WATER QUALITY MODELING FRAMEWORK FOR RIVER HEALTH

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CONTENT

1.0 Title of the thesis and abstract

1.1 Title of the thesis

Water quality modeling framework for river health

1.2 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 in estimating and maintaining 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 was found effective in determining 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), Ammonium N (NH3-N), and pH. The sensitivity analysis, conducted through upstream stretch water quality simulation, showed 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 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 provides a river water quality management, which can be applied to other studies for restoring or maintaining the river's health.

2.0 A brief description of the state of the art of the research topic

Rivers play a crucