representing additional COD load input from the wastewater discharges up to 18.5 km. ISS and CBODs followed a slight decreasing trend beyond 6.5 km. NH_3-N decreases from 27.8 mg/L to 23.7 mg/L from 6.5 to 18.6 km, remaining constant further downstream. DO drastically reduces to 0.5 mg/L downstream of 6.5 km. The resultant pH value reduces further beyond 6.5 km and remains at 7.6.

Significant differences in RMSE values were observed between the calibration and validation stages, reflecting the influence of point source loading on the river's water quality. The RMSE data for winter and pre-monsoon are shown in **Tables 5.33 and 5.34**, respectively. For the winter season, RMSE values for the calibration and validation are 17.8% & 69.6% for ISS, 0.05% & 1.1% for DO, 30.1% & 36.6% for CBODs, 48.5% & 117.3% for CBODf, 8.8% & 10.4% for NH_3-N, 2.4% & 0.2% for pH. For the Pre-monsoon season, RMSE values for the calibration and validation are 27.3% & 56.6% for ISS, 4.11% & 29.8% for DO, 56.4% & 21.5% for CBODs, 3.9% & 96.8% for CBODf, 28% & 5.7% for NH_3-N, 2.7% & 2% for pH. A high degree of variation in observed water quality data resulted in inconsistent model performance with a large difference in fitness value: 9.11 in calibration and 4.26 in the validation for winter, 7.74 in calibration and 2.84 in validation for pre-monsoon. Such variability was expected as the downstream stretch is affected by heavy point source discharges and fluctuating pollution loads. Despite the notable discrepancies in RMSE value, the calibrated model is considered acceptable as it reasonably simulates the system under varying conditions and captures the overall trends. The calibrated model was used to depict various scenarios to assess the river's carrying capacity.

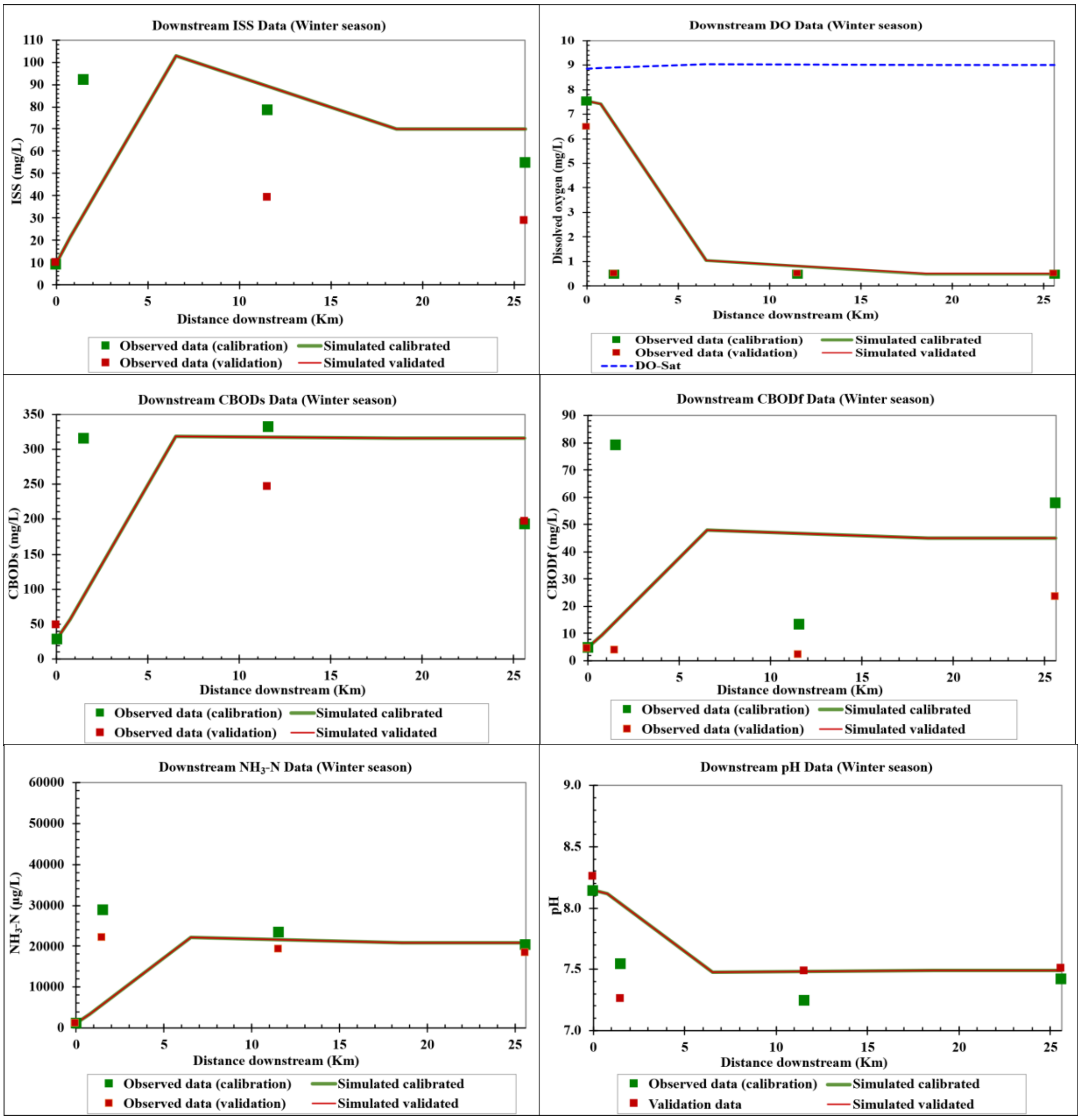


FIGURE 5.9 Model output for downstream stretch (winter season)

TABLE 5.33 Model fitness and RMSE values for the downstream stretch (winter season)

Parameters	ISS	DO	CBODs	CBODf	NH_3-N	pH	Model fitness
Calibration	17.8%	0.05%	30.1%	48.5%	8.8%	2.4%	9.11
Validation	69.6%	1.1%	36.6%	117.3%	10.4%	0.2%	4.26

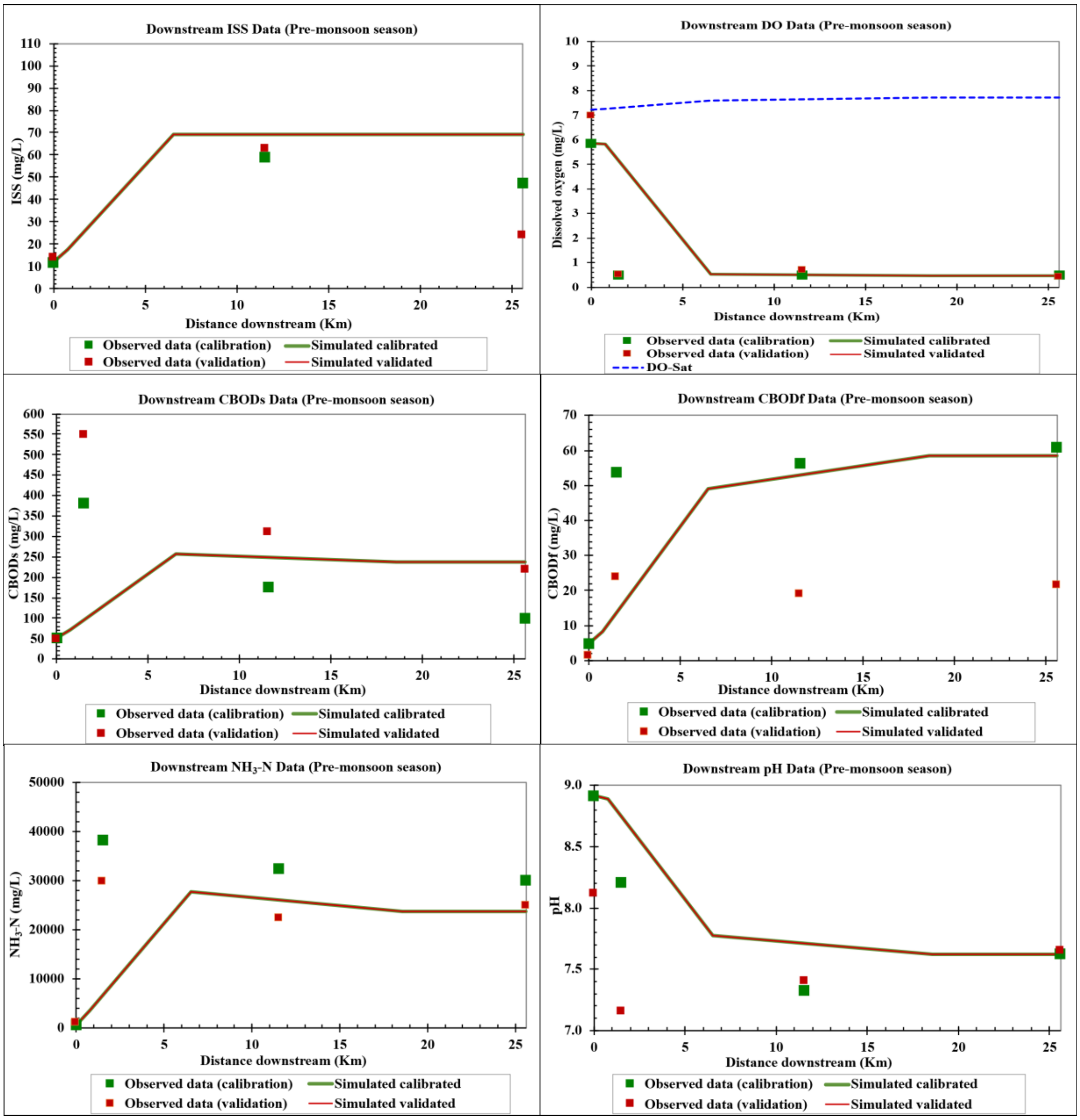


FIGURE 5.10 Model output for downstream stretch (pre-monsoon season)

TABLE 5.34 Model fitness and RMSE values for the downstream stretch (pre-monsoon season)

Parameters	ISS	DO	CBODs	CBODf	NH_3-N	pH	Model fitness
Calibration	27.3%	4.11%	56.4%	3.9%	28.0%	2.7%	7.74
Validation	56.6%	29.8%	21.5%	96.8%	5.7%	2.0%	2.84

5.7.3 Scenario Analysis

The downstream stretch of the river is affected mainly by the wastewater discharges. The norms for the discharges into the surface water bodies have been stipulated in the Environment (Protection) Rules, 1986, listed in **Table 5.35**. Further, a minimum DO value of 4.0 mg/L is required as per the CPCB criteria for the propagation of wildlife and species. Taking into consideration these criteria, various scenarios were simulated for the calibrated model of the downstream stretch.

TABLE 5.35 General standards for the discharge of effluent into inland surface water

Parameter	**Standards Inland surface water**
Suspended solids mg/L, Max.	100
pH Value	5.5 to 9.0
Ammonical nitrogen (as N), mg/L Max.	50
Total Kjeldahl Nitrogen (as NH_3) mg/L, Max.	100
Biochemical Oxygen demand [3 days at 27°C] mg/L max.	30
Chemical Oxygen Demand, mg/L, max.	250

Source: The Environment (Protection) Rules, 1986, Schedule VI - General standards for discharge of environmental pollutants as per standards [182]

The calibrated model with headwater flow of 235.93 m^3/s showed that the simulated values of CBODs and CBODf during winter and CBODf during pre-monsoon exceeded the standard discharge norms. Further, a simulated DO value of 0.5 mg/L at the downstream end during both seasons is much less than the minimum DO of 4.0 mg/L required for the survival of the river's ecological system. The simulated value of other parameters remains within the standard discharge norms. Therefore, various scenarios were simulated to ascertain the standard requirements of CBODs & CBODf in winter and CBODf in pre-monsoon along with the minimum DO requirement.

The criteria of scenarios include -

1.) Reduction in pollution load
2.) Increase in river inflow
3.) Wastewater flow reduction

The scenarios were run by altering percentages of pollution load and wastewater flow reduction as well as increasing river inflow. The simulations also include different combinations of the above criteria to achieve the standards. **Tables 5.36 and 5.37** shows the results of various scenarios run for the downstream stretch for winter and pre-monsoon seasons.

Winter season:

The results of scenario I indicate that by reducing the pollution load by 30%, the CBODs value below 250 mg/L can be achieved, but CBODf value remains above 30 mg/L as per the standard requirement. Further reduction in pollution load by 50% will be able to simulate a model with the value of CBODs and CBODf within the standard requirement with the value of DO 1.22 mg/L.

For scenario II, the discharge standard requirement was checked by increasing the river inflow subsequently by 10%. The results showed that the river can accommodate the existing pollution load, confirming the discharge standard requirements of CBODs and CBODf with a 70% increase in river inflow i.e. 401.08 m^3/s of flow. But the DO value was found to be much lower at 0.96 mg/L.

In scenario III, the model was simulated for scenarios considering a 30% reduction of the existing pollution load and by increasing the river inflow subsequently from 30% increased inflow. The results indicate that for a 30% reduction in existing pollution load and with a 30% increase in inflow (306.70 m^3/s), the discharge criteria for CBODs and CBODf can be met, with a DO value of 1.09 mg/L. The scenarios with a further increase in river inflow were run to check the increase in the DO value. It was found that even after an increase in the river inflow by 60% (i.e. 377.49 m^3/s), the DO value of only 1.44 mg/L can be achieved at the downstream end.

To achieve a DO value of 4.0 mg/L at the downstream end, the criteria of scenario III are altered, considering a 50% reduction of pollution load, with an increase in river inflow from 50% in scenario IV. The simulation revealed CBODs (124.45 mg/L) and CBODf (18.21 mg/L) within the standard criteria and DO of 2.04 mg/L, with a reduction in pollution load and an increase in river inflow by 50%. Further increases in river inflow by 60% and 70% simulated a DO with slightly higher values of 2.23 and 2.40 mg/L, respectively.

Simulation with the modifications in wastewater inflow and load as in Scenario 5.1 resulted in CBODs (232.66 mg/L) below 250 mg/L and a little higher value of CBODf > 30 mg/L (32.69 mg/L) with 30% reduction in wastewater flow. The reduction in CBODf of less than 30 mg/L was further achieved with the 30% reduction in pollution load as in scenario 5.2, in combination with scenario 5.1.

To achieve a minimum DO of 4.0 mg/L, scenarios were run by modifying the wastewater flow and pollution load reduction, and river inflow increase criteria in combinations. The DO was found to be 2.06 mg/L with 30%, 30% and 50% criteria modifications, which further increased to 2.99 mg/L and 3.89 mg/L by modifications with 30%, 50% & 50% and 50%, 50% & 50% criteria, respectively. DO value of 4.06 mg/L was achieved with 50%, 50% & 60% criteria, with all other parameters satisfying the discharge norms requirement.
Scenario 7 indicates good water quality of the river under the condition of no pollution load input.

Pre-monsoon season:
By reducing the pollution load input up to 30% as simulated in Scenario 1, CBODf was found to be 41.05 mg/L at the downstream end. Further reduction to 50% resulted in a little higher value of simulated CBODf > 30 mg/L (30.85 mg/L) with a DO of 1.31 mg/L.

Scenario 2, with the criteria of an increase in river inflow, indicates that a reduction in CBODf to 35.53 mg/L was achieved even with the 70% increase in river flow i.e. from 235.93 m^3/s to 401.08 m^3/s, with a little increase in DO value from 0.53 mg/L to 0.9 mg/L. For scenario 3, considering a 30% reduction of pollution load and an increase in river inflow from 30% to so on, the simulation resulted in CBODf < 30 mg/L (29.52 mg/L) and DO of 1.31 mg/L for 50% increase in river inflow (353.90 m^3/s).

Scenario 4 showed simulated CBODf of 24.16 mg/L and DO of 2.11 mg/L with 50% of reduction in pollution load and 50% increase in river inflow i.e. 353.90 m^3/s. The increase in DO was checked by further increasing the river inflow. The results indicate an increase in DO to 2.41 mg/L by 70% increase in inflow.

From scenario 5.1, it can be seen that reducing wastewater flow by 30% is sufficient to meet the standard requirement criteria of CBODf (42.13 mg/L). Combining this criterion with 30% reduction in pollution load, scenario 5.2, the reduction in CBODf can be achieved to 31.06 mg/L, a little higher than the standard criteria.

Combining the criteria of wastewater flow reduction, pollution load reduction and an increase in river inflow as depicted in scenario 6, showed simulated CBODf of 24.22 mg/L and DO of 2.12 mg/L with 30%, 30% & 50% criteria in scenario 6.1. The increase in DO to 4.0 mg/L was checked by altering these criteria. The results showed an increase in DO to 3.10 mg/L with 30%, 50% &50%, scenario 6.2. The DO of 4.0 mg/L can be achieved with 50%, 50% & 50% criteria.

The river water indicates very good water quality with no pollution load, as simulated in scenario 7.

TABLE 5.36 Scenario analysis for downstream stretch (winter season)

		Sr. No.	Scenario	Flow in river, m^3/s	ISS mg/L	DO mg/L	CBODs mg/L	CBODf mg/L	NH_3-N ug/L	pH
	Calibrated model		**Avg. flow**	**235.93**	**69.97**	**0.50**	**316.19**	**45.13**	**20821.69**	**7.49**
			Discharge standard		**100.00**	**-**	**250.00**	**30.00**	**-**	**5.5-9.0**
			Minimum DO requirement as per CPCB criteria		**-**	**4.00**	**-**	**-**	**-**	**-**
SC1	Reduction in pollution load	1.1	30% reduction	235.93	50.31	0.78	228.49	32.17	14130.02	7.50
		1.2	**50% reduction**	**235.93**	**37.20**	**1.22**	**170.11**	**23.97**	**9803.16**	**7.51**
SC2	River inflow modifications	2.1	10% increase in river river inflow	259.52	66.13	0.56	291.29	41.48	18936.26	7.49
		2.2	20% increase in river river inflow	283.12	62.76	0.62	270.33	38.44	17357.61	7.49
		2.3	30% increase in river inflow	306.71	59.80	0.68	252.45	35.88	16018.15	7.50
		2.4	40% increase in river inflow	330.30	57.16	0.75	237.02	33.68	14868.74	7.50
		2.5	50% increase in river inflow	353.90	54.79	0.82	223.56	31.79	13872.84	7.50
		2.6	60% increase in river inflow	377.49	52.66	0.89	211.73	30.15	13002.67	7.50
		2.7	**70% increase in river inflow**	**401.08**	**50.72**	**0.96**	**201.24**	**28.71**	**12236.72**	**7.50**
SC3	Pollution load and river inflow modifications	**3.1**	**30% reduction in pollution load and 30% increase in river inflow**	**306.71**	**43.31**	**1.09**	**184.09**	**26.09**	**10891.53**	**7.51**
		3.2	30% reduction in pollution load and 40% increase river inflow	330.30	41.49	1.21	173.35	24.67	10125.64	7.51
		3.3	30% reduction in pollution load and 50% increase in river inflow	353.90	39.87	1.32	163.99	23.44	9465.81	7.51
		3.4	30% reduction in pollution load and 60% increase in river inflow	377.49	38.40	1.44	155.77	22.38	8892.50	7.52
SC4	Pollution load and river inflow modifications	4.1	50% reduction in pollution load and 50% increase in river inflow	353.90	29.92	2.06	124.45	18.21	6692.45	7.54
		4.2	50% reduction in pollution load and 60% increase in river inflow	377.49	28.90	2.23	118.64	17.49	6317.06	7.55
		4.3	**50% reduction in pollution load and 70% increase in river inflow**	**401.08**	**27.98**	**2.40**	**113.49**	**16.85**	**5989.31**	**7.56**

		Sr. No.	Scenario	Flow in river, m^3/s	ISS mg/L	DO mg/L	CBODs mg/L	CBODf mg/L	NH_3-N ug/L	pH
SC5	Wastewater flow and pollution load modifications	5.1	30% reduction in wastewater flow	235.93	50.94	0.75	232.66	32.69	14388.81	7.51
		5.2	**30% reduction in wastewater flow and 30% reduction in pollution load**	**235.93**	**37.00**	**1.21**	**170.24**	**23.92**	**9759.64**	**7.52**
SC6	River inflow, Wastewater flow and pollution load modifications	6.1	30% reduction in wastewater flow 30% reduction in pollution load 50% increase in river inflow	353.90	29.69	2.06	123.97	18.12	6626.93	7.55
		6.2	30% reduction in wastewater flow and 50% reduction in pollution load 50% increase in river inflow	353.90	22.66	2.99	96.14	14.51	4809.62	7.60
		6.3	50% reduction in wastewater flow and 50% reduction in pollution load 50% increase in river inflow	353.90	17.75	3.89	77.00	11.94	3615.93	7.68
		6.4	**50% reduction in wastewater flow and 50% reduction in pollution load 60% increase in river inflow**	**377.49**	**17.27**	**4.06**	**74.03**	**11.55**	**3451.21**	**7.69**
SC7	No pollution load	7	No pollution load	235.93	4.61	6.82	27.99	4.87	737.76	8.08

TABLE 5.37 Scenario analysis for downstream stretch (pre-monsoon season)

		Sr. No.	Scenario	Flow in river, m^3/s	ISS mg/L	DO mg/L	CBODs mg/L	CBODf mg/L	NH_3-N ug/L	pH
	Calibrated model		**Avg. flow**	**235.93**	**69.08**	**0.48**	**236.51**	**58.46**	**23725.33**	**7.62**
				Discharge standard	**100.00**	**-**	**250.00**	**30.00**	**-**	**5.5-9.0**
				Minimum DO requirement as per CPCB criteria	**-**	**4.00**	**-**	**-**	**-**	**-**
SC1	Reduction in pollution load	1.1	30% reduction	235.93	51.72	0.79	177.97	41.05	14874.85	14.87
		1.2	**50% reduction**	**235.93**	**40.15**	**1.31**	**138.92**	**30.85**	**9340.16**	**9.34**
SC2	River inflow modifications	2.1	10% increase in river inflow	259.52	64.19	0.53	220.48	53.23	21291.73	7.63
		2.2	20% increase in river inflow	283.12	60.07	0.59	206.95	48.92	19262.67	7.64
		2.3	30% increase in river inflow	306.71	56.55	0.65	195.40	45.32	17548.53	7.64
		2.4	40% increase in river inflow	330.30	53.51	0.71	185.41	42.28	16084.31	7.65
		2.5	50% increase in river inflow	353.90	50.86	0.77	176.69	39.69	14821.67	7.65
		2.6	60% increase in river inflow	377.49	48.53	0.83	169.01	37.46	13723.93	7.66
		2.7	**70% increase in river inflow**	**401.08**	**46.46**	**0.90**	**162.19**	**35.53**	**12762.74**	**7.66**
SC3	Pollution load and river inflow modifications	3.1	30% reduction in pollution load and 30% increase in river inflow	306.71	43.00	1.09	149.44	32.87	10858.64	7.65
		3.2	30% reduction in pollution load and 40% increase river inflow	330.30	40.89	1.20	142.51	31.05	9929.53	7.66
		3.3	**30% reduction in pollution load and 50% increase in river inflow**	**353.90**	**39.04**	**1.31**	**136.47**	**29.52**	**9138.22**	**7.67**
		3.4	30% reduction in pollution load and 60% increase in river inflow	377.49	37.42	1.41	131.15	28.23	8458.89	7.68
SC4	Pollution load and river inflow modifications	4.1	50% reduction in pollution load and 50% increase in river inflow	353.90	31.16	2.11	109.66	24.16	5823.20	7.70
		4.2	50% reduction in pollution load and 60% increase in river inflow	377.49	30.01	2.26	105.92	23.40	5426.69	7.72
		4.3	**50% reduction in pollution load and 70% increase in river inflow**	**401.08**	**28.99**	**2.41**	**102.60**	**22.74**	**5087.01**	**7.73**

		Sr. No.	Scenario	Flow in river, m^3/s	ISS mg/L	DO mg/L	CBODs mg/L	CBODf mg/L	NH_3-N ug/L	pH
SC5	Wastewater flow and pollution load modifications	5.1	30% reduction in wastewater flow	235.93	52.66	0.76	180.69	42.13	15151.80	7.64
		5.2	**30% reduction in wastewater flow and 30% reduction in pollution load**	**235.93**	**40.29**	**1.30**	**139.06**	**31.06**	**9232.97**	**7.66**
SC6	River inflow, Wastewater flow and pollution load modifications	6.1	30% reduction in wastewater flow 30% reduction in pollution load 50% increase in river inflow	353.90	31.15	2.12	109.44	24.22	5718.13	7.71
		6.2	30% reduction in wastewater flow and 50% reduction in pollution load 50% increase in river inflow	353.90	25.56	3.10	90.51	21.04	3813.37	7.79
		6.3	**50% reduction in wastewater flow and 50% reduction in pollution load 50% increase in river inflow**	**353.90**	**21.75**	**4.00**	**77.55**	**18.73**	**2693.86**	**7.91**
SC7	No pollution load	7	No pollution load	235.93	11.94	6.69	43.82	10.98	264.51	8.76

CHAPTER 6

Conclusions and Recommendations

6.1 Conclusions

The study highlights the importance of multivariate statistical techniques for assessing river water quality and identifying primary pollutant sources. A review of water quality models found QUAL2Kw to be the best-fit model for the study's objective. Water quality simulations for different stretches using the QUAL2Kw model helped frame scenarios for maintaining water quality and the river's health. The following conclusions are drawn from the results and discussions.

Multivariate statistical analysis

ANOVA analysis indicates significant variations in all water quality parameters ($p<0.05$) except for temperature among the sampling sites. Temperature, colour, NH_3N, Chloride, and Nitrate were found to correlate with the seasons ($p<0.05$), highlighting the impact of seasonal phenomena.

Box and whisker plots facilitated the identification of water quality patterns, revealing that water quality deteriorates with increasing distance downstream. It showed the highest chemical pollution in the downstream stretch, largely due to wastewater discharges. The plots indicated that the highest levels of physical parameters (pH, colour, TS, TDS, EC), nutrient parameters (NH_3N), and chemical parameters (COD, chloride) occurred during the pre-monsoon season. The decreasing trend of these parameters during the monsoon season revealed a dilution effect. Dissolved oxygen (DO) levels were highest in winter and lowest in the pre-monsoon period.

Hierarchical cluster analysis grouped the 11 sites into three clusters based on similar characteristics. The upstream sites, US-1 to US-4, and the middle stream site, MS-1, were grouped in a cluster, having minimal anthropogenic influence, and were categorized as less polluted sites (LP). The middle stream sites MS-2 to MS-3 and the downstream site DS-1 formed another cluster and were categorized as moderately polluted (MP) sites affected by recreational and anthropogenic activities, whereas the downstream sites DS-2 to DS-4 were grouped as highly polluted (HP) sites burdened by external pollution loads.

PCA and FA enabled the investigation of significant water quality variables for three distinct groups of sites. This analysis was performed after eliminating highly correlated and dependable variables, focusing on ten key water quality parameters: sample temperature, pH, TDS, NH_3N, chloride, COD, BOD, DO, sulphate, and nitrate. The scree plot obtained from this analysis indicated the number of principal components (eigenvalue > 1) to retain for further study. The analysis revealed four PCs for LP and HP sites and three PCs for MP sites, explaining the maximum contributions to the overall variance (62.38% for LP, 60.32% for MP, and 67.18 % for HP sites). The factor load matrix outlined the variance contribution to each principal component, highlighting the significant water quality variables. Parameters contributing to variability in water quality were determined based on absolute factor loadings >=0.6. Physical parameters (TDS), chemical parameters (Cl, COD, DO), and nutrient parameters (sulphate, nitrate) were significant across all LP, MP, and HP sites. Sample temperature was significant at both LP and HP sites, whereas other chemical parameters (pH, NH_3-N) were significant for MP and HP sites.

The study found that anthropogenic activities and surface runoff were the major sources of water quality variations for LP and MP sites, whereas HP sites were additionally impacted by wastewater discharges.

Water quality simulation by QUAL2Kw modeling

Based on the significant water quality parameters and input data requirements, the model was simulated for six water quality parameters, including inorganic suspended solids (ISS), dissolved oxygen (DO), CBOD slow (CBODs), CBOD fast (CBODf), ammonia N (NH_3-N), and pH.

The model was applied to the individual stretch. The upstream stretch was simulated as a control, and for model sensitivity analysis for the monsoon season datasets. Middle stream and downstream stretches were simulated for the critical period of pre-monsoon and winter to identify and frame water quality management scenarios.

The upstream stretch was used as a control for the monsoon season datasets, warming up the model for 2012-2013, followed by model calibration with 2014-2018 datasets and model validation for 2019-2021 data. Simulating without calibration and validation for the 2012-2013 dataset resulted in inconsistent model performance, highlighting the need for calibration and validation to ensure accuracy. The auto-calibration process provided satisfactory results, with a fitness value of 5.29. The validated model confirmed its accuracy, reflected by a fitness value of 4.65. Significant differences in RMSE values between calibrated and validated outputs for ISS (44% & 0.6%), CBODf (9.6% & 44.4%), and pH (14.5% & 65.6%) indicated variations in water quality across sites, influenced by surface runoff during the monsoon season. Sensitivity analysis revealed the model's high sensitivity to headwater flow, hydrolysis rate for CBODs, oxidation rate for CBODf, and depth coefficient.

Middle stream:

The simulated results showed that DO decreases with the increase in distance downstream. However, DO remained above 5.0 mg/L at the end for the pre-monsoon season, fulfilling the minimum DO requirement of rivers of 4.0 mg/L. During winter, the DO at the end was about 6.5 mg/L, indicating good water quality.

The differences in RMSE values from calibration and validation indicate variations in the observed data of water quality parameters impacted by point source discharges from Indira Bridge and Subhas Bridge.

The simulated model was in good conformity with the observed data. The calibrated model showed good fitness, as confirmed by the validated model (7.06 & 5.77 for winter, 6.43 & 6.78 for pre-monsoon season). Therefore, it was applied to simulate various scenarios to ascertain the minimum requirement of self-purification capacity and best use water quality according to CPCB’s water quality classification by 1) modifying river inflow and 2) modifying the pollution load.

For the winter season, the calibrated model with an average flow of 19.90 m^3/s satisfied the Class A water quality criteria with DO >6.0 mg/L (6.85 mg/l) and pH between 6.5 and 8.5

(7.86). The simulated BOD (CBODf) was slightly above 2.0 mg/L (2.21 mg/L) of the Class A criteria. The scenario analysis depicted the following.

- An increase in the headwater flow by 50% i.e. 29.85 m^3/s, resulted in a decrease in the CBODf value to 2.0 mg/L, improving the water quality with satisfying Class A criteria.
- A minimum flow of 10 m^3/s is required to maintain the water quality to satisfy the Class B outdoor bathing criteria with the existing pollution load.
- The reduction in the existing pollution load from point sources by 20% improved the water quality to Class A.

For the pre-monsoon season, the simulated calibrated model, with an average flow of 18.73 m^3/s, showed water quality satisfying Class B criteria, with a DO value of> 5.0 (5.28 mg/L), a BOD value of <3.0 mg/L (1.54 mg/L), and a pH value between 6.5 and 8.8 (7.73). The following points were drawn from the scenario analysis.

- An increase in headwater flow by 50%, i.e. 28.10 m^3/s, showed improved water quality but remained within Class B criteria.
- With the reduction in headwater flow beyond 30%, i.e. 13.11 m^3/s, the water quality degrades from Class B to Class C as the DO fell below 5.0 mg/L. A scenario depicts that a minimum flow of 13.11 m^3/s is required to maintain water quality within Class B criteria for the existing pollution load.
- The reduction in the point source load by 20% and 50% improved the DO value, but remained within Class B criteria for the average flow of 18.73 m^3/s.

Downstream:

The drastic rise in ISS, CBODs, CBODf, and NH_3-N concentrations downstream of the Headwater up to 6.5 km revealed a high pollution load input within the stretch. The simulated model of the downstream stretch for the minimum flow of 235.93 m^3/s described the water quality trend, in parity with the observed water quality data for the winter and pre-monsoon.

The sharp rise in ISS, CBODs, CBODf, and NH_3-N levels downstream of the headwater up to 6.5 km indicated a significant pollution load entering this area. Beyond 6.5 km downstream, their concentrations fluctuated, reflecting the influence of point source inputs from various locations across both seasons. The resulting DO sharply decline from 7.4 at the headwater to 1.0 mg/L at 6.5 km and ultimately dropped to 0.5 mg/L at the downstream end during winter. In the pre-monsoon season, DO further decreased to below 0.5 mg/L at the downstream end.

The point source discharges of industrial and domestic wastewater entering the stretch from various locations resulted in high variations in water quality parameters. This resulted in a high discrepancy in the model fitness of calibration and validation outputs, 9.11 & 4.26 for the winter season, and 7.74 & 2.84 for the pre-monsoon season. The calibrated model reasonably described the variations and showed good model performance. Therefore, it was adopted for framing various water quality scenarios.

The calibrated simulated model, with a headwater flow of 235.93 m^3/s for the winter and pre-monsoon seasons, showed that the CBODf for both seasons and the CBODs for winter exceeded the standard discharge limits of 30 mg/L and 250 mg/L, respectively. Simulated DO at the downstream end for both seasons remained at 0.5 mg/L, which was much below the minimum DO of 4.0 mg/L needed for wildlife and fish to survive. The scenarios were simulated for three different criteria: 1) reduction in pollution load, 2) increase in river inflow, and 3) reduction in wastewater flow to meet discharge standards.

For the winter season, the following conclusion is drawn from the scenario analysis.

- A 50% reduction in the current pollution load, with a river inflow of 235.93 m^3/s, can meet the standard discharge limits for CBODs and CBODf, with a DO of 1.22 mg/L.
- To meet the discharge standards for the current pollution load, river inflow needs to increase by 70%, which equals 401.08 m^3/s, but the DO level remains at 0.96 mg/L.
- By reducing the current pollution load by 50% and increasing the river inflow by 50% i.e. 353.90 m^3/s, the DO of the river can be maintained around 2.0 mg/L.
- From the consequent simulation of the model by combining the criteria, it was found that the DO value of 4.06 mg/L can be achieved by reducing the current wastewater flow and pollution load by 50% and increasing the river inflow by 60%, i.e. 377.50 m^3/s.

The scenario analysis for the pre-monsoon season resulted in the following conclusion.

- Only by reducing the current pollution load to 50%, the simulated CBODf showed a slightly higher value than the discharge norms (30.85 mg/L) with a DO of 1.31 mg/L.

- The simulation, even with an increase in river inflow up to 70%, i.e. 401.08 m^3/s, cannot satisfy the CBODf discharge limit (35.53 mg/L), and a nominal increase in DO from 0.53 to 0.9 mg/L can be achieved.
- The discharge limit for CBODf can be met with a 30% reduction in current pollution load and an increase in river inflow by 50%, i.e. 353.90 m^3/s with a DO of 1.31 mg/L.
- The subsequent simulation showed that a DO of 4.0 mg/L can be maintained with a river inflow of 353.90 m^3/s with a 50% reduction in both current wastewater inflow and pollution load.

The study concludes that multivariate statistical analysis methods, including ANOVA, Box-whisker plots, cluster analysis (CA) and principal component analysis (PCA), are highly useful for determining water quality variations and identifying the most significant variables responsible for those variations. The application of QUAL2Kw modeling is effective in establishing pollution load scenarios that help maintain river health. Once the model is developed for a particular river system, it provides quick and precise real-time information to assess the health of the river. The proposed water quality modeling framework, depicted in section 3.2.3, can be applied to other river systems and is useful to researchers and water quality managers to maintain the water quality of the river for its intended uses.

6.2 Major Findings

Overall, the following major findings emerged from the water quality modelling of the Sabarmati River:

- River water quality was most critical during the **pre-monsoon and winter seasons**. Monsoon runoff and dilution improved water quality, while post-monsoon solid concentration parameters were lower than during the monsoon due to reduced runoff.
- The **upstream stretch** (Dharoi Dam to Sapteshwar Mahadev Bridge) exhibited good water quality with minimal anthropogenic influence. As monsoon conditions represented the best water quality, this season was used to understand the requirements for QUAL2Kw model calibration, sensitivity analysis and to obtain the best-fit model.
- The **middle and downstream stretches** were identified as the most critical due to anthropogenic activities and wastewater discharges. Therefore, simulations focused on these stretches during the pre-monsoon and winter, representing the critical periods.

- The **middle stretch** (Karai Syphon to Rishi Dadhichi Bridge) was moderately polluted but satisfied CPCB Class B criteria for DO and BOD under existing conditions. A minimum flow of 13.11 m^3/s is required to maintain Class B standards during pre-monsoon, while increasing flow to 29.85 m^3/s can achieve CPCB Class A standards, except in the pre-monsoon season.
- For the **downstream stretch** (Vasna Barrage to Saroda Bridge), a flow of 401.08 m^3/s was sufficient to meet the discharge standards (COD < 250 mg/L and BOD < 30 mg/L) under existing pollution loads, except during pre-monsoon. However, this flow was inadequate to sustain river self-purification and ecosystem health. Ecological conditions could be maintained with a flow of 377.50 m^3/s combined with a 50% reduction in existing pollution load and wastewater discharge.

6.3 Recommendations

The research study reveals that combining multivariate statistical analysis with QUAL2Kw modeling of a river provides a comprehensive and effective approach for assessing and maintaining river water quality. The study confirms that the river's water quality is significantly influenced by spatial and temporal variations, making their estimation essential for determining the key variables affecting water quality.

The application of multivariate statistical methods, including ANOVA, box-whisker plots, cluster analysis (CA) and principal components analysis (PCA), proved effective in estimating water quality variations, identifying pollution sources, determining the extent of pollution and recognizing most influencing variables. These methods facilitate identification of key water quality variables required for estimating pollution load capacity and water quality modeling.

Based on a comprehensive review of identified water quality models, QUAL2Kw offers several advantages, including its free availability, user-friendly design, Microsoft Excel interface, auto calibration system and successful applications to several Indian rivers such as Tapi, Yamuna, Godavari, Periyar, and Kshipra. Furthermore, scenario analysis demonstrated that QUAL2Kw is a valuable decision support tool for evaluating water quality management strategies and self-purification requirements. It enables estimation of the pollution load reduction and minimum flow required to maintain the ecology and health of the river.

Based on the outcome of the study, the following recommendations have been proposed for assessing and maintaining the health of the river. The recommendations are intended to support future scope and to ensure long-term sustainability of the river. It will serve as a scientific basis for researchers, water quality managers, policy makers, and environmental regulatory authorities to design effective water quality management programs.

Strengthen continuous water quality monitoring:
A continuous water quality monitoring program at regular intervals should be implemented to capture spatiotemporal variations accurately. Real-time monitoring stations should be established to determine sudden changes in water quality.

Classification of river reaches and identification of pollution sources:
River reaches should be classified based on pollution load and water quality conditions. Application of multivariate statistical analysis methods, including ANOVA, box-whisker plots, cluster analysis and principal component analysis, identifies the extent of variation and influencing variables. Thus, it helps reduce redundant variables and monitoring costs.

Assess assimilative or pollution load carrying capacity through water quality modeling:
The QUAL2Kw should be applied to future studies. The models should be developed for classified river stretches and season-specific. The reliability of the Models depends on data input. The data required to input the model, including water flow, point- and non-point discharges, and hydraulic characteristics, should be measured and maintained. The model should be calibrated to optimize parameters and validated to ensure its performance using specific datasets. The application of the best-fit model provides a reliable prediction output. The model should be updated with recent datasets to improve its reliability.

Simulate pollution management scenarios:
The QUAL2Kw model, once developed for a specific reach, can be used as a decision support tool by simulating various scenarios for improving water quality and reducing the pollution load. This analysis helps identify various strategies for river water quality management.

Maintain adequate environmental flow:

The flow required to maintain the self-purification capacity of the river should be assessed and maintained. It is essential to preserve the dissolved oxygen level required for river ecology and its health.

Strengthen compliance and control point and non-point sources of pollution:

The compliance monitoring of domestic and industrial wastewater discharged into the river should be strengthened. Pollution control initiatives should be encouraged and promoted. Initiatives, like zero liquid discharge by industries, should be rewarded. Other discharges into the river, like offerings, idol immersion and waste disposal from local areas, should be restricted and strictly monitored. Sustainable agricultural practices, use of organic fertilizers, rainwater harvesting and recharge, and stormwater management practices should be encouraged. These initiatives minimize the pollution load of the river, improve its water quality and the sustainability of the river basin.

Implement a river health management framework:

A robust framework proposed in the study provides the step-by-step procedure for assessing and maintaining the river's health. A framework should be implemented and coordinated among statutory bodies, industries, research institutions and water resource managers. It can be utilized as part of integrated river basin management. It can also be implemented as a water resource management strategy under a policy framework. It will help to restore and conserve pristine river water sources. Such an effort supports sustainable river basin management and aligns with the sustainable development goal (SDG), SDG 6 - Clean water and sanitation.

6.4 Limitations of the Study

The study and its findings are based on the dataset collected from 2012-2021. The water quality datasets comprise December 2012 – November 2021. During the period, the water quality varied widely, with many initiatives taken for river protection, viz. river front development, restrictions on idol immersion etc. and also included the corona period.

The microbiological parameters, coliforms, heavy metals, pesticides, etc. were not considered because of the unavailability of consistent data for the said period.

6.5 Future Scope

The study encompasses the water quality assessment of identified stretches using limited monitoring sites, including the upstream stretch (Dharoi Dam to Sapteshwar Mahadev Bridge), middle stream (Karai Dam to Rushi Dadhichi Bridge) and the downstream stretch (Vasna Barrage to Saroda Bridge), using 2012-2021 datasets. Water quality scenario simulations were performed only for the critical seasons i.e. pre-monsoon and winter, and focused on middle and downstream stretches for the identified significant parameters. Therefore, the scope of future work includes the following:

- The status of the current water quality can be identified from a more recent dataset. The current pollution load into the river should be measured, which provides the current water quality status, which can be further input to the model to identify the pollution load scenarios.
- The simulations of water quality of a river and scenarios for any specific period enable a researcher/water quality manager to determine the current water quality status. It can provide measures for further improvement in the current water quality for its intended best use.
- There is a further scope to simulate water quality for biological parameters to determine and confirm its quality for a specific purpose.
- Simulations with nutrient parameters can provide compliance with water quality standards and provide measures to control and identify agricultural management practices.
- Other emerging contaminants like heavy metals, pesticides and potentially toxic elements are also one of the major concerns. Their continuous discharge, even at low concentrations, from municipal or industrial wastewater, agricultural runoff, and storm water runoff poses a significant environmental concern. They are persistent in nature and have bioaccumulation potential, which may cause serious risks to human health and aquatic ecosystem. The inclusion of these parameters in future assessment and modeling can further strengthen water resource management and long-term sustainability of riverine resources for future generations.

List of References

1. Ji, Z. G. (2017). *Hydrodynamics and water quality: Modeling rivers, lakes, and estuaries*. John Wiley & Sons. https://doi.org/10.1002/9781119371946
2. Pinto, U., & Maheshwari, B. L. (2011). River health assessment in peri-urban landscapes: An application of multivariate analysis to identify the key variables. *Water Research*, *45*(13), 3915–3924. https://doi.org/10.1016/j.watres.2011.04.044
3. Srinivasa Rao, G. V. R., Rajesh Kumar, M., Sreejani, T. P., & Sravya, P. V. R. (2019). Multivariate Statistical Analysis of River Water Quality—A Study on River Godavari in Andhra Pradesh. In *Water Resources and Environmental Engineering II:Climate and Environment* (pp. 69–77). Springer Singapore. https://doi.org/10.1007/978-981-13-2038-5_7
4. CPCB. (2021). *National Inventory of Sewage Treatment Plants*. Central Pollution Control Board, New Delhi.
5. CPCB. (2019). *ENVIS Newsletter, July-Sep. 2019* (Vol. July-Sep).
6. Global Water Partnership, & International Network of Basin Organization. (2009). *A Handbook for Integrated Water Resources Management in Basins*. *Strategy* (Vol. 74).
7. LI, Y., XU, L., & LI, S. (2009). Water quality analysis of the Songhua River basin using multivariate techniques. *Journal of Water Resource and Protection*, *01*(02), 110–121. https://doi.org/10.4236/jwarp.2009.12015
8. CPCB. (2007). *Central Pollution Control Board - Guidelines for Water Quality Monitoring*. *Central Pollution Control Board*.
9. Nguyen, T. H., Helm, B., Hettiarachchi, H., Caucci, S., & Krebs, P. (2019). The selection of design methods for river water quality monitoring networks: a review. *Environmental Earth Sciences*. https://doi.org/10.1007/s12665-019-8110-x
10. Canter, L. W. (2018). *River water quality monitoring*. *River Water Quality Monitoring*. CRC Press. https://doi.org/10.1201/9781351076418
11. Kannel, P. R., Lee, S., Kanel, S. R., & Khan, S. P. (2007). Chemometric application in classification and assessment of monitoring locations of an urban river system. *Analytica Chimica Acta*, *582*(2), 390–399. https://doi.org/10.1016/j.aca.2006.09.006
12. Kannel, P. R., Kanel, S. R., Lee, S., & Lee, Y. S. (2011). Chemometrics in assessment of seasonal variation of water quality in fresh water systems. *Environmental Monitoring and Assessment*, *174*(1), 529–545. https://doi.org/10.1007/s10661-010-1476-6

13. Simeonov, V., Stratis, J. A., Samara, C., Zachariadis, G., Voutsa, D., Anthemidis, A., … Kouimtzis, T. (2003). Assessment of the surface water quality in Northern Greece. *Water Research*, *37*(17), 4119–4124. https://doi.org/10.1016/S0043-1354(03)00398-1
14. González, S. O., Almeida, C. A., Calderón, M., Mallea, M. A., & González, P. (2014). Assessment of the water self-purification capacity on a river affected by organic pollution: application of chemometrics in spatial and temporal variations. *Environmental Science and Pollution Research*, *21*(18), 10583–10593. https://doi.org/10.1007/s11356-014-3098-y
15. Shrestha, S., & Kazama, F. (2007). Assessment of surface water quality using multivariate statistical techniques: A case study of the Fuji river basin, Japan. *Environmental Modelling & Software*, *22*(4), 464–475. https://doi.org/10.1016/j.envsoft.2006.02.001
16. de Medeiros, G. A., de Lima Tresmondi, A. C. C., de Queiroz, B. P. V., Fengler, F. H., Rosa, A. H., Fialho, J. M., … Ribeiro, A. I. (2017). Water quality, pollutant loads, and multivariate analysis of the effects of sewage discharges into urban streams of Southeast Brazil. *Energy, Ecology and Environment*, *2*(4). https://doi.org/10.1007/s40974-017-0062-y
17. Noori, R., Sabahi, M. S., Karbassi, A. R., Baghvand, A., & Taati Zadeh, H. (2010). Multivariate statistical analysis of surface water quality based on correlations and variations in the data set. *Desalination*, *260*(1–3), 129–136. https://doi.org/10.1016/j.desal.2010.04.053
18. Sinha, S., Gupta, A. K., Bhatt, K., Pandey, K., Rai, U. N., & Singh, K. P. (2006). Distribution of metals in the edible plants grown at Jajmau, Kanpur (India) receiving treated tannery wastewater: Relation with physico-chemical properties of the soil. *Environmental Monitoring and Assessment*, *115*(1–3), 1–22. https://doi.org/10.1007/s10661-006-5036-z
19. Singh, K. P., Malik, A., & Sinha, S. (2005). Water quality assessment and apportionment of pollution sources of Gomti river (India) using multivariate statistical techniques—a case study. *Analytica Chimica Acta*, *538*(1–2), 355–374. https://doi.org/10.1016/j.aca.2005.02.006
20. Bennett, J. P., & Rathbun, R. E. (1971). *Reaeration in Open-Channel Flow* (Vol. 737). US Department of the Interior, Geological Survey.
21. Hanelore, M. (2013). The process of self-purification in the rivers. In *International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology*

Management, SGEM. https://doi.org/10.5593/SGEM2013/BC3/S12.052

22. Tian, S., Wang, Z., & Shang, H. (2011). Study on the self-purification of Juma River. In *Procedia Environmental Sciences* (Vol. 11, pp. 1328–1333). https://doi.org/10.1016/j.proenv.2011.12.199
23. Basant, N., Gupta, S., Malik, A., & Singh, K. P. (2010). Linear and nonlinear modeling for simultaneous prediction of dissolved oxygen and biochemical oxygen demand of the surface water - A case study. *Chemometrics and Intelligent Laboratory Systems*, *104*(2), 172–180. https://doi.org/10.1016/j.chemolab.2010.08.005
24. Vagnetti, R., Miana, P., Fabris, M., & Pavoni, B. (2003). Self-purification ability of a resurgence stream. *Chemosphere*, *52*(10), 1781–1795. https://doi.org/10.1016/S0045-6535(03)00445-4
25. Karthiga, D. M., Mano, B. E., Geethamani, R., & Abinaya, S. (2017). Self-purification capacity of Bhavani River, India. *Research Journal of Engineering Science*, *6*(3), 1–9.
26. Susilowati, S., Sutrisno, J., Masykuri, M., & Maridi, M. (2018). Dynamics and factors that affects DO-BOD concentrations of Madiun River. In *AIP Conference Proceedings* (Vol. 2049, p. 020052). American Institute of Physics Inc. https://doi.org/10.1063/1.5082457
27. Streeter, H., & Phelps, E. (1925). A study of the pollution and natural purification of the Ohio River. *Public Health Bulletin*, *146*.
28. Pradana, H. A., Novita, E., Wahyuningsih, S., & Pamungkas, R. (2019). Analysis of deoxygenation and reoxygenation rate in the Indonesia River (a case study: Bedadung River East Java). In *IOP Conference Series: Earth and Environmental Science* (Vol. 243, p. 012006). https://doi.org/10.1088/1755-1315/243/1/012006
29. CPCB. (2017). Water Quality Data. Retrieved April 27, 2022, from https://cpcb.nic.in/water-quality-criteria-2/
30. Bhutiani, R., & Khanna, D. R. (2007). Ecological study of river Suswa: Modeling DO and BOD. *Environmental Monitoring and Assessment*, *125*(1–3), 183–19. https://doi.org/10.1007/s10661-006-9251-4
31. Singh, K. P., Basant, A., Malik, A., & Jain, G. (2009). Artificial neural network modeling of the river water quality-A case study. *Ecological Modelling*, *220*(6), 888–895. https://doi.org/10.1016/j.ecolmodel.2009.01.004
32. Mishra, B. K., Regmi, R. K., Masago, Y., Fukushi, K., Kumar, P., & Saraswat, C. (2017). Assessment of Bagmati river pollution in Kathmandu Valley: Scenario-based modeling and analysis for sustainable urban development. *Sustainability of Water*

Quality and Ecology, *9*, 67–77. https://doi.org/10.1016/j.swaqe.2017.06.001

33. Tyagi, B., Gakkhar, S., & Bhargava, D. S. (1999). Mathematical modelling of stream DO-BOD accounting for settleable BOD and periodically varying BOD source. *Environmental Modelling and Software*, *14*(5), 461–471. https://doi.org/10.1016/S1364-8152(98)00091-7
34. Ayoko, G. A., Singh, K., Balerea, S., & Kokot, S. (2007). Exploratory multivariate modeling and prediction of the physico-chemical properties of surface water and groundwater. *Journal of Hydrology*, *336*(1–2), 115–124. https://doi.org/10.1016/j.jhydrol.2006.12.013
35. Moghimi Nezad, S., Ebrahimi, K., & Kerachian, R. (2018). Investigation of seasonal self-purification variations of Karun River, Iran. *Amirkabir Journal of Civil Engineering*, *49*(4), 193–196.
36. Wilk, P., Orlinska-Wozniak, P., & Gebala, J. (2018). The river absorption capacity determination as a tool to evaluate state of surface water. *Hydrology and Earth System Sciences*, *22*(2), 1033–1050. https://doi.org/10.5194/hess-22-1033-2018
37. USEPA. (n.d.). Clean Water Act Section 303(d): Impaired Waters and Total Maximum Daily Loads (TMDLs). Retrieved from https://www.epa.gov/tmdl
38. Wang, Q., Li, S., Jia, P., Qi, C., & Ding, F. (2013). A review of surface water quality models. *The Scientific World Journal*, *2013*. https://doi.org/10.1155/2013/231768
39. Martin, J. L., McCutcheon, S. C., & Schottman, R. W. (2018). *Hydrodynamics and Transport for Water Quality Modeling*. CRC Press. https://doi.org/10.1201/9780203751510
40. Loucks, D. P., & Van Beek, E. (2017). *Water resource systems planning and management: An introduction to methods, models, and applications*. Springer.
41. Haldar, S., Mandal, S. K., Thorat, R. B., Goel, S., Baxi, K. D., Parmer, N. P., … Mody, K. H. (2014). Water pollution of Sabarmati River - A Harbinger to potential disaster. *Environmental Monitoring and Assessment*, *186*(4), 2231–2242. https://doi.org/10.1007/s10661-013-3532-5
42. Kumar, R. N., Solanki, R., & Kumar, N. J. I. (2012). Spatial Variation in Phytoplankton Diversity in the Sabarmati River at Ahmedabad, Gujarat, India. *Annals of Environmental Science*, *6*, 13–28. Retrieved from www.rnkumar.co.in;www.ritankumar.co.in.
43. Qureshi, I., Gandhi, D., Zarad, S., & Gandhi, H. (2018). A study of physicochemical and biological characteristics of Sabarmati River water in Ahmedabad city, Gujarat,

India. *Journal of Industrial Pollution Control*, *34*(1), 1877–1881.

44. Shah, K. A., & Joshi, G. S. (2017). Evaluation of water quality index for River Sabarmati, Gujarat, India. *Applied Water Science*, *7*(3). https://doi.org/10.1007/s13201-015-0318-7

45. Giri, A., Bharti, V. K., Kalia, S., Kumar, K., Raj, T., & Chaurasia, O. P. (2019). Utility of multivariate statistical analysis to identify factors contributing river water quality in two different seasons in cold-arid high-altitude region of Leh-Ladakh, India. *Applied Water Science*, *9*(26). https://doi.org/10.1007/s13201-019-0902-3

46. Kowalkowski, T., Zbytniewski, R., Szpejna, J., & Buszewski, B. (2006). Application of chemometrics in river water classification. *Water Research*, *40*(4), 744 – 752. https://doi.org/10.1016/j.watres.2005.11.042

47. Azhar, S. C., Aris, A. Z., Yusoff, M. K., Ramli, M. F., & Juahir, H. (2015). Classification of river water quality using multivariate analysis. *Procedia Environmental Sciences*, *30*, 79–84. https://doi.org/10.1016/j.proenv.2015.10.014

48. Kumari, M., Tripathi, S., Pathak, V., & Tripathi, B. D. (2013). Chemometric characterization of river water quality. *Environmental Monitoring and Assessment*, *185*, 3081–3092. https://doi.org/10.1007/s10661-012-2774-y

49. Gull, S., Shah, S. R., & Dar, A. M. (2023). Application of multivariate statistical methods to enhance the water quality monitoring system of Kashmir Valley with special emphasis on side-stream pollution. *Aqua Water Infrastructure, Ecosystems and Society*, *72*(2), 202–220. https://doi.org/10.2166/aqua.2023.230

50. Hayek, A., Andaloussi, S. A., Tabaja, N., Toufaily, J., Garnie-Zarli, E., & Hamieh, T. (2021). Multivariate spatial and temporal analysis to study the variation of physico-chemical parameters in Litani River, Lebanon. *American Journal of Analytical Chemistry*, *12*(11), 373–391. https://doi.org/10.4236/ajac.2021.1211023

51. Varol, M., Gökot, B., Bekleyen, A., & Şen, B. (2012). Water quality assessment and apportionment of pollution sources of Tigris River (Turkey) using multivariate statistical techniques-a case study. *River Research and Applications*, *28*(9), 1428–1438. https://doi.org/10.1002/rra.1533

52. Ouyang, Y. (2005). Evaluation of river water quality monitoring stations by principal component analysis. *Water Research*, *39*(12), 2621–2635. https://doi.org/10.1016/j.watres.2005.04.024

53. Maina, M. M., & Yunusa, A. (2020). Assessment of water quality and identification of pollutants flowing into river musa using principal component analysis. *IOP Conference*

Series: Earth and Environmental Science, *445*(1), 012014. https://doi.org/10.1088/1755-1315/445/1/012014

54. Cox, B. A. (2003). A review of currently available in-stream water-quality models and their applicability for simulating dissolved oxygen in lowland rivers. In *Science of the Total Environment* (Vol. 314–316). https://doi.org/10.1016/S0048-9697(03)00063-9
55. Sharma, D., & Kansal, A. (2013). Assessment of river quality models: A review. *Reviews in Environmental Science and Biotechnology*. https://doi.org/10.1007/s11157-012-9285-8
56. Ranjith, S., Shivapur, A. V., Kumar, P. S. K., Hiremath, C. G., & Dhungana, S. (2019). Water quality model for streams: a review. *Journal of Environmental Protection*, *10*(12), 1612–1648. https://doi.org/10.4236/jep.2019.1012097
57. Kannel, P. R., Kanel, S. R., Lee, S., Lee, Y. S., & Gan, T. Y. (2011). A review of public domain water quality models for simulating dissolved oxygen in rivers and streams. *Environmental Modeling and Assessment*, *16*(2). https://doi.org/10.1007/s10666-010-9235-1
58. Costa, C. M. da S. B., Leite, I. R., Almeida, A. K., & de Almeida, I. K. (2021). Choosing an appropriate water quality model—a review. *Environmental Monitoring and Assessment*, *193*(1), 38. https://doi.org/10.1007/s10661-020-08786-1
59. Ejigu, M. T. (2021). Overview of water quality modeling. *Cogent Engineering*, *8*(1), 1891711. https://doi.org/10.1080/23311916.2021.1891711
60. Chen, Y., Song, L., Liu, Y., Yang, L., & Li, D. (2020, September 1). A review of the artificial neural network models for water quality prediction. *Applied Sciences (Switzerland)*. MDPI AG. https://doi.org/10.3390/app10175776
61. Zhou, Y. (2020). Real-time probabilistic forecasting of river water quality under data missing situation: Deep learning plus post-processing techniques. *Journal of Hydrology*, *589*, 125164. https://doi.org/10.1016/j.jhydrol.2020.125164
62. Krapu, C., & Borsuk, M. (2019). Probabilistic programming: A review for environmental modellers. *Environmental Modelling and Software*, *114*, 40–48. https://doi.org/10.1016/j.envsoft.2019.01.014
63. Wu, J., Wang, Z., & Dong, L. (2021). Prediction and analysis of water resources demand in Taiyuan City based on principal component analysis and BP neural network. *Aqua Water Infrastructure, Ecosystems and Society*, *70*(8), 1272–1286. https://doi.org/10.2166/aqua.2021.205
64. Jiang, Y., Li, C., Sun, L., Guo, D., Zhang, Y., & Wang, W. (2021). A deep learning

algorithm for multi-source data fusion to predict water quality of urban sewer networks. *Journal of Cleaner Production*, *318*, 128533. https://doi.org/10.1016/j.jclepro.2021.128533

65. Wu, J., & Wang, Z. (2022). A hybrid model for water quality prediction based on an artificial neural network, wavelet transform, and long short-term memory. *Water (Switzerland)*, *14*(4), 610. https://doi.org/10.3390/w14040610
66. Mateus, M., Vieira, R. da S., Almeida, C., Silva, M., & Reis, F. (2018). ScoRE-A simple approach to select a water quality model. *Water (Switzerland)*, *10*(12), 1811. https://doi.org/10.3390/w10121811
67. Boah, D. K., & Twum, S. B. (2020). A review of water quality optimisation models and techniques. *Journal of Applied Mathematics and Physics*, *08*(03), 424–433. https://doi.org/10.4236/jamp.2020.83032
68. Riecken, S. (1995). *A compendium of water quality models*. Water Quality Branch, Ministry of Environment, Lands and Parks.
69. Singh, S., & Upadhyay, S. (2024). Basic concept of mathematical modelling. *International Journal of Creative Research Thoughts*, *12*(10), 434–438.
70. Park, S. S., & Lee, Y. S. (2002). A water quality modeling study of the Nakdong River, Korea. *Ecological Modelling*, *152*(1), 65–75. https://doi.org/10.1016/S0304-3800(01)00489-6
71. Noor, S. S. M., & Saad, N. A. (2025). A review on QUAL2K water quality model: comparative analysis with other models, recent advances and future directions. In *E3S Web of Conferences* (Vol. 599, p. 02008). EDP Sciences. https://doi.org/10.1051/e3sconf/202459902008
72. Pelletier, G. J., & Chapra, S. C. (2008). *QUAL2Kw user manual (version 5.1) : A Modeling framework for simulating river and stream water quality*.
73. Turner, D. F., Pelletier, G. J., & Kasper, B. (2009). Dissolved oxygen and pH modeling of a periphyton dominated, nutrient enriched river. *Journal of Environmental Engineering*, *135*(8), 645–652. https://doi.org/10.1061/(asce)0733-9372(2009)135:8(645)
74. Mummidivarapu, S. K., Rehana, S., & Rao, Y. R. S. (2023). Mapping and assessment of river water quality under varying hydro-climatic and pollution scenarios by integrating QUAL2K, GEFC, and GIS. *Environmental Research*, *239*, 117250. https://doi.org/10.1016/j.envres.2023.117250
75. Pelletier, G. J., & Chapra, S. C. (2008). *QUAL2Kw theory and documentation (version*

5.1), A modeling framework for simulating river and stream water quality. Washington: Department of ecology.

76. Pelletier, G. J., Chapra, S. C., & Tao, H. (2006). QUAL2Kw - A framework for modeling water quality in streams and rivers using a genetic algorithm for calibration. *Environmental Modelling and Software*, *21*(3), 419–425. https://doi.org/10.1016/j.envsoft.2005.07.002
77. Sharma, D., Kansal, A., & Pelletier, G. (2017). Water quality modeling for urban reach of Yamuna River, India (1999–2009), using QUAL2Kw. *Applied Water Science*, *7*(3), 1535–1559. https://doi.org/10.1007/s13201-015-0311-1
78. Raeisi, N., Moradi, S., & Scholz, M. (2022). Surface Water Resources Assessment and Planning with the QUAL2KW Model: A Case Study of the Maroon and Jarahi Basin (Iran). *Water (Switzerland)*, *14*(5), 705. https://doi.org/10.3390/w14050705
79. Poza, R. A., Faizaturrohmah, N., Kurnianingtyas, E., Awfa, D., Azizah, R. N., Nuha, M. U., … others. (2026). Modeling quality and pollution load capacity of the Musi River using QUAL2Kw. *Journal of Engineering Environtmental Energy and Science*, *5*(2), 109–122.
80. Ghorbani, Z., Amanipoor, H., & Battaleb-Looie, S. (2022). Water quality simulation of Dez River in Iran using QUAL2KW model. *Geocarto International*, *37*(4), 1126–1138. https://doi.org/10.1080/10106049.2020.1762763
81. Tran, C. N., Yossapol, C., Tantemsapya, N., Kosa, P., & Kongkhiaw, P. (2022). Water quality simulation and dissolved oxygen change scenarios in Lam Takhong River in Thailand. *Journal of Sustainable Development of Energy, Water and Environment Systems*, *10*(1), 1–13. https://doi.org/10.13044/j.sdewes.d9.0389
82. Pramaningsih, V., Suprayogi, S., & Purnama, I. L. S. (2020). Pollution load capacity analysis of BOD, COD, and TSS in Karang Mumus River, Samarinda. *Indonesian Journal of Chemistry*, *20*(3), 626–637. https://doi.org/10.22146/ijc.44296
83. Angello, Z. A., Behailu, B. M., & Tränckner, J. (2021). Selection of optimum pollution load reduction and water quality improvement approaches using scenario basedwater quality modeling in little akaki river, Ethiopia. *Water (Switzerland)*, *13*(5), 584. https://doi.org/10.3390/w13050584
84. Kannel, P. R., Lee, S., Kanel, S. R., Lee, Y.-S., & Ahn, K.-H. (2007). Application of QUAL2Kw for water quality modeling and dissolved oxygen control in the river Bagmati. *Environmental Monitoring and Assessment*, *125*(1), 201–217. https://doi.org/10.1007/s10661-006-9255-0

85. Babamiri, O., Vanaei, A., Guo, X., Wu, P., Richter, A., & Ng, K. T. W. (2021). Numerical simulation of water quality and self-purification in a mountainous river using QUAL2KW. *Journal of Environmental Informatics*, *37*(1), 26–35. https://doi.org/10.3808/jei.202000435
86. Khonok, A., Tabrizi, M. S., Babazadeh, H., Saremi, A., & Ghaleni, M. M. (2022). Sensitivity analysis of water quality parameters related to flow changes in regulated rivers. *International Journal of Environmental Science and Technology*, *19*(4), 3001–3014. https://doi.org/10.1007/s13762-021-03421-z
87. Nikolaidis, N. P., Karageorgis, A. P., Kapsimalis, V., Marconis, G., Drakopoulou, P., Kontoyiannis, H., … Pagou, K. (2006). Circulation and nutrient modeling of Thermaikos Gulf, Greece. *Journal of Marine Systems*, *60*(1–2), 51–62. https://doi.org/10.1016/j.jmarsys.2005.11.007
88. Ambrose, R. B., Wool, T. A., Martin, J. L., Connolly, J. P., & Schanz, R. W. (1991). *WASP.5X. A Hydrodynamic and Water Quality Model—Model Theory, User's Manual, and Programmer's Guide* (Vol. 600). Environmental Research Laboratory.
89. Ambrose, R. B., & Wool, T. (2017). *WASP8 Stream Transport - Model Theory and User's Guide*.
90. Ambrose, R. B., Wool, T. A., & Martin, J. L. (2001). *The Water Quality Analysis Simulation Program, WASP6, User Manual*. USEPA: Athens, GA.
91. Wool, T., Ambrose, R. B., Martin, J. L., & Comer, A. (2020). WASP 8: The next generation in the 50-year evolution of USEPA's water quality model. *Water (Switzerland)*, *12*(5), 1398. https://doi.org/10.3390/W12051398
92. Fitriana, F., Yudianto, D., & Seo, Y. C. (2025). Comparative analysis of water quality models for the Cibarani Irrigation Channel using WASP and QUAL2Kw. *Sustinere: Journal of Environment and Sustainability*, *9*(2), 162–172. https://doi.org/10.22515/sustinere.jes.v9i2.487
93. Melaku Canu, D., Solidoro, C., & Umgiesser, G. (2004). Erratum to "Modelling the responses of the Lagoon of Venice ecosystem to variations in physical forcings." *Ecological Modelling*, *175*(2), 197–216. https://doi.org/10.1016/j.ecolmodel.2004.01.010
94. Gordillo, G., Morales-Hernández, M., & García-Navarro, P. (2020). Finite volume model for the simulation of 1D unsteady river flow and water quality based on the WASP. *Journal of Hydroinformatics*, *22*(2), 327–345. https://doi.org/10.2166/hydro.2019.080

95. Ziemińska-Stolarska, A., & Kempa, M. (2021). Modeling and monitoring of hydrodynamics and surface water quality in the sulejów dam reservoir, poland. *Water (Switzerland)*, *13*(3), 296. https://doi.org/10.3390/w13030296
96. Diansyukma, A., Saraswati, S. P., & Yuliansyah, A. T. (2021). Analysis of the Carrying Capacity and the Total Maximum Daily Loads of the Karang Mumus Sub-watershed in Samarinda City Using the WASP Method. *Journal of the Civil Engineering Forum*, *7*(2), 209–222. https://doi.org/10.22146/jcef.62826
97. Mahalakshmi, G., Kumar, M., & Ramasamy, T. (2018). Assessment of surface water quality of Noyyal River using WASP Model. *Asian Journal of Engineering and Applied Technology*, *7*(1), 37–40. https://doi.org/10.51983/ajeat-2018.7.1.865
98. Li, Y., Li, Z., Dai, J., Rad, S., Xie, X., Qi, S., & Xu, B. (2025). Non-point source pollution transport and photocatalytic degradation effect in the Mudong River basin of Huixian Wetland based on WASP model. *Environmental Monitoring and Assessment*, *197*(12), 1349. https://doi.org/10.1007/s10661-025-14773-1
99. Ambrose, R. B., & Wool, T. A. (2009). *WASP7 Stream Transport-Model Theory and User's guide, Supplement to Water Quality Analysis Simulation Program (WASP) User Documentation*. National Exposure Research Laboratory, Office of Research and Development, US Environmental Protection Agency, Athens, Georgia.
100. Ambrose, R. B., Wool, T. A., Martin, J. L., & others. (1993). *The water quality analysis simulation program, WASP5, Part A: Model documentation*. Environmental Research Laboratory, US Environmental Protection Agency, Athens, GA.
101. Yang, C.-P., Kuo, J.-T., Lung, W.-S., Lai, J.-S., & Wu, J.-T. (2007). Water quality and ecosystem modeling of tidal wetlands. *Journal of Environmental Engineering*, *133*(7), 711–721. https://doi.org/10.1061/(asce)0733-9372(2007)133:7(711)
102. Kuo, J. T., Lung, W. S., Yang, C. P., Liu, W. C., Yang, M. Der, & Tang, T. S. (2006). Eutrophication modelling of reservoirs in Taiwan. *Environmental Modelling and Software*, *21*(6), 829–844. https://doi.org/10.1016/j.envsoft.2005.03.006
103. Shabani, A., Woznicki, S. A., Mehaffey, M., Butcher, J., Wool, T. A., & Whung, P. Y. (2021). A coupled hydrodynamic (HEC-RAS 2D) and water quality model (WASP) for simulating flood-induced soil, sediment, and contaminant transport. *Journal of Flood Risk Management*, *14*(4), e12747. https://doi.org/10.1111/jfr3.12747
104. Obin, N., Tao, H., Ge, F., & Liu, X. (2021). Research on water quality simulation and water environmental capacity in lushui river based on WASP model. *Water (Switzerland)*, *13*(20), 2819. https://doi.org/10.3390/w13202819

105. Ramos-Ramírez, L. Á., Guevara-Luna, M. A., Chiriví-Salomón, J. S., & Muñoz-Nieto, D. M. (2020). Simulation of Cr-III dispersion in the high bogota river basin using the WASP model. *Revista Facultad de Ingenieria*, (97), 30–40. https://doi.org/10.17533/UDEA.REDIN.20191155
106. Mbuh, M. J., Mbih, R., & Wendi, C. (2019). Water quality modeling and sensitivity analysis using Water Quality Analysis Simulation Program (WASP) in the Shenandoah River watershed. *Physical Geography*, *40*(2), 127–148. https://doi.org/10.1080/02723646.2018.1507339
107. Yao, H., Qian, X., Yin, H., Gao, H., & Wang, Y. (2015). Regional risk assessment for point source pollution based on a water quality model of the taipu river, China. *Risk Analysis*, *35*(2), 265–277. https://doi.org/10.1111/risa.12259
108. Hosseini, N., Johnston, J., & Lindenschmidt, K.-E. (2017). Impacts of climate change on the water quality of a regulated prairie river. *Water*, *9*(3), 199.
109. Lai, Y. C., Yang, C. P., Hsieh, C. Y., Wu, C. Y., & Kao, C. M. (2011). Evaluation of non-point source pollution and river water quality using a multimedia two-model system. *Journal of Hydrology*, *409*(3–4), 583–595. https://doi.org/10.1016/j.jhydrol.2011.08.040
110. Gao, L., & Li, D. (2014). A review of hydrological/water-quality models. *Frontiers of Agricultural Science and Engineering*, *1*(4), 267–276. https://doi.org/10.15302/J-FASE-2014041
111. Neitsch, S. L., Arnold, J. G., Kiniry, J. R., & Williams, J. R. (2009). *Soil and Water Assessment Tool theoretical document version 2009, Texas Water Resources Institute Technical Report No. 406*. College Station: Texas A&M University.
112. Neitsch, S. L., Arnold, J. G., Kiniry, J. R., & Williams, J. R. (2005). *Soil and Water Assessment Tool, Theoretical documentation version 2005*. Texas A&M University.
113. Arnold, J. G., Kiniry, J. R., Srinivasan, R., Williams, J. R., Haney, E. B., & Neitsch, S. L. (2012). *Soil and Water Assessment Tools (SWAT):Input/Output Documentation, Version 2012*. Texas Water Resource Institute.
114. Seo, M., Yen, H., Kim, M.-K., & Jeong, J. (2014). Transferability of SWAT Models between SWAT2009 and SWAT2012. *Journal of Environmental Quality*, *43*(3), 869–880. https://doi.org/10.2134/jeq2013.11.0450
115. Wang, A., Wang, J., Luan, B., Wang, S., & Huo, Z. (2025). Source trancing analysis of nitrogen in the upper reach of Xin'an River Basin based on SWAT model. *Ecological Indicators*, *175*, 113554. https://doi.org/10.1016/j.ecolind.2025.113554

116. Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., Veith, T. L., … T. L. Veith. (2007). Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. *Transactions of the ASABE*, *50*(3), 885–900. https://doi.org/10.13031/2013.23153
117. Arnold, J. G., Moriasi, D. N., Gassman, P. W., Abbaspour, K. C., White, M. J., Srinivasan, R., … Jha, M. K. (2012). SWAT: Model use, calibration, and validation. *Transactions of the ASABE*, *55*(4), 1491–1508.
118. Arnold, J. G., Srinivasan, R., Muttiah, R. S., & Williams, J. R. (1998). Large area hydrologic modeling and assessment part I: Model development. *Journal of the American Water Resources Association*, *34*(1), 73–89. https://doi.org/10.1111/j.1752-1688.1998.tb05961.x
119. Gassman, P. W., Reyes, M. R., Green, C. H., & Arnold, J. G. (2007). The soil and water assessment tool: historical development, applications, and future research directions. *Transactions of the ASABE*, *50*(4), 1211–1250. https://doi.org/10.13031/2013.23637
120. Chen, Y., Shuai, J., Zhang, Z., Shi, P., & Tao, F. (2014). Simulating the impact of watershed management for surface water quality protection: A case study on reducing inorganic nitrogen load at a watershed scale. *Ecological Engineering*, *62*, 61–70. https://doi.org/10.1016/j.ecoleng.2013.10.023
121. Malik, M. A., Dar, A. Q., & Jain, M. K. (2022). Modelling streamflow using the SWAT model and multi-site calibration utilizing SUFI-2 of SWAT-CUP model for high altitude catchments, NW Himalaya's. *Modeling Earth Systems and Environment*, *8*(1), 1203–1213. https://doi.org/10.1007/s40808-021-01145-0
122. Epelde, A. M., Cerro, I., Sánchez-Pérez, J. M., Sauvage, S., Srinivasan, R., & Antigüedad, I. (2015). Application of the SWAT model to assess the impact of changes in agricultural management practices on water quality. *Hydrological Sciences Journal*, 1–19. https://doi.org/10.1080/02626667.2014.967692
123. Shoemaker, L., Dai, T., Koenig, J., & Hantush, M. (2005). *TMDL model evaluation and research needs*. Washington, DC, USA: National Risk Management Research Laboratory, US Environmental Protection Agency.
124. Warn, A. E. (1987). SIMCAT-A catchment simulation model for planning investment for river quality. *Systems Analysis in Water Quality Management. Pergamon Press New York*, 211–218.
125. Warn, T. (2007). *SIMCAT 10.1-A guide and reference for users*. Environment Agency.
126. Crabtree, B., Kelly, S., Green, H., Squibbs, G., & Mitchell, G. (2009). Water

Framework Directive Catchment Planning: A Case Study Apportioning Loads and Assessing Environmental Benefits of Programme of Measures. In *Water Science and Technology* (Vol. 59, pp. 407–416). https://doi.org/10.22618/tp.ei.20162.120002

127. Warn, T. (2010). *SIMCAT 11.5: A Guide and Reference for Users*. Environment Agency.
128. Tsakiris, G., & Alexakis, D. (2012). Water quality models : An overview. *European Water*, *37*, 33–46.
129. Crabtree, B., Seward, A. J., & Thompson, L. (2006). A case study of regional catchment water quality modelling to identify pollution control requirements. *Water Science and Technology*, *53*(10), 47–54. https://doi.org/10.2166/wst.2006.296
130. Jacobs UK Limited. (2007). *Appendix 24 . 5 – SIMCAT Modelling Assessment of the Operational Phase of the AWPR affecting the River Dee and its Tributaries*. Aberdeen Western Peripheral Route Environmental Statement Appendices.
131. Hankin, B., Bielby, S., Pope, L., & Douglass, J. (2016). Catchment-scale sensitivity and uncertainty in water quality modelling. *Hydrological Processes*, *30*(22), 4004–4018. https://doi.org/10.1002/hyp.10976
132. DHI. (1993). *MIKE11, User Guide & Reference Manual*. Danish Hydraulics Institute.
133. DHI. (1996). *MIKE21: User Guide and Reference Manual*. Danish Hydraulic Institute.
134. DHI. (1996). *MIKE 3 Eutrophication Module, User guide and Reference manual, Release 2. 7*. Danish Hydraulic Institute.
135. DHI. (2017). *MIKE 11: A Modelling system for Rivers and Channels, Reference Manual*. Danish Hydraulic Institute.
136. DHI. (2022). *Mike+ River networking modeling, User guide*. Danish Hydraulic Institute.
137. Minh, H. V. T., Tri, V. P. D., Ut, V. N., Avtar, R., Kumar, P., Dang, T. T. T., … Downes, N. K. (2022). A Model-Based Approach for Improving Surface Water Quality Management in Aquaculture using MIKE 11: A case of the Long Xuyen Quadangle, Mekong Delta, Vietnam. *Water (Switzerland)*, *14*(3), 412. https://doi.org/10.3390/w14030412
138. Doan, Q. T., Chen, Y. C., & Mishra, P. K. (2013). Numerical modeling in water quality management for rivers - case study of the Day/Nhue River sub-basin, Vietnam. *International Journal of Earth Sciences and Engineering*, *6*(5), 1111–1119.
139. Kumar, K. S., Galkate, R. V., & Tiwari, H. L. (2021). River basin modelling for Shipra River using MIKE BASIN. *ISH Journal of Hydraulic Engineering*, *27*(2), 188–199.

https://doi.org/10.1080/09715010.2018.1534219

140. Dehkordi, D. K., & Kashkuli, H. A. (2015). Water quality improvement of Hendijan River by use of Mike11 model. *Advances in Environmental Biology*, *9*(3), 319–327.

141. Kamel, A. (2008). Application of a hydrodynamic MIKE 11 model for the Euphrates River in Iraq. *Slovak Journal of Civil Engineering*, *2*(1), 1–7.

142. Olowe, K. O., & Kumarasamy, M. vellaisamy. (2018). Assessment of some existing water quality models. *Nature Environment and Pollution Technology*, *17*(3).

143. Edinger, J. E., & Buchak, E. M. (1975). A hydrodynamic, two-dimensional reservoir model-—The computational basis: Cincinnati, Ohio. *US Army Corps of Engineers*, *94*.

144. EHL. (1986). *Environmental and Hydraulic Laboratories, CE-QUAL-W2 User's Manual, Instruction Rpt. E-86-1*. US Army Engineer Waterways Experiment Station, Vicksburg, MS.

145. Cole, T. M., & Wells, S. A. (2018). *CE-QUAL-W2: A Two-Dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model, Version 4.1*. Department of Civil and Environmental Engineering, Portland State University, Portland.

146. Wells, S. A. (2021). *CE-QUAL-W2: A Two-Dimensional, Later-ally Averaged, Hydrodynamic and Water Quality Model, Version 4.5, User Manual: Part 1 Introduction, Model Download Package, How to Run the Model*. Department of Civil and Environmental Engineering Portland State University Portland.

147. Wells, S. A. (2021). *CE-QUAL-W2: A Two-Dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model, Version 4.5, User Manual: Part 5 – Model Utilities*. Department of Civil and Environmental Engineering Portland State University Portland.

148. Al-Murib, M. D., & Wells, S. A. (2019). Hydrodynamic and Total Dissolved Solids Model of the Tigris River Using CE-QUAL-W2. *Environmental Processes*, *6*(3), 619–641. https://doi.org/10.1007/s40710-019-00381-y

149. Deus, R., Brito, D., Mateus, M., Kenov, I., Fornaro, A., Neves, R., & Alves, C. N. (2013). Impact evaluation of a pisciculture in the Tucuruí reservoir (Pará, Brazil) using a two-dimensional water quality model. *Journal of Hydrology*, *487*, 1–12. https://doi.org/10.1016/j.jhydrol.2013.01.022

150. Park, Y., Cho, K. H., Kang, J. H., Lee, S. W., & Kim, J. H. (2014). Developing a flow control strategy to reduce nutrient load in a reclaimed multi-reservoir system using a 2D hydrodynamic and water quality model. *Science of the Total Environment*, *466–467*. https://doi.org/10.1016/j.scitotenv.2013.07.041

151. Patel, H. B., & Jariwala, N. D. (2024). Determining assimilative capacity of River Tapi using QUAL2Kw Model. *Water Conservation and Management*, *8*(2), 217–226. https://doi.org/10.26480/wcm.02.2024.217.226

152. Sarda, P., & Sadgir, P. (2015). Water Quality Modeling and Management of Surface Water using Soft Tool. *International Journal of Science, Engineering and Technology Research*, *4*(9).

153. Gupta, R. C., Gupta, A. K., & Shrivastava, R. K. (2013). Water quality modelling of a stretch of River Kshipra (India). *Nature Environment and Pollution Technology*, *12*(3), 511–516.

154. Lakshmi, E., & Madhu, G. (2020). Evaluation and modelling of dissolved oxygen and reaeration rate in River Periyar, South India. *Indian Journal of Scientific Research*, *10*(2). https://doi.org/10.32606/ijsr.v10.i2.00001

155. Sharma, J. R., & Paithankar, Y. (2014). *Sabarmati basin, Version 2.0, Central Water Commission (CWC), Ministry of water resources, Govt. of India*.

156. CWC. (2020). *Water year book 2018-2019, Mahi, Sabarmati and other west flowing rivers*. Central Water Commission (CWC), Mahi & Tapi Basin, Hydrological Observation, Gandhinagar.

157. NWRWS. (2025). Sabarmati River. *Narmada, Water Resources, Water Supply and Kalpsar Department (Water Resources Division)*. Retrieved November 30, 2025, from https://guj-nwrws.gujarat.gov.in/showpage.aspx?contentid=1564&lang=english

158. Patel, A., & Chitnis, K. (2022). Application of fuzzy logic in river water quality modelling for analysis of industrialization and climate change impact on Sabarmati river. *Water Supply*, *22*(1), 238–250. https://doi.org/10.2166/ws.2021.275

159. Parikh, N. (2023, February 3). Sabarmati second most polluted river in India. *The Times of India*. Retrieved from https://timesofindia.indiatimes.com/city/ahmedabad/sabarmati-second-most-polluted-river-in-india/articleshow/97564660.cms

160. GEMI. (2021). *Comprehensive Report of Sabarmati, Tapi, Narmada, Mahisagar, Damanganga and Hiran River (Monitoring Period: 2012-19), report no. GEMI/RCM/224(8)(5)/2021-22/13*. Retrieved from https://www.furuno.com/en/systems/coastal-monitoring/

161. GEMI. (2016). *A Comprehensive Report on River and Coastal Monitoring Gujarat, report no. GEMI/CRCM/2016/24*.

162. Kothari, C. R. ., & Garg, G. (2019). *Research methodology : Methods & techniques*

(Fourth.). New Age International Publishers.

163. Khaledian, Y., Ebrahimi, S., Natesan, U., Basatnia, N., Nejad, B. B., Bagmohammadi, H., & Zeraatpisheh, M. (2018). Assessment of Water Quality Using Multivariate Statistical Analysis in the Gharaso River, Northern Iran. In *Urban Ecology, Water Quality and Climate Change. Water Science and Technology Library, vol 84* (pp. 227–253). Springer. https://doi.org/10.1007/978-3-319-74494-0_18
164. Yang, W., Zhao, Y., Wang, D., Wu, H., Lin, A., & He, L. (2020). Using principal components analysis and IDW interpolation to determine spatial and temporal changes of surfacewater quality of Xin'Anjiang River in Huangshan, China. *International Journal of Environmental Research and Public Health*, *17*(8), 2942. https://doi.org/10.3390/ijerph17082942
165. Hamed, M. A. R. (2019). Application of surface water quality classification models using principal components analysis and cluster analysis. *Journal of Geoscience and Environment Protection*, *07*, 26–41. https://doi.org/10.4236/gep.2019.76003
166. Tripathi, M., & Singal, S. K. (2019). Use of principal component analysis for parameter selection for development of a novel water quality index: A case study of river Ganga, India. *Ecological Indicators*, *96*, 430–436. https://doi.org/10.1016/j.ecolind.2018.09.025
167. GEMI. (2025). Gujarat Environment Management Institute. Retrieved November 30, 2025, from https://gemi.gujarat.gov.in/
168. Patel, P., Bablani, S., & Patel, A. (2020). Impact assessment of urbanization and industrialization using water quality index on Sabaramati River, Ahmedabad. In *Proceedings of the 4th International Conference: Innovative Advancement in Engineering & Technology (IAET)*. https://doi.org/10.2139/ssrn.3553800
169. Singh, K. P., Malik, A., Mohan, D., & Sinha, S. (2004). Multivariate statistical techniques for the evaluation of spatial and temporal variations in water quality of Gomti River (India) - A case study. *Water Research*, *38*(18), 3980–3992. https://doi.org/10.1016/j.watres.2004.06.011
170. Bhat, S. A., Meraj, G., Yaseen, S., & Pandit, A. K. (2014). Statistical Assessment of Water Quality Parameters for Pollution Source Identification in Sukhnag Stream: An Inflow Stream of Lake Wular (Ramsar Site), Kashmir Himalaya. *Journal of Ecosystems*, *2014*. https://doi.org/10.1155/2014/898054
171. Inc., M., George, T., Franklin, B., & Stensel David H. (2017). *Wastewater engineering: Treatment and reuse* (4th editio.). McGraw-Hill Education.

172. Lestari, H., Haribowo, R., & Yuliani, E. (2019). Determination of Pollution Load Capacity Using QUAL2Kw Program on The Musi River Palembang. *Civil and Environmental Science*, *002*(02), 105–116. https://doi.org/10.21776/ub.civense.2019.00202.4
173. Chapra, S. C. (2008). *Surface water-quality modeling*. Waveland press.
174. Kannel, P. R., Lee, S., Lee, Y. S., Kanel, S. R., Pelletier, G. J., & Kim, H. (2007). Application of automated QUAL2Kw for water quality modeling and management in the Bagmati River, Nepal. *Ecological Modelling*, *202*(3–4), 503–517. https://doi.org/10.1016/j.ecolmodel.2006.12.033
175. Hobson, A. J. (2013). *Using QUAL2Kw as a Decision Support Tool : Considerations for Data Collection , Calibration , and Numeric Nutrient Criteria by*. *Utah state university*. Utah state university,Logan, Utah. Retrieved from http://digitalcommons.usu.edu/etd
176. Mulla, N. H., Krishna, B. M., Kumar, B. M., Arunkumar, K., & Lahori, M. T. B. (2024). River Water Quality Modeling Using Automated QUAL2Kw. In *Hydraulic and Civil Engineering Technology IX* (pp. 1486–1498). IOS Press. https://doi.org/10.3233/ATDE241149
177. Kori, B. B., Shashidhar, T., & Mise, S. (2013). Application of automated QUAL2Kw for water quality modeling in the River Karanja, India, *2*(2), 193–203.
178. IS2296. (1992). *Indian standard Surface Water Quality, Bureau of Indian Standards, New Delhi*.
179. CPCB. (2019). *Indicative guidelines for restoration of water bodies*.
180. Waturu, M., Sitoki, L., Lalah, J., Mbao, E. O., & Kahuthu, W. D. (2022). Application of QUAL2kw and Forecasting models for assessment of pollutants in upper Athi River catchment in Kenya. *African Journal of Pure and Applied Sciences*, *3*(2), 221–236. https://doi.org/10.33886/ajpas.v3i2.296
181. GPCB. (2023). *Action taken report in O.A. No. 798 of 2023 [PB]*. Retrieved from https://www.greentribunal.gov.in/sites/default/files/news_updates/Action Taken Report by GPCB in OA No. 798 of 2023 (In re News article titled as Ahmedabad Municipal Corporation’s Dirty Secret on River Pollution).pdf
182. EPA. (1986). Schedule VI - General standards for discharge of environmental pollutants Part A : Effluents. In *The Environment (Protection) rules*. Ministry of Environment and Forest (MoEF).

APPENDICES

APPENDIX A: Sample water quality data

Location	Location code	Date of Sampling	Sample Temp. 'C	pH	Color (Hazen)	TS mg/L	TDS mg/L	TSS mg/L	Turbidity (NTU)	NH_3N mg/L	Chloride as Cl- mg/L	Total Alkalinity mg/L	Total Hardness mg/L	COD mg/L	BOD mg/L	DO mg/L	Conductivity (µS/cm)	Sulphate mg/L	Nitrate mg/L
Dharoi Dam	S-5	26-May-2014	32	8.57	5	164	150	2	1	1	60	7	90	12	6	7	7531	-	-
		1-Aug-2014	29	8.63	10	152	118	4	4.7	0.5	45	15	100	3	1	4	668	-	-
		8-Oct-2014	27	8.92	10	174	158	4	7.7	0.5	21	13	76.05	1	1	7	321	-	-
		19-Dec-2014	19	8.28	15	162	116	10	27.8	0.58	29	58	128.7	24	5	9	348	-	-
		25-Mar-2015	24	8.18	10	246	220	12	1.4	1.36	32	123	130	13	1.65	5	373	7.3	0.82
		25-Jun-2015	26	8.34	5	286	232	28	5	0.665	34	138	110	19	0.27	1	329	9.53	0.16
		23-Sep-2015	27	8.39	5	212	192	6	3.7	0.62	18.38	115	130	12	1.49	6	292	3.01	0.27
		17-Dec-2015	21.2	7.84	10	210	192	10	12	0.64	55.43	145	150	18	0.50	6	336	27.77	3.58
Valasana	S-6	26-May-2014	30	7.59	5	322	302	4	1.2	0.5	100	40	170	2	2	7	1389	-	-
		1-Aug-2014	30	7.61	15	206	204	6	16.2	0.5	45	23	90	7	4	6	595	-	-
		8-Oct-2014	28	7.8	10	442	412	8	3.2	0.5	107	33	217.74	0.1	2	5	830	-	-
		1-Jan-2015	17	7.75	5	370	306	1	2	2	76	216	290	1	2.04	6	702	-	-
		25-Mar-2015	25	7.72	15	442	418	4	2.2	0.99	80	226	230	18	3	4	738	15.2	0.95
		25-Jun-2015	25	7.49	10	362	108	240	520	0.894	19.26	326	70	48	0.43	1	210	0.2	0.32
		23-Sep-2015	28	8.12	15	434	388	16	7	0.68	77	200	220	19	4	8	670	50.34	1.53
		17-Dec-2015	23.2	7.77	20	420	404	10	5.7	0.73	100	246	260	13	3	6	710	29.08	15.14
Fudeda	S-7	26-May-2014	31	7.55	5	370	336	2	1	0.5	120	43	200	2	0.1	5	1632	-	-
		1-Aug-2014	31	7.84	5	242	228	2	7.4	0.5	60	23	150	10	3	6	846	-	-
		8-Oct-2014	29	7.89	10	452	424	12	10.1	0.5	111	31	217.99	1	1	5	858	-	-
		1-Jan-2015	17	8.02	10	398	334	1	2.9	0.5	92	222	180	1	2.04	7	756	-	-

Location	Location code	Date of Sampling	Sample Temp. 'C	pH	Color (Hazen)	TS mg/L	TDS mg/L	TSS mg/L	Turbidity (NTU)	NH_3N mg/L	Chloride as Cl- mg/L	Total Alkalinity mg/L	Total Hardness mg/L	COD mg/L	BOD mg/L	DO mg/L	Conductivity (µS/cm)	Sulphate mg/L	Nitrate mg/L
		25-Mar-2015	25	7.72	10	446	436	6	3	2	92	226	230	14	1.27	4	781	12.86	0.47
		25-Jun-2015	25	7.64	10	550	484	40	27	0.894	120	258	220	38	0.31	1	807	13.58	0.21
		23-Sep-2015	29	8.12	10	392	362	14	5.6	0.656	77	211	210	15	4	8	659	9.17	1.47
		17-Dec-2015	23.7	7.95	10	446	432	8	7.5	0.76	103	242	260	20	1.35	6	756	28.87	14.47
Sapteshwar Mahadev	S-8	26-May-2014	31	7.71	5	406	390	2	1.3	1	140	45	210	13	1	6	1810	-	-
		1-Aug-2014	31	7.72	5	314	300	6	6.2	0.5	86	27	110	11	3	6	1013	-	-
		8-Oct-2014	28	7.86	10	516	470	4	4.7	0.5	113	17	222.07	1	2	6	946	-	-
		1-Jan-2015	17	7.98	5	392	330	1	1.4	0.59	98	11	260	1	3	6	790	-	-
		25-Mar-2015	25	7.67	25	478	458	8	2.3	1	108	233	260	8	1.36	6	854	9.78	0.65
		25-Jun-2015	26	7.69	10	548	500	20	13	0.715	114	333	240	38	0.36	1	833	1.1	0.14
		23-Sep-2015	28	7.45	5	966	938	8	1	0.68	241	414	570	14	1.98	6	1629	22.62	6.2
		17-Dec-2015	23.5	8.16	20	440	412	4	3	0.77	104	241	250	11	0.61	8	741	28.23	14.21
Narmada	S-11	16-Jun-2014	29	8.34	5	262	254	4	1.2	1	20	14	110	4	0.6	6	-	-	-
		11-Aug-2014	26	8.23	15	200	192	1	4.2	0.5	8	17	138.37	6	2	6	317	-	-
		29-Oct-2014	28	8.32	5	150	140	8	2.9	0.5	7	17	107.83	10	1	7	270	-	-
		1-Jan-2015	19	8.47	10	110	84	2	3.2	0.7	14.32	115	120	1.58	0.30	8	266	-	-
		15-May-2015	27	8.16	5	158	132	12	2	0.71	7.15	120	110	30	0.77	5	280	9.76	0.05
		6-Jul-2015	30	8.41	5	186	170	12	6	0.648	5.84	146	110	9	1.53	7	252	1.22	0.13
		2-Oct-2015	27	8.59	5	218	198	6	3.4	0.61	8.37	112	100	14	3	7	251	39.03	6.81
		31-Dec-2015	23.8	8.57	5	242	218	10	5.6	0.63	12.05	138	140	21	2.52	9	332	5.67	13.9
Subhas Bridge	S-12	2-May-2014	35	7.38	25	442	420	14	53	2	60	190	130	59	3	3	831	-	-
		24-Jul-2014	26	8.01	20	468	408	40	45.9	0.5	50	39	110	47	20	4	640	-	-
		15-Oct-2014	25	7.88	10	188	168	4	3.9	0.5	14	14	79.56	8	1	6	319	-	-
		7-Jan-2015	19	7.59	5	274	242	2	5	2	23	141	118.8	23	5	5	391	-	-
		14-May-2015	24	7.63	50	426	335	55	34	1	68	238	120	90	47	1	730	24.77	0.05

Location	Location code	Date of Sampling	Sample Temp. 'C	pH	Color (Hazen)	TS mg/L	TDS mg/L	TSS mg/L	Turbidity (NTU)	NH_3N mg/L	Chloride as Cl- mg/L	Total Alkalinity mg/L	Total Hardness mg/L	COD mg/L	BOD mg/L	DO mg/L	Conductivity (µS/cm)	Sulphate mg/L	Nitrate mg/L
		1-Jul-2015	27	7.98	0	252	226	10	7	0.62	18.16	155	120	22	12	1	335	10.09	0.28
		2-Oct-2015	27	8.48	5	220	210	4	5.3	0.64	9.68	124	120	18	5	8	281	37.12	0.93
		28-Dec-2015	26	7.84	30	210	184	10	10	0.8	14.27	134	150	24	4	6	318	33.04	7.89
Rishi Dadhichi Bridge	S-13	2-May-2014	35	7.5	20	552	498	48	63	0.5	60	180	100	54	3	3	970	-	-
		24-Jul-2014	25	7.94	20	466	384	46	47.6	0.5	40	10	120	53	22	3	699	-	-
		15-Oct-2014	25	7.93	10	188	174	8	5.3	0.5	14	20	79.82	5	2	5	333	-	-
		7-Jan-2015									-								
		14-May-2015	25	7.68	50	442	410	22	33	5	71	270	140	70	39	1	757	24.04	0.05
		1-Jul-2015	27	8.3	0	218	202	6	6	0.62	11.84	148	110	15	4	6	295	8.3	0.19
		2-Oct-2015	28	8.14	5	218	190	14	9.3	0.765	14.45	129	120	20	6	7	319	40.45	0.16
		28-Dec-2015	24.8	7.96	25	210	184	10	9.2	2	12.52	132	160	23	6	9	307	30.12	8.01
Vasna Barrage	S-18	2-Jun-2014	31	8.45	10	442	410	26	6.9	0.5	80	38	130	38	25	3	-	-	-
		11-Aug-2014	27	7.44	5	304	238	68	3.3	0.5	29	20	126.76	11	3	2	471	-	-
		29-Oct-2014	27	8.44	5	180	160	8	9.2	0.5	21	19	117.63	12	5	8	352	-	-
		17-Jan-2015	20	8.1	5	250	240	1	1.1	1	17.28	145	118.8	14	6	3	330	-	-
		15-May-2015	29	9.04	5	338	286	20	32	0.78	46	178	110	40	22	5	503	12.06	0.05
		6-Jul-2015	30	7.86	10	248	224	10	8	0.65	22	170	120	39	40	5	354	3.83	0.17
		7-Oct-2015	27	8.22	5	236	208	10	7	0.69	18.32	126	120	10	1.38	7	313	31.08	5.7
		31-Dec-2015	26.9	8.52	10	248	224	14	10.1	0.77	20	147	140	41	4	9	367	4.44	11.5
Narol-Sarkhej	S-19	16-Jun-2014	30	7.59	50	1564	1464	90	42.5	7	430	118	220	331	122	0.5	-	-	-
		11-Aug-2014	28	6.9	40	1496	1050	334	179	6	281	57	220.45	648	419	0.5	2451	-	-
		29-Oct-2014	28	7.2	25	926	850	64	22.9	2	207	51	235.27	151	84	0.5	1560	-	-
		17-Jan-2015	19	8.33	30	1248	1028	156	45	18	176	351	168.3	272	125	BDL	1291	-	-
		15-May-2015	37	8.27	15	4238	3768	374	135	74	1295	1290	200	980	579	0.5	6530	321.97	0.05
		6-Jul-2015	31	8.09	250	4810	4196	482	154	55	1394	1050	210	1576	671	0.5	6490	433.89	0.77

Location	Location code	Date of Sampling	Sample Temp. 'C	pH	Color (Hazen)	TS mg/L	TDS mg/L	TSS mg/L	Turbidity (NTU)	NH_3N mg/L	Chloride as Cl- mg/L	Total Alkalinity mg/L	Total Hardness mg/L	COD mg/L	BOD mg/L	DO mg/L	Conductivity (µS/cm)	Sulphate mg/L	Nitrate mg/L
		7-Oct-2015	28	8.44	100	12690	12348	244	148	528	5749	1866	550	2301	1211	0.5	20900	1470.37	65.3
		31-Dec-2015	26.9	7.22	500	1348	1170	144	109	26	304	498	210	528	271	0.5	2100	133.38	37.75
Kamod Bridge	S-20	16-Jun-2014	31	7.4	40	1962	1836	122	41.2	6	670	92	300	296	58	0.5	-	-	-
		11-Aug-2014	30	7.21	30	1348	1170	106	80	3	338	65	227.11	181	53	0.5	2688	-	-
		29-Oct-2014	26	7.33	500	1912	1816	62	33.8	3	493	67	284.28	210	167	0.5	3235	-	-
		17-Jan-2015	19	8.33	30	694	552	132	20	6	123	211	148.5	142	34	BDL	847	-	-
		15-May-2015	29	7.5	5	1798	1628	112	74	39	539	717	260	355	243	0.5	3120	194.06	0.05
		6-Jul-2015	32	7.48	150	1510	1352	96	62	26	403	578	240	167	101	0.5	2380	110.12	0.4
		7-Oct-2015	29	7.43	50	1012	948	38	33	16	270	394	270	156	80	0.5	1701	237.02	31
		31-Dec-2015	28.1	7.25	500	1724	1600	86	75	28	504	591	290	383	195	0.5	2870	211.85	42.3
Saroda Bridge	S-21	16-Jun-2014	31	7.87	50	1588	1484	94	57	5	490	113	250	243	50	0.5	-	-	-
		11-Aug-2014	30	7.44	30	1452	1286	46	69	3	374	66	229.03	182	69	0.5	2879	-	-
		29-Oct-2014	26	7.46	60	660	624	32	21.1	1	149	43	186.25	58	31	1	1190	-	-
		17-Jan-2015	23	7.29	30	960	736	220	54	12	224	271	168.3	246	94	BDL	1166	-	-
		15-May-2015	27	7.57	5	1476	1342	116	64	39	427	673	250	298	137	0.5	2610	136.21	0.05
		6-Jul-2015	32	7.5	100	1438	1324	60	61	27	418	589	250	197	96	0.5	2350	93.53	0.46
		7-Oct-2015	29	7.36	50	880	830	32	26	13	210	325	190	166	87	0.5	1380	155.67	24.5
		31-Dec-2015	30.5	7.53	500	1430	1368	34	52	29	418	591	280	269	138	0.5	2570	150.95	35.15

[Source: Gujarat Environment Management Institute (GEMI), Gandhiangar]

APPENDIX B: Sample meteorological data

INDEX	YEAR	MN	HR	MDBT	MDPT	MWSP
42647	2012	1	0	13.5	7.7	4.1
42647	2012	1	12	14.5	7.6	4.5
42647	2012	1	24	22.6	9.4	7.2
42647	2012	1	36	25.7	8.6	7.2
42647	2012	1	48	24.8	8.7	6.1
42647	2012	1	60	18.8	9.7	3
42647	2012	1	72	16.6	8.8	4.3
42647	2012	1	84	14.4	8.2	3.5
42647	2012	2	0	15.3	7.5	3.7
42647	2012	2	12	16.3	7.6	5
42647	2012	2	24	25.1	8.4	8.4
42647	2012	2	36	28.9	8.2	8.1
42647	2012	2	48	28.4	8.3	7.7
42647	2012	2	60	21.7	9.7	4.8
42647	2012	2	72	18.8	8.7	4.7
42647	2012	2	84	16.4	7.8	3.8
42647	2012	3	0	20.1	11.1	5.2
42647	2012	3	12	22.3	12.5	5.2
42647	2012	3	24	30.3	12	7.9
42647	2012	3	36	34.1	10.9	7.5
42647	2012	3	48	34.1	10.8	7.2
42647	2012	3	60	26.2	12.3	2.5
42647	2012	3	72	23.5	11.3	3.4
42647	2012	3	84	21.5	10.4	3.8
42647	2012	4	0	26.2	18.6	5.6
42647	2012	4	12	28.3	20.1	7
42647	2012	4	24	33.8	19.4	7.3
42647	2012	4	36	37.9	18.3	8.2
42647	2012	4	48	38.3	17.5	7.6
42647	2012	4	60	32.3	17.8	4.4
42647	2012	4	72	29.8	17.9	4.7
42647	2012	4	84	28	17.5	4.5
42647	2012	5	0	28	23.1	6.9
42647	2012	5	12	30.1	23.7	6.7
42647	2012	5	24	35	22.6	7
42647	2012	5	36	39.6	20.3	7.5
42647	2012	5	48	40.5	18.6	8.5
42647	2012	5	60	34.7	21.5	6.9
42647	2012	5	72	31.8	22.5	6.7
42647	2012	5	84	30.1	22	6.6

INDEX	YEAR	MN	HR	MDBT	MDPT	MWSP
42647	2012	6	0	28.9	24.2	7.8
42647	2012	6	12	30.7	24.9	8.1
42647	2012	6	24	34.5	23.9	8.7
42647	2012	6	36	37.8	22.9	8
42647	2012	6	48	37.7	22.5	9
42647	2012	6	60	33.1	24.4	10.9
42647	2012	6	72	31	24.4	9.4
42647	2012	6	84	29.7	24	7.8
42647	2012	7	0	28	24.9	7.1
42647	2012	7	12	28.9	25.4	6.7
42647	2012	7	24	31.4	25.6	7.7
42647	2012	7	36	33.4	25.6	6.9
42647	2012	7	48	33.7	25.1	7.6
42647	2012	7	60	31	25.5	7.4
42647	2012	7	72	29.9	25.2	8.2
42647	2012	7	84	28.8	24.6	8.3
42647	2012	8	0	26.6	24.2	6.3
42647	2012	8	12	27.4	24.6	6.3
42647	2012	8	24	30	24.9	7.1
42647	2012	8	36	31.1	24.9	6.1
42647	2012	8	48	31	25.2	6
42647	2012	8	60	28.9	25	5.5
42647	2012	8	72	28	25	6
42647	2012	8	84	27.2	24.3	6.4
42647	2012	9	0	25.8	24.5	3.8
42647	2012	9	12	27.2	24.8	5.3
42647	2012	9	24	30.1	25.1	5.5
42647	2012	9	36	31.7	25	5.7
42647	2012	9	48	30.9	25.1	5.7
42647	2012	9	60	27.8	25.2	4.4
42647	2012	9	72	26.9	24.8	4.8
42647	2012	9	84	26.2	24.5	4.6
42647	2012	10	0	22.7	18.1	1.6
42647	2012	10	12	25.8	18	3.3
42647	2012	10	24	32.7	18.6	5.1
42647	2012	10	36	35	17.5	4.8
42647	2012	10	48	33.3	18.7	4.4
42647	2012	10	60	26.5	19.9	0.6
42647	2012	10	72	24.4	19.8	1.2
42647	2012	10	84	23.6	18.9	1.6
42647	2012	11	0	17.1	12.4	1.3
42647	2012	11	12	20.5	12.4	4.4

INDEX	YEAR	MN	HR	MDBT	MDPT	MWSP
42647	2012	11	24	28.8	13.2	6.8
42647	2012	11	36	31.4	12.3	5.8
42647	2012	11	48	29.2	14.4	3.2
42647	2012	11	60	21.4	14.5	2.5
42647	2012	11	72	19	13.6	1.7
42647	2012	11	84	18	12.9	1.4
42647	2012	12	0	16.7	12.1	5.4
42647	2012	12	12	18.1	12.1	6.5
42647	2012	12	24	26	14.1	8.3
42647	2012	12	36	29.1	13.9	7.8
42647	2012	12	48	27.6	14.4	5.2
42647	2012	12	60	20.9	14.3	3.3
42647	2012	12	72	18.9	13.3	4.1
42647	2012	12	84	17.7	12.6	3.9

INDEX

MN Month

HR Hour Code

Code	UTC	IST	Code	UTC	IST
00	**00**	**0530**	**48**	**12**	**1730**
12	**03**	**0830**	**60**	**15**	**2030**
24	**06**	**1130**	**72**	**18**	**2330**
36	**09**	**1430**	**84**	**21**	**0230**

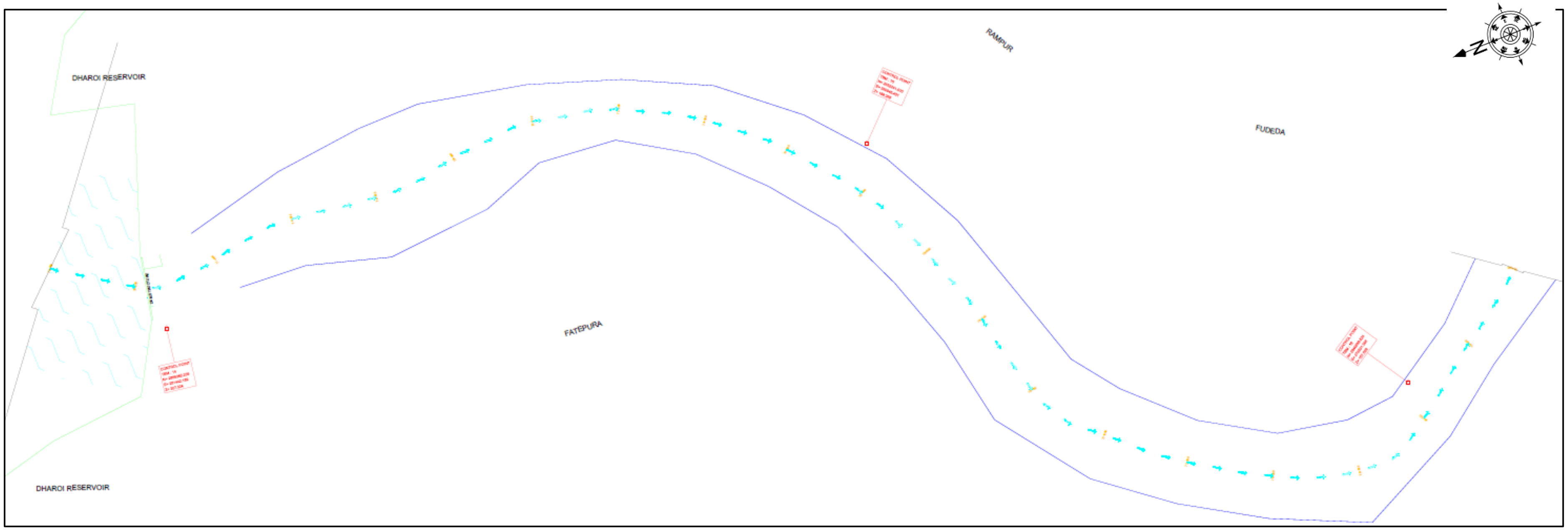
MDBT Mean Dry Bulb Temperature in °C

MDPT Mean Wet Bulb Temperature in °C

MWSP Mean Wind Speed in kmph

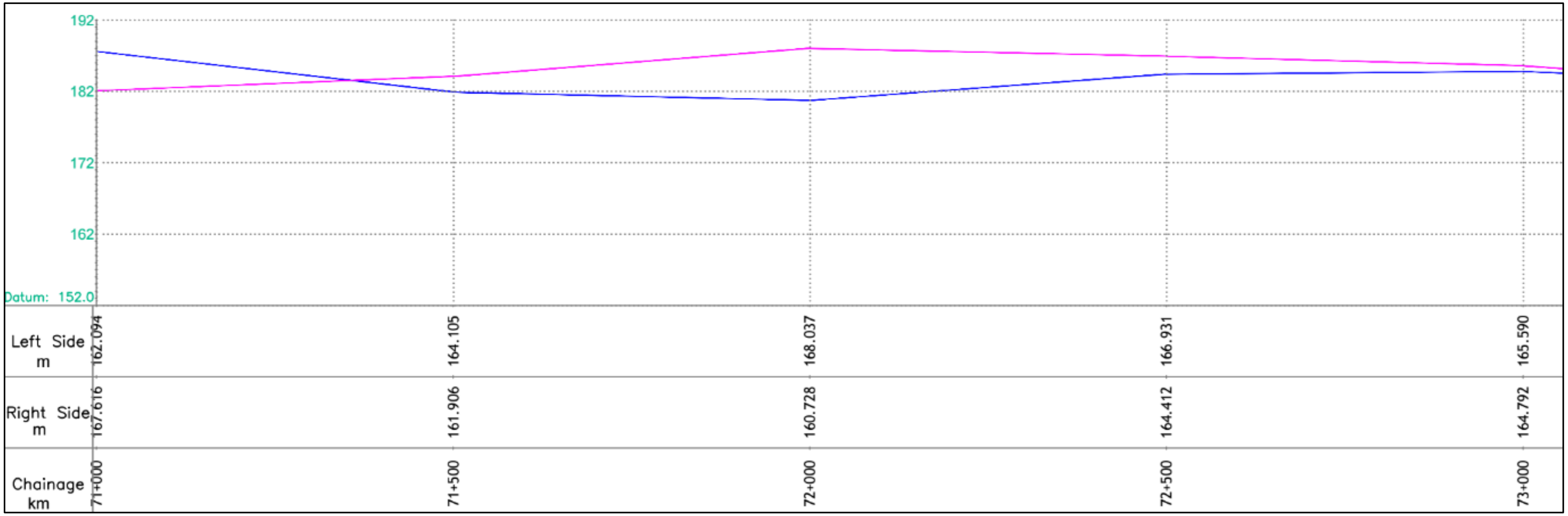
[Source: Indian Meteorological Department (IMD)]

APPENDIX C: Sample data of river alignment and profile

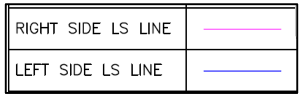


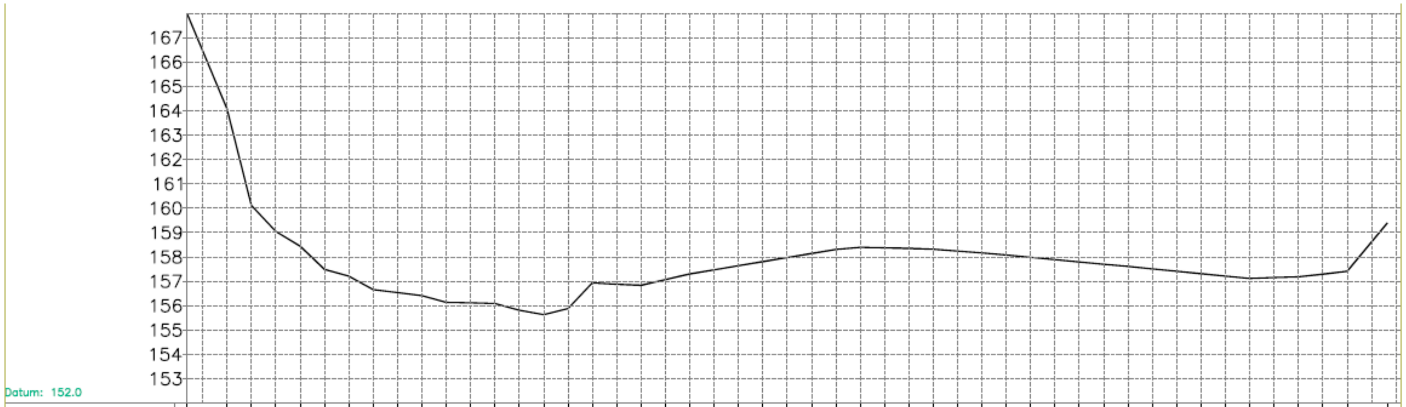
Route alignment

RIVER BANK	
TBM STONE	
WATER FLOW	
ALIGNMENT CHAINAGE	00+000



L- section of the river (Ch. 71 km to 73 km)





Offset	OGL
-246.377	167.989
-230.000	164.084
-220.000	160.120
-210.000	159.048
-200.000	158.444
-190.000	157.490
-180.000	157.210
-170.000	156.658
-160.000	156.538
-150.000	156.409
-140.000	156.138
-130.000	156.119
-120.000	156.093
-110.000	155.811
-100.000	155.633
-90.000	155.882
-80.000	156.937
-70.000	156.884
-60.000	156.837
-50.000	157.074
-40.000	157.304
-30.000	157.473
-20.000	157.641
-10.000	157.809
-0.042	157.977
10.000	158.142
20.000	158.305
30.000	158.392
40.000	158.372
50.000	158.352
60.000	158.318
70.000	158.246
80.000	158.164
90.000	158.083
100.000	157.989
110.000	157.894
120.000	157.798
130.000	157.703
140.000	157.612
150.000	157.508
160.000	157.411
170.000	157.314
180.000	157.216
190.000	157.119
200.000	157.154
210.000	157.188
220.000	157.295
230.000	157.413
246.408	159.394

Cross section of Sabarmati River Chainage 74 km + 890m

[Source: Gujarat Environment Management Institute (GEMI), Gandhinagar]

APPENDIX D: Sample data of Dharoi Dam discharge into the river

Month	**Bypass outlet (B.P.O.) Cumecs**		**B.P.O. (mcft/day)**	**Spillway**	**Spillway (mcft/day)**	**Total (mcft/day)**	**Total (m3/s)**
	Total (mcft)	Avg. (mcft/day)	**Calculated**	Monthly (mcft)	**Calculated**		
			A		**B**	**A+B**	
Monsoon (June - August)							
2012-2013							
Jun-12	129.6	-	4.320	0	0.000	4.320	**1.416**
Jul-12	55.8	-	1.800	0	0.000	1.800	**0.590**
Jun-13	181.8	5.15	6.060	23.5	0.783	6.843	**2.243**
Jul-13	21.69	-	0.700	0	0.000	0.700	**0.229**
2014-2018							
Jun-14	99.36	-	3.312	0	0.000	3.312	**1.085**
Jul-14	0.45	0.01	0.015	15.97	0.515	0.530	**0.174**
Jun-15	119.66	3.39	3.989	0	0.000	3.989	**1.307**
Jul-15	61.58	1.74	1.986	5573.71	179.797	181.784	**59.570**
Aug-15	86.04	2.44	2.775	8722.14	281.359	284.135	**93.111**
Jun-16	151.14	4.28	5.038	0	0.000	5.038	**1.651**
Jul-16	13.5	0.38	0.435	0	0.000	0.435	**0.143**
Aug-16	18.9	0.53	0.610	10101.39	325.851	326.461	**106.981**
Jun-17	248.6	7.07	8.287	0	0.000	8.287	**2.716**
Jul-17	59.8	1.69	1.929	0	0.000	1.929	**0.632**
Aug-17	0	0	0.000	9381	302.613	302.613	**99.166**
2019-2021							
Aug-20	16.38	0.46	0.528	0	0.000	0.528	**0.173**
Jun-21	-	-	-	8048.6	268.287	268.287	**87.918**

[Source: Dharoi Dam Division, Mehsana]

APPENDIX E Sample data of Water level referenced from Derol water gauge station of CWC

Date	Time	Gauge m	Water Level m	Discharge m^3/s	Observed/ Computed	Top Width m	Wetted Perimeter m	Radius m	Velocity m/s	Manning	Area m^2	Slope	Max Velocity m/s	Mode of Crossing	Method of velocity observation
Monsoon (June–August) 2012-2013															
12-07-2012	8:00:00 AM	0.50	87.50	7.70	C	-	-	-	-	-	-	-	-	-	-
13-07-2012	8:00:00 AM	0.65	87.65	11.91	D	252.57	252.70	1.13	0.04	0.279	285.45	0.000117	0.47	Wading	Current Meter
14-07-2012	8:30:00 AM	0.50	87.50	5.60	O	50.69	50.70	0.20	0.55	0.007	10.27	0.000117	0.53	Wading	Current Meter
15-07-2012	8:00:00 AM	0.45	87.45	6.50	C	-	-	-	-	-	-	-	-	-	-
16-07-2012	8:00:00 AM	0.40	87.40	5.40	C	-	-	-	-	-	-	-	-	-	-
17-07-2012	8:00:00 AM	0.38	87.38	5.00	C	-	-	-	-	-	-	-	-	-	-
18-07-2012	8:00:00 AM	0.37	87.37	4.80	C	-	-	-	-	-	-	-	-	-	-
19-07-2012	8:00:00 AM	0.33	87.33	4.04	C	-	-	-	-	-	-	-	-	-	-
20-07-2012	8:00:00 AM	0.30	87.30	3.50	C	-	-	-	-	-	-	-	-	-	-
21-07-2012	8:00:00 AM	0.29	87.29	3.35	C	-	-	-	-	-	-	-	-	-	-
22-07-2012	8:00:00 AM	0.28	87.28	3.19	C	-	-	-	-	-	-	-	-	-	-
23-07-2012	8:00:00 AM	0.28	87.28	3.19	C	-	-	-	-	-	-	-	-	-	-
24-07-2012	8:00:00 AM	0.27	87.27	3.03	C	-	-	-	-	-	-	-	-	-	-
25-07-2012	8:00:00 AM	0.26	87.26	2.88	C	-	-	-	-	-	-	-	-	-	-
26-07-2012	8:00:00 AM	0.26	87.26	2.88	C	-	-	-	-	-	-	-	-	-	-
27-07-2012	8:00:00 AM	0.26	87.26	2.88	C	-	-	-	-	-	-	-	-	-	-
28-07-2012	8:00:00 AM	0.25	87.25	2.73	C	-	-	-	-	-	-	-	-	-	-
29-07-2012	8:00:00 AM	0.24	87.24	2.58	C	-	-	-	-	-	-	-	-	-	-
30-07-2012	8:00:00 AM	0.23	87.23	2.30	C	-	-	-	-	-	-	-	-	-	-
31-07-2012	8:00:00 AM	0.23	87.23	2.30	C	-	-	-	-	-	-	-	-	-	-
01-08-2012	8:00:00 AM	0.23	87.23	2.44	C	-	-	-	-	-	-	-	-	-	-
02-08-2012	8:00:00 AM	0.22	87.22	2.30	C	-	-	-	-	-	-	-	-	-	-
03-08-2012	8:00:00 AM	0.22	87.22	2.30	C	-	-	-	-	-	-	-	-	-	-

Date	Time	Gauge m	Water Level m	Discharge m³/s	Observed/ Computed	Top Width m	Wetted Perimeter m	Radius m	Velocity m/s	Manning	Area m²	Slope	Max Velocity m/s	Mode of Crossing	Method of velocity observation
04-08-2012	8:00:00 AM	0.21	87.21	2.17	C	-	-	-	-	-	-	-	-	-	-
05-08-2012	8:00:00 AM	0.21	87.21	2.17	C	-	-	-	-	-	-	-	-	-	-
06-08-2012	8:00:00 AM	0.20	87.20	2.04	C	-	-	-	-	-	-	-	-	-	-
07-08-2012	8:00:00 AM	0.20	87.20	2.04	C	-	-	-	-	-	-	-	-	-	-
08-08-2012	8:00:00 AM	0.19	87.19	1.91	C	-	-	-	-	-	-	-	-	-	-
09-08-2012	8:00:00 AM	0.19	87.19	1.91	C	-	-	-	-	-	-	-	-	-	-
10-08-2012	8:00:00 AM	0.19	87.19	1.91	C	-	-	-	-	-	-	-	-	-	-
11-08-2012	8:00:00 AM	0.18	87.18	1.79	C	-	-	-	-	-	-	-	-	-	-
12-08-2012	8:00:00 AM	0.18	87.18	1.79	C	-	-	-	-	-	-	-	-	-	-
13-08-2012	8:00:00 AM	0.30	87.30	3.52	C	-	-	-	-	-	-	-	-	-	-
14-08-2012	8:00:00 AM	0.32	87.32	3.87	C	-	-	-	-	-	-	-	-	-	-
15-08-2012	8:00:00 AM	0.31	87.31	3.69	C	-	-	-	-	-	-	-	-	-	-
16-08-2012	8:00:00 AM	0.30	87.30	3.52	C	-	-	-	-	-	-	-	-	-	-
17-08-2012	8:00:00 AM	0.30	87.30	3.52	C	-	-	-	-	-	-	-	-	-	-
18-08-2012	8:00:00 AM	0.29	87.29	3.35	C	-	-	-	-	-	-	-	-	-	-
19-08-2012	8:00:00 AM	0.28	87.28	3.19	C	-	-	-	-	-	-	-	-	-	-
20-08-2012	8:00:00 AM	0.28	87.28	3.19	C	-	-	-	-	-	-	-	-	-	-
21-08-2012	8:00:00 AM	0.27	87.27	3.03	C	-	-	-	-	-	-	-	-	-	-
22-08-2012	8:00:00 AM	0.27	87.27	3.03	C	-	-	-	-	-	-	-	-	-	-
23-08-2012	8:00:00 AM	0.26	87.26	2.88	C	-	-	-	-	-	-	-	-	-	-
24-08-2012	8:00:00 AM	0.26	87.26	2.88	C	-	-	-	-	-	-	-	-	-	-
25-08-2012	8:00:00 AM	0.25	87.25	2.73	C	-	-	-	-	-	-	-	-	-	-
26-08-2012	8:00:00 AM	0.25	87.25	2.73	C	-	-	-	-	-	-	-	-	-	-
27-08-2012	8:00:00 AM	0.25	87.25	2.73	C	-	-	-	-	-	-	-	-	-	-
28-08-2012	8:00:00 AM	0.24	87.24	2.58	C	-	-	-	-	-	-	-	-	-	-
29-08-2012	8:00:00 AM	0.24	87.24	2.58	C	-	-	-	-	-	-	-	-	-	-

Date	Time	Gauge m	Water Level m	Discharge m^3/s	Observed/ Computed	Top Width m	Wetted Perimeter m	Radius m	Velocity m/s	Manning	Area m^2	Slope	Max Velocity m/s	Mode of Crossing	Method of velocity observation
30-08-2012	8:00:00 AM	0.24	87.24	2.58	C	-	-	-	-	-	-	-	-	-	-
31-08-2012	8:00:00 AM	0.24	87.24	2.58	C	-	-	-	-	-	-	-	-	-	-
19-06-2013	8:00:00 AM	0.10	87.10	0.00	O	-	-	-	-	-	-	-	-	-	-
20-06-2013	8:00:00 AM	0.10	87.10	0.00	O	-	-	-	-	-	-	-	-	-	-
21-06-2013	8:00:00 AM	0.09	87.09	0.00	O	-	-	-	-	-	-	-	-	-	-
22-06-2013	8:00:00 AM	0.09	87.09	0.00	O	-	-	-	-	-	-	-	-	-	-
23-06-2013	8:00:00 AM	0.09	87.09	0.00	O	-	-	-	-	-	-	-	-	-	-
24-06-2013	8:00:00 AM	0.08	87.08	0.00	O	-	-	-	-	-	-	-	-	-	-
25-06-2013	8:00:00 AM	0.08	87.08	0.00	O	-	-	-	-	-	-	-	-	-	-
26-06-2013	8:00:00 AM	0.07	87.07	0.00	O	-	-	-	-	-	-	-	-	-	-
27-06-2013	8:00:00 AM	0.07	87.07	0.00	O	-	-	-	-	-	-	-	-	-	-
28-06-2013	8:00:00 AM	0.07	87.07	0.00	O	-	-	-	-	-	-	-	-	-	-
29-06-2013	8:00:00 AM	0.07	87.07	0.00	O	-	-	-	-	-	-	-	-	-	-
30-06-2013	8:00:00 AM	0.06	87.06	0.00	O	-	-	-	-	-	-	-	-	-	-
01-07-2013	8:00:00 AM	0.06	87.06	0.00	O	-	-	-	-	-	-	-	-	-	-
02-07-2013	8:00:00 AM	0.06	87.06	0.00	O	-	-	-	-	-	-	-	-	-	-
03-07-2013	8:00:00 AM	0.06	87.06	0.00	O	-	-	-	-	-	-	-	-	-	-
04-07-2013	8:00:00 AM	0.06	87.06	0.00	O	-	-	-	-	-	-	-	-	-	-
05-07-2013	8:00:00 AM	0.11	87.11	0.00	O	-	-	-	-	-	-	-	-	-	-
06-07-2013	8:00:00 AM	0.10	87.10	0.00	O	-	-	-	-	-	-	-	-	-	-
07-07-2013	8:00:00 AM	0.09	87.09	0.00	O	-	-	-	-	-	-	-	-	-	-
08-07-2013	8:00:00 AM	0.08	87.08	0.00	O	-	-	-	-	-	-	-	-	-	-
09-07-2013	8:00:00 AM	0.08	87.08	0.00	O	-	-	-	-	-	-	-	-	-	-
10-07-2013	8:00:00 AM	0.08	87.08	0.00	O	-	-	-	-	-	-	-	-	-	-
11-07-2013	8:00:00 AM	0.08	87.08	0.00	O	-	-	-	-	-	-	-	-	-	-
12-07-2013	8:00:00 AM	0.07	87.07	0.00	O	-	-	-	-	-	-	-	-	-	-

Date	Time	Gauge m	Water Level m	Discharge m^3/s	Observed/ Computed	Top Width m	Wetted Perimeter m	Radius m	Velocity m/s	Manning	Area m^2	Slope	Max Velocity m/s	Mode of Crossing	Method of velocity observation
13-07-2013	8:00:00 AM	0.80	87.80	25.81	D	93.48	93.55	0.70	0.39	0.022	65.90	0.000117	0.28	Bridge	Current Meter
14-07-2013	8:00:00 AM	0.70	87.70	21.20	D	55.49	55.51	0.32	1.21	0.004	17.55	0.000117	0.47	Bridge	Current Meter
15-07-2013	9:00:00 AM	0.40	87.40	9.68	O	70.00	70.20	0.72	0.19	0.046	50.85	0.000117	0.39	Wading	Current Meter
16-07-2013	9:00:00 AM	0.38	87.38	8.98	O	70.00	70.18	0.69	0.19	0.045	48.30	0.000117	0.36	Wading	Current Meter
17-07-2013	8:00:00 AM	0.25	87.25	0.00	O	-	-	-	-	-	-	-	-	-	-
13-07-2013	8:00:00 AM	0.23	87.23	0.00	O	-	-	-	-	-	-	-	-	-	-
14-07-2013	8:00:00 AM	0.18	87.18	0.00	O	-	-	-	-	-	-	-	-	-	-
15-07-2013	9:00:00 AM	0.17	87.17	0.00	O	-	-	-	-	-	-	-	-	-	-
16-07-2013	9:00:00 AM	0.15	87.15	0.00	O	-	-	-	-	-	-	-	-	-	-
23-07-2013	10:00:00 AM	0.14	87.14	0.00	O	-	-	-	-	-	-	-	-	-	-
24-07-2013	8:00:00 AM	1.00	88.00	43.07	O	63.72	63.77	0.56	1.22	0.006	35.43	0.000117	0.32	Bridge	Current Meter
25-07-2013	9:00:00 AM	0.60	87.60	16.98	D	52.74	52.76	0.23	1.40	0.003	12.14	0.000117	0.39	Bridge	Current Meter
26-07-2013	9:00:00 AM	0.50	87.50	12.47	O	125.00	125.19	0.56	0.18	0.041	69.50	0.000117	0.28	Wading	Current Meter
27-07-2013	9:00:00 AM	0.39	87.39	8.67	O	92.00	92.24	0.62	0.15	0.052	56.90	0.000117	0.34	Wading	Current Meter
28-07-2013	9:00:00 AM	0.35	87.35	6.77	O	90.00	90.22	0.56	0.13	0.055	50.90	0.000117	0.32	Wading	Current Meter
29-07-2013	8:00:00 AM	0.29	87.29	5.65	O	83.00	83.22	0.55	0.12	0.058	45.55	0.000117	0.32	Wading	Current Meter
30-07-2013	9:00:00 AM	0.25	87.25	5.52	C	-	-	-	-	-	-	-	-	-	-
31-07-2013	9:00:00 AM	0.65	87.65	13.03	O	54.12	54.13	0.27	0.88	0.005	14.81	0.000117	0.23	Bridge	Current Meter
01-08-2013	9:00:00 AM	0.40	87.40	8.58	O	90.00	90.19	0.71	0.13	0.064	63.90	0.000117	0.27	Wading	Current Meter
02-08-2013	10:30:00 AM	0.31	87.31	6.10	O	24.17	24.17	0.04	6.75	0.000	0.90	0.000117	0.32	Wading	Current Meter
03-08-2013	9:00:00 AM	2.60	89.60	169.33	O	245.00	245.14	1.02	0.67	0.020	251.10	0.000183	0.99	Bridge	Current Meter
04-08-2013	9:00:00 AM	1.65	88.65	74.53	O	100.96	101.05	0.89	0.83	0.012	90.20	0.000117	0.43	Bridge	Current Meter
05-08-2013	9:00:00 AM	0.60	87.60	15.85	O	125.00	125.14	0.72	0.18	0.050	90.32	0.000117	0.25	Wading	Current Meter
06-08-2013	9:00:00 AM	0.37	87.37	8.10	O	101.00	101.11	0.59	0.14	0.056	59.50	0.000117	0.30	Wading	Current Meter
07-08-2013	9:00:00 AM	0.30	87.30	6.28	O	100.00	100.10	0.54	0.12	0.061	53.76	0.000117	0.21	Wading	Current Meter
08-08-2013	9:00:00 AM	0.20	87.20	4.99	O	97.00	97.09	0.49	0.11	0.064	47.70	0.000117	0.17	Wading	Current Meter

Date	Time	Gauge m	Water Level m	Discharge m^3/s	Observed/ Computed	Top Width m	Wetted Perimeter m	Radius m	Velocity m/s	Manning	Area m^2	Slope	Max Velocity m/s	Mode of Crossing	Method of velocity observation
09-08-2013	9:00:00 AM	0.17	87.17	3.52	O	96.00	96.08	0.46	0.08	0.080	43.68	0.000117	0.13	Wading	Current Meter
10-08-2013	9:00:00 AM	0.16	87.16	3.46	O	96.00	96.08	0.44	0.08	0.077	42.48	0.000117	0.14	Wading	Current Meter
11-08-2013	8:00:00 AM	0.19	87.19	3.67	O	96.00	96.07	0.44	0.09	0.071	42.00	0.000117	0.17	Wading	Current Meter
12-08-2013	9:00:00 AM	0.17	87.17	3.68	C	-	-	-	-	-	-	-	-	-	-
13-08-2013	9:00:00 AM	0.20	87.20	4.88	O	66.00	66.11	0.49	0.15	0.045	32.48	0.000117	0.18	Wading	Current Meter
14-08-2013	9:00:00 AM	0.19	87.19	4.55	O	66.00	66.06	0.50	0.14	0.049	33.05	0.000117	0.19	Wading	Current Meter
15-08-2013	8:00:00 AM	0.19	87.19	4.51	O	66.00	66.06	0.50	0.14	0.049	32.80	0.000117	0.19	Wading	Current Meter
16-08-2013	9:00:00 AM	0.40	87.40	9.78	D	68.50	68.59	0.62	0.23	0.034	42.77	0.000117	0.45	Wading	Current Meter
17-08-2013	9:00:00 AM	0.25	87.25	6.37	O	65.50	65.60	0.55	0.18	0.041	35.94	0.000117	0.22	Wading	Current Meter
18-08-2013	8:00:00 AM	0.21	87.21	4.62	O	65.00	65.10	0.52	0.14	0.052	34.12	0.000117	0.18	Wading	Current Meter
19-08-2013	9:00:00 AM	0.19	87.19	4.11	C	-	-	-	-	-	-	-	-	-	-
20-08-2013	9:00:00 AM	0.15	87.15	3.32	O	64.00	64.07	0.47	0.11	0.058	29.87	0.000117	0.14	Wading	Current Meter
21-08-2013	9:00:00 AM	0.14	87.14	3.18	O	64.00	64.07	0.45	0.11	0.057	28.72	0.000117	0.14	Wading	Current Meter
22-08-2013	9:00:00 AM	0.12	87.12	2.61	O	64.00	64.06	0.43	0.10	0.064	27.31	0.000117	0.13	Wading	Current Meter
23-08-2013	9:00:00 AM	0.10	87.10	2.69	O	64.00	64.06	0.42	0.10	0.060	26.74	0.000117	0.12	Wading	Current Meter
24-08-2013	9:00:00 AM	0.09	87.09	2.56	O	64.00	64.06	0.41	0.10	0.062	26.47	0.000117	0.12	Wading	Current Meter
25-08-2013	8:00:00 AM	0.08	87.08	2.48	O	64.00	64.06	0.41	0.10	0.063	26.24	0.000117	0.11	Wading	Current Meter
26-08-2013	9:00:00 AM	0.07	87.07	1.84	C	-	-	-	-	-	-	-	-	-	-
27-08-2013	9:00:00 AM	0.07	87.07	2.18	O	63.95	64.00	0.40	0.09	0.069	25.61	0.000117	0.12	Wading	Current Meter
28-08-2013	9:00:00 AM	0.07	87.07	2.09	O	63.95	64.00	0.40	0.08	0.070	25.31	0.000117	0.12	Wading	Current Meter
29-08-2013	9:00:00 AM	0.06	87.06	2.01	O	63.90	63.95	0.39	0.08	0.071	24.96	0.000117	0.11	Wading	Current Meter
30-08-2013	9:00:00 AM	0.06	87.06	1.89	O	63.90	63.95	0.38	0.08	0.074	24.54	0.000117	0.10	Wading	Current Meter
31-08-2013	9:00:00 AM	0.06	87.06	1.82	O	63.70	63.75	0.38	0.08	0.076	24.29	0.000117	0.10	Wading	Current Meter

O = observed discharge, C=Computed discharge, D=discarded discharge (values changed as per rating curve)

[Source: Central Water Commission (CWC), Mahi Division, Gandhinagar]

APPENDIX F : Sample data of the Sabarmati Escape water release (For the year 2016-2017)

Day	Jul-16	Aug-16	Sep-16	Oct-16	Nov-16	Dec-16	Jan-17	Feb-17	Mar-17	Apr-17	May-17	Jun-17
1	529	1613	3702	1047	388	500	1052	1008	926	1086	212	210
2	537	1632	3832	843	512	505	1338	1010	989	1103	210	209
3	506	1641	4231	1083	258	504	1330	998	1179	1088	193	212
4	422	1726	4635	3132	255	506	1322	1132	1172	1096	208	212
5	365	4146	4948	4872	255	510	1324	1706	1172	1082	210	213
6	422	3124	4250	5033	362	517	1136	1348	1173	1085	210	208
7	554	4288	3996	5372	256	575	1014	1072	1177	1090	207	211
8	691	4879	4146	5031	257	671	1013	1078	1177	1082	210	207
9	777	5168	2975	5532	255	668	1012	1095	1179	1092	210	210
10	815	3159	1865	1267	257	667	1133	1023	1175	1096	209	210
11	803	3298	1200	2380	255	662	1174	847	1168	1098	209	212
12	812	3620	1015	1511	255	661	1167	847	1179	912	210	215
13	815	3489	1129	1453	257	668	1167	846	1181	659	208	213
14	821	1060	1049	497	257	669	1167	843	1180	594	211	309
15	941	3051	1122	502	435	666	1172	844	1161	592	209	486
16	1245	3871	1367	383	503	669	1177	956	1180	593	211	645
17	1403	3012	1420	329	508	683	1177	1213	1177	592	213	760
18	1406	2140	1143	428	500	671	1140	1230	1165	597	213	766
19	1408	2195	1460	272	494	654	995	664	1178	599	213	606
20	1413	2581	1999	600	506	658	996	458	1177	390	209	664
21	1405	2029	3661	611	506	667	1004	673	1169	209	209	760
22	1508	1188	1245	482	512	672	1013	668	1124	209	210	762
23	1575	1107	1510	256	514	672	1006	668	1098	209	210	758
24	1572	1812	1300	256	509	670	1007	779	1080	210	211	758
25	1398	2307	1083	252	505	691	1012	889	925	210	209	760
26	1243	2669	1051	250	512	839	1012	935	926	212	209	759
27	1230	3061	1065	255	511	837	1012	933	1015	211	211	754
28	1233	3042	1066	256	508	834	1005	930	1086	211	209	756
29	1463	3512	1089	254	505	844	1001	-	1090	209	210	950
30	1617	4351	1089	255	500	845	1001	-	1096	211	211	1023
31	1617	4371	-	257	-	902	999	-	1075	-	211	-

[Source: Narmada System Control Room, Sardar Sarovar Narmada Nigam Ltd. (SSNNL), Gandhinagar]

APPENDIX G: Sample data of water level referenced from hourly water level data (in m) of the Subhas Bridge station of CWC

Date	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00
15-06-2012	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00
16-06-2012	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00
17-06-2012	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00
18-06-2012	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00
19-06-2012	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00	39.00
20-06-2012	39.00	39.00	39.00	39.00	39.00	39.00	39.10	39.10	39.15	39.15	39.20	39.20	39.30	39.40	39.50	39.60	39.70	39.70	39.70	39.70	39.70	39.80	39.80	39.80
21-06-2012	39.80	39.80	39.80	39.90	39.90	39.90	40.15	40.20	40.20	40.20	40.21	40.22	40.23	40.25	40.27	40.28	40.29	40.30	40.30	40.30	40.30	40.30	40.30	40.30
22-06-2012	40.30	40.30	40.30	40.30	40.30	40.30	40.30	40.30	40.31	40.32	40.33	40.34	40.35	40.35	40.36	40.38	40.40	40.41	40.42	40.43	40.43	40.43	40.43	40.43
23-06-2012	40.44	40.44	40.44	40.44	40.44	40.44	40.44	40.44	40.44	40.44	40.45	40.46	40.47	40.48	40.50	40.50	40.50	40.50	40.50	40.50	40.50	40.50	40.50	40.50
24-06-2012	40.50	40.50	40.50	40.50	40.50	40.50	40.51	40.52	40.52	40.52	40.52	40.52	40.52	40.52	40.52	40.52	40.52	40.52	40.52	40.52	40.52	40.52	40.52	40.52
25-06-2012	40.52	40.52	40.52	40.54	40.54	40.56	40.57	40.58	40.59	40.60	40.61	40.61	40.62	40.63	40.63	40.63	40.63	40.64	40.64	40.64	40.64	40.65	40.65	40.65
26-06-2012	40.66	40.66	40.67	40.68	40.69	40.70	40.71	40.71	40.71	40.71	40.73	40.75	40.86	40.89	40.90	40.93	40.94	40.96	41.00	41.00	41.01	41.03	41.05	41.07
27-06-2012	41.09	41.12	41.14	41.15	41.16	41.17	41.19	41.20	41.22	41.24	41.26	41.26	41.26	41.26	41.27	41.27	41.27	41.28	41.28	41.28	41.28	41.29	41.29	41.29
28-06-2012	41.30	41.30	41.30	41.30	41.30	41.30	41.30	41.30	41.30	41.30	41.30	41.30	41.30	41.30	41.30	41.30	41.31	41.32	41.32	41.32	41.32	41.32	41.32	41.32
29-06-2012	41.32	41.32	41.32	41.31	41.31	41.30	41.29	41.28	41.27	41.27	41.26	41.26	41.25	41.24	41.23	41.22	41.21	41.21	41.21	41.20	41.20	41.20	41.20	41.20
30-06-2012	41.19	41.19	41.19	41.18	41.18	41.18	41.18	41.18	41.17	41.17	41.17	41.17	41.16	41.16	41.16	41.17	41.18	41.20	41.20	41.20	41.20	41.20	41.20	41.20
01-07-2012	41.20	41.20	41.20	41.20	41.20	41.20	41.20	41.21	41.21	41.22	41.22	41.22	41.22	41.22	41.23	41.23	41.23	41.23	41.24	41.24	41.25	41.25	41.25	41.25
02-07-2012	41.26	41.26	41.26	41.27	41.27	41.28	41.29	41.29	41.30	41.30	41.30	41.30	41.30	41.30	41.31	41.32	41.33	41.34	41.35	41.36	41.37	41.37	41.38	41.38
03-07-2012	41.39	41.39	41.39	41.40	41.40	41.40	41.45	41.45	41.46	41.48	41.48	41.48	41.48	41.48	41.48	41.48	41.48	41.48	41.47	41.47	41.47	41.47	41.46	41.46
04-07-2012	41.46	41.46	41.46	41.48	41.50	41.52	41.53	41.55	41.55	41.55	41.55	41.55	41.54	41.53	41.52	41.51	41.50	41.49	41.49	41.48	41.48	41.48	41.48	41.48
05-07-2012	41.47	41.47	41.47	41.47	41.47	41.47	41.47	41.47	41.47	41.47	41.47	41.47	41.47	41.47	41.47	41.47	41.46	41.45	41.45	41.45	41.45	41.45	41.45	41.45
06-07-2012	41.45	41.45	41.45	41.45	41.45	41.45	41.45	41.45	41.45	41.45	41.45	41.45	41.45	41.45	41.44	41.44	41.44	41.44	41.44	41.44	41.44	41.44	41.44	41.44
07-07-2012	41.44	41.44	41.44	41.43	41.43	41.42	41.40	41.40	41.39	41.38	41.38	41.38	41.37	41.36	41.35	41.35	41.34	41.33	41.33	41.33	41.32	41.32	41.31	41.31
08-07-2012	41.30	41.30	41.30	41.28	41.27	41.26	41.22	41.19	41.18	41.16	41.15	41.14	41.13	41.12	41.10	41.10	41.10	41.10	41.07	41.04	41.00	41.00	40.98	40.98
09-07-2012	40.97	40.97	40.97	40.96	40.95	40.94	40.87	40.87	40.86	40.86	40.85	40.85	40.83	40.82	40.80	40.79	40.78	40.77	40.76	40.76	40.75	40.75	40.75	40.75
10-07-2012	40.74	40.74	40.74	40.73	40.72	40.71	40.68	40.65	40.63	40.60	40.60	40.60	40.59	40.58	40.57	40.57	40.57	40.56	40.56	40.56	40.56	40.55	40.55	40.55
11-07-2012	40.54	40.54	40.54	40.53	40.53	40.52	40.49	40.46	40.45	40.45	40.43	40.42	40.42	40.41	40.40	40.39	40.39	40.38	40.38	40.37	40.36	40.36	40.35	40.35

Date	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	00:00
12-07-2012	40.34	40.34	40.34	40.33	40.32	40.31	40.31	40.30	40.25	40.20	40.20	40.20	40.20	40.18	40.18	40.17	40.16	40.16	40.15	40.14	40.13	40.12	40.12	40.12
13-07-2012	40.11	40.11	40.11	40.10	40.10	40.10	40.10	40.10	40.10	40.08	40.08	40.07	40.07	40.06	40.05	40.05	40.05	40.05	40.04	40.03	40.02	40.02	40.02	40.02
14-07-2012	40.01	40.01	40.01	40.01	40.01	40.01	40.01	40.01	40.01	40.01	40.01	40.01	40.01	40.01	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00
15-07-2012	39.99	39.99	39.99	39.99	39.99	39.99	39.99	39.98	39.98	39.98	39.98	39.98	39.98	39.98	39.97	39.97	39.97	39.97	39.97	39.97	39.96	39.96	39.96	39.96
16-07-2012	39.96	39.96	39.96	39.96	39.96	39.96	39.96	39.96	39.96	39.96	39.96	39.96	39.96	39.96	39.95	39.95	39.95	39.95	39.95	39.95	39.95	39.95	39.95	39.95
17-07-2012	39.95	39.95	39.95	39.95	39.95	39.95	39.95	39.95	39.95	39.95	39.95	39.94	39.94	39.94	39.94	39.94	39.93	39.93	39.93	39.93	39.93	39.93	39.93	39.93
18-07-2012	39.93	39.93	39.93	39.93	39.93	39.93	39.93	39.93	39.93	39.93	39.92	39.92	39.92	39.92	39.92	39.92	39.92	39.92	39.91	39.91	39.91	39.91	39.91	39.91
19-07-2012	39.91	39.91	39.91	39.91	39.91	39.91	39.91	39.91	39.91	39.91	39.91	39.91	39.90	39.89	39.89	39.89	39.89	39.89	39.89	39.88	39.88	39.88	39.88	39.88
20-07-2012	39.88	39.88	39.88	39.88	39.88	39.88	39.88	39.88	39.88	39.88	39.88	39.88	39.87	39.87	39.87	39.87	39.87	39.87	39.87	39.87	39.87	39.87	39.87	39.87
21-07-2012	39.87	39.87	39.87	39.86	39.86	39.86	39.86	39.86	39.86	39.86	39.85	39.85	39.85	39.85	39.85	39.85	39.85	39.85	39.85	39.85	39.85	39.85	39.85	39.85
22-07-2012	39.85	39.85	39.85	39.85	39.85	39.85	39.85	39.85	39.85	39.85	39.85	39.85	39.85	39.85	39.85	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84
23-07-2012	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84
24-07-2012	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84
25-07-2012	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.84	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83
26-07-2012	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83
27-07-2012	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.83	39.84	39.84	39.85	39.85	39.85	39.86	39.86	39.86	39.86
28-07-2012	39.90	39.96	40.04	40.07	40.10	40.14	40.15	40.16	40.19	40.22	40.23	40.25	40.26	40.26	40.27	40.28	40.29	40.30	40.30	40.30	40.30	40.32	40.35	40.38
29-07-2012	40.39	40.40	40.41	40.43	40.45	40.48	40.50	40.52	40.52	40.53	40.54	40.55	40.56	40.57	40.57	40.58	40.59	40.60	40.60	40.60	40.61	40.61	40.61	40.61
30-07-2012	40.62	40.62	40.62	40.64	40.66	40.68	40.70	40.73	40.74	40.75	40.76	40.47	40.47	40.48	40.49	40.80	40.81	40.82	40.83	40.84	40.85	40.85	40.85	40.86
31-07-2012	40.87	40.88	40.89	40.89	40.90	40.90	40.90	40.90	40.91	40.92	40.93	40.94	40.95	40.97	40.99	40.99	40.99	41.00	41.00	41.00	41.00	41.00	41.00	41.00

[Source: Central Water Commission (CWC), Mahi Division, Gandhinagar]

APPENDIX H : Sample data of water discharge from Vasna Barrage

Day Wise Cusecs - Mcft - Mcm InFlow by NMC and outflow to Fatehwadi Canal and Sabarmati River

(June-August 2015)

Date	Discharge Released from N.M.C.			Discharge released in canal (Irrigation)			Discharge released in d/s river (Surplus)		
	Day Cusecs	Mcft.	Mcm.	Day Cusecs	Mcft.	Mcm.	Day Cusecs	Mcft.	Mcm.
	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00
1-Jun-15	263.00	22.73	0.64	Nil	-	-	Nil	-	-
2-Jun-15	259.00	22.39	0.63	Nil	-	-	Nil	-	-
3-Jun-15	255.00	22.04	0.62	Nil	-	-	Nil	-	-
4-Jun-15	251.00	21.69	0.61	Nil	-	-	Nil	-	-
5-Jun-15	249.00	21.52	0.61	Nil	-	-	Nil	-	-
6-Jun-15	249.00	21.52	0.61	Nil	-	-	Nil	-	-
7-Jun-15	249.00	21.52	0.61	Nil	-	-	Nil	-	-
8-Jun-15	249.00	21.52	0.61	Nil	-	-	Nil	-	-
9-Jun-15	264.00	22.82	0.65	Nil	-	-	Nil	-	-
10-Jun-15	264.00	22.82	0.65	Nil	-	-	Nil	-	-
11-Jun-15	253.00	21.87	0.62	Nil	-	-	Nil	-	-
12-Jun-15	247.00	21.35	0.60	Nil	-	-	Nil	-	-
13-Jun-15	237.00	20.48	0.58	Nil	-	-	Nil	-	-
14-Jun-15	237.00	20.48	0.58	Nil	-	-	Nil	-	-
15-Jun-15	253.00	21.87	0.62	35.00	3.03	0.09	Nil	-	-
16-Jun-15	253.00	21.87	0.62	Nil	-	-	Nil	-	-
17-Jun-15	259.00	22.39	0.63	Nil	-	-	Nil	-	-
18-Jun-15	261.00	22.56	0.64	Nil	-	-	Nil	-	-
19-Jun-15	257.00	22.21	0.63	Nil	-	-	Nil	-	-
20-Jun-15	257.00	22.21	0.63	163.87	14.16	0.40	Nil	-	-
21-Jun-15	292.00	25.24	0.71	148.54	12.84	0.36	Nil	-	-
22-Jun-15	290.00	25.06	0.71	150.00	12.96	0.37	Nil	-	-
23-Jun-15	290.00	25.06	0.71	208.62	18.03	0.51	916.83	79.24	2.24
24-Jun-15	287.00	24.81	0.70	133.20	11.51	0.33	2743.00	237.08	6.71
25-Jun-15	3736.00	322.90	9.14	Nil	-	-	3696.00	319.45	9.05
26-Jun-15	4138.00	357.65	10.13	62.41	5.39	0.15	1472.29	127.25	3.60
27-Jun-15	2118.00	183.06	5.18	556.83	48.13	1.36	1017.58	87.95	2.49
28-Jun-15	2308.00	199.48	5.65	849.08	73.39	2.08	189.37	16.37	0.46
29-Jun-15	1340.00	115.82	3.28	903.54	78.09	2.21	Nil	-	-
30-Jun-15	1020.00	88.16	2.50	777.16	67.17	1.90	Nil	-	-
30-Jun-15	**20885.00**	**1805.10**	**51.11**	**3988.25**	**344.71**	**9.76**	**10035.07**	**867.34**	**24.56**
1-Jul-15	1020.00	88.16	2.50	742.00	64.13	1.82	Nil	-	-
2-Jul-15	1020.00	88.16	2.50	742.00	64.13	1.82	Nil	-	-
3-Jul-15	1288.00	111.32	3.15	742.00	64.13	1.82	Nil	-	-
4-Jul-15	1619.00	139.93	3.96	787.83	68.09	1.93	Nil	-	-
5-Jul-15	1005.00	86.86	2.46	1030.62	89.08	2.52	Nil	-	-
6-Jul-15	1319.00	114.00	3.23	923.75	79.84	2.26	Nil	-	-
7-Jul-15	1277.00	110.37	3.13	855.29	73.92	2.09	Nil	-	-
8-Jul-15	1350.00	116.68	3.30	803.91	69.48	1.97	Nil	-	-
9-Jul-15	2040.00	176.32	4.99	986.83	85.29	2.42	Nil	-	-
10-Jul-15	1513.00	130.77	3.70	1162.50	100.48	2.85	Nil	-	-
11-Jul-15	1502.00	129.82	3.68	1095.91	94.72	2.68	Nil	-	-
12-Jul-15	2065.00	178.48	5.05	1153.33	99.68	2.82	Nil	-	-
13-Jul-15	2736.00	236.47	6.70	1410.65	121.92	3.45	58.33	5.04	0.14
14-Jul-15	1536.00	132.76	3.76	1346.61	116.39	3.30	Nil	-	-

Date	Discharge Released from N.M.C.			Discharge released in canal (Irrigation)			Discharge released in d/s river (Surplus)		
	Day Cusecs	Mcft.	Mcm.	Day Cusecs	Mcft.	Mcm.	Day Cusecs	Mcft.	Mcm.
	1.00	**2.00**	**3.00**	**4.00**	**5.00**	**6.00**	**7.00**	**8.00**	**9.00**
15-Jul-15	2069.00	178.82	5.06	1334.37	115.33	3.27	Nil	-	-
16-Jul-15	1558.00	134.66	3.81	1125.00	97.23	2.75	Nil	-	-
17-Jul-15	1460.00	126.19	3.57	1111.83	96.10	2.72	Nil	-	-
18-Jul-15	670.00	57.91	1.64	1107.04	95.68	2.71	Nil	-	-
19-Jul-15	596.00	51.51	1.46	769.00	66.46	1.88	Nil	-	-
20-Jul-15	599.00	51.77	1.47	710.00	61.37	1.74	Nil	-	-
21-Jul-15	1125.00	97.23	2.75	700.00	60.50	1.71	199.20	17.22	0.49
22-Jul-15	1621.00	140.10	3.97	750.66	64.88	1.84	Nil	-	-
23-Jul-15	2372.00	205.01	5.81	1039.04	89.80	2.54	Nil	-	-
24-Jul-15	989.00	85.48	2.42	1029.54	88.98	2.52	Nil	-	-
25-Jul-15	989.00	85.48	2.42	842.87	72.85	2.06	979.75	84.68	2.40
26-Jul-15	429.00	37.08	1.05	156.45	13.52	0.38	2799.16	241.93	6.85
27-Jul-15	5044.00	435.96	12.34	129.58	11.20	0.32	729.94	63.09	1.79
28-Jul-15	10443.00	902.59	25.56	Nil	-	-	12139.37	1049.21	29.71
29-Jul-15	9425.00	814.61	23.07	Nil	-	-	81312.33	7027.86	199.00
30-Jul-15	6936.00	599.48	16.98	Nil	-	-	90870.12	7853.94	222.40
31-Jul-15	1012.00	87.47	2.48	Nil	-	-	31135.37	2691.04	76.20
31-Jul-15	**68627.00**	**5931.46**	**167.96**	**24588.61**	**2125.20**	**60.18**	**220223.57**	**19034.02**	**538.98**
1-Aug-15	4031.00	348.40	9.87	Nil	-	-	10531.50	910.24	25.77
2-Aug-15	2024.00	174.94	4.95	796.54	68.85	1.95	8913.83	770.43	21.82
3-Aug-15	500.00	43.22	1.22	995.29	86.02	2.44	7205.83	622.80	17.64
4-Aug-15	1037.00	89.63	2.54	1146.25	99.07	2.81	4790.75	414.07	11.72
5-Aug-15	1030.00	89.02	2.52	1277.99	110.46	3.13	4295.50	371.26	10.51
6-Aug-15	2424.00	209.51	5.93	1241.66	107.32	3.04	3421.58	295.73	8.37
7-Aug-15	3043.00	263.01	7.45	1200.00	103.72	2.94	4699.50	406.18	11.50
8-Aug-15	1490.00	128.78	3.65	1195.00	103.28	2.92	2351.08	203.20	5.75
9-Aug-15	2054.00	177.53	5.03	1200.00	103.72	2.94	1946.16	168.21	4.76
10-Aug-15	1512.00	130.68	3.70	1200.00	103.72	2.94	1391.79	120.29	3.41
11-Aug-15	1558.00	134.66	3.81	1200.00	103.72	2.94	1087.00	93.95	2.66
12-Aug-15	2040.00	176.32	4.99	1160.02	100.26	2.84	1400.60	121.05	3.43
13-Aug-15	1201.00	103.80	2.94	1170.00	101.12	2.86	14324.91	1238.11	35.06
14-Aug-15	1552.00	134.14	3.80	986.33	85.25	2.41	16195.41	1399.78	39.64
15-Aug-15	1450.00	125.32	3.55	817.62	70.67	2.00	6212.91	536.98	15.21
16-Aug-15	1020.00	88.16	2.50	1111.25	96.05	2.72	1569.54	135.66	3.84
17-Aug-15	515.00	44.51	1.26	1285.00	111.06	3.14	1667.45	144.12	4.08
18-Aug-15	1054.00	91.10	2.58	1224.79	105.86	3.00	3784.91	327.13	9.26
19-Aug-15	2366.00	204.49	5.79	1168.12	100.96	2.86	2549.00	220.31	6.24
20-Aug-15	3093.00	267.33	7.57	1170.00	101.12	2.86	3172.79	274.23	7.77
21-Aug-15	2490.00	215.21	6.09	1170.00	101.12	2.86	1114.83	96.36	2.73
22-Aug-15	1901.00	164.30	4.65	1170.00	101.12	2.86	1009.75	87.27	2.47
23-Aug-15	2528.00	218.50	6.19	1170.00	101.12	2.86	1192.33	103.05	2.92
24-Aug-15	1538.00	132.93	3.76	1170.00	101.12	2.86	810.00	70.01	1.98
25-Aug-15	1537.00	132.84	3.76	1148.75	99.29	2.81	158.37	13.69	0.39
26-Aug-15	1744.00	150.73	4.27	1121.87	96.96	2.75	Nil	-	-
27-Aug-15	2038.00	176.15	4.99	1174.00	101.47	2.87	Nil	-	-
28-Aug-15	1013.00	87.55	2.48	1041.79	90.04	2.55	Nil	-	-
29-Aug-15	2084.00	180.12	5.10	1076.41	93.03	2.63	Nil	-	-
30-Aug-15	1667.00	144.08	4.08	1149.37	99.34	2.81	Nil	-	-

Date	Discharge Released from N.M.C.			Discharge released in canal (Irrigation)			Discharge released in d/s river (Surplus)		
	Day Cusecs	Mcft.	Mcm.	Day Cusecs	Mcft.	Mcm.	Day Cusecs	Mcft.	Mcm.
	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00
31-Aug-15	1705.00	147.36	4.17	1170.00	101.12	2.86	Nil	-	-
31-Aug-15	**55239.00**	**4774.33**	**135.19**	**34108.05**	**2947.97**	**83.48**	**105797.32**	**9144.11**	**258.93**
1-Sep-15	1860.00	160.76	4.55	1200.00	103.72	2.94	Nil	-	-
2-Sep-15	1873.00	161.88	4.58	1300.00	112.36	3.18	Nil	-	-
3-Sep-15	2010.00	173.73	4.92	1300.00	112.36	3.18	Nil	-	-
4-Sep-15	1670.00	144.34	4.09	1300.00	112.36	3.18	Nil	-	-
5-Sep-15	2084.00	180.12	5.10	1312.50	113.44	3.21	50.00	4.32	0.12
6-Sep-15	2010.00	173.73	4.92	1319.16	114.02	3.23	Nil	-	-
7-Sep-15	1873.00	161.88	4.58	1300.00	112.36	3.18	Nil	-	-
8-Sep-15	1873.00	161.88	4.58	1300.00	112.36	3.18	Nil	-	-
9-Sep-15	1859.00	160.67	4.55	1208.33	104.44	2.96	Nil	-	-
10-Sep-15	2205.00	190.58	5.40	1300.00	112.36	3.18	Nil	-	-
11-Sep-15	2024.00	174.94	4.95	1332.08	115.13	3.26	Nil	-	-
12-Sep-15	2024.00	174.94	4.95	1385.00	119.71	3.39	Nil	-	-
13-Sep-15	1788.00	154.54	4.38	1343.95	116.16	3.29	Nil	-	-
14-Sep-15	1831.00	158.25	4.48	1319.16	114.02	3.23	Nil	-	-
15-Sep-15	1846.00	159.55	4.52	1270.00	109.77	3.11	Nil	-	-
16-Sep-15	1802.00	155.75	4.41	1423.33	123.02	3.48	133.33	11.52	0.33
17-Sep-15	1705.00	147.36	4.17	1885.00	162.92	4.61	Nil	-	-
18-Sep-15	1705.00	147.36	4.17	1548.20	133.81	3.79	5041.00	435.70	12.34
19-Sep-15	2775.00	239.84	6.79	735.00	63.53	1.80	4558.00	393.95	11.16
20-Sep-15	3026.00	261.54	7.41	735.00	63.53	1.80	1518.00	131.20	3.72
21-Sep-15	1501.00	129.73	3.67	735.00	63.53	1.80	967.00	83.58	2.37
22-Sep-15	1183.00	102.25	2.90	830.00	71.74	2.03	1172.66	101.35	2.87
23-Sep-15	4721.00	408.04	11.55	871.87	75.36	2.13	3013.00	260.41	7.37
24-Sep-15	2980.00	257.56	7.29	752.56	65.04	1.84	985.45	85.17	2.41
25-Sep-15	1513.00	130.77	3.70	760.00	65.69	1.86	60.08	5.19	0.15
26-Sep-15	1027.00	88.76	2.51	760.00	65.69	1.86	Nil	-	-
27-Sep-15	1027.00	88.76	2.51	762.00	65.86	1.86	Nil	-	-
28-Sep-15	1536.00	132.76	3.76	690.50	59.68	1.69	Nil	-	-
29-Sep-15	1501.00	129.73	3.67	761.04	65.78	1.86	Nil	-	-
30-Sep-15	1020.00	88.16	2.50	842.50	72.82	2.06	Nil	-	-
30-Sep-15	**57852.00**	**5000.17**	**141.59**	**33582.18**	**2902.52**	**82.19**	**17498.52**	**1512.40**	**42.83**

[Source: Vasna Barrage Division, Ahmedabad]

List of Publications

1. Darji, J., Lodha, P., & Tyagi, S. (2022). Assimilative capacity and water quality modeling of rivers: a review. Aqua Water Infrastructure, Ecosystems and Society, 71(10), 1127–1147. https://doi.org/10.2166/aqua.2022.063
2. Darji, J., & Lodha, P. (2025). Analyzing Spatial and Temporal Variations in Water Quality and Identifying Key Influencing Factors in the Sabarmati River System, Western India. Water Conservation Science and Engineering, 10(6). https://doi.org/10.1007/s41101-024-00335-y
3. Darji, J. S., & Lodha, P. P. (2025). QUAL2Kw–A Water Quality Modeling Tool for Rivers and Streams: A Review. IJSAT-International Journal on Science and Technology, 16(3). https://doi.org/10.71097/IJSAT.v16.i3.7594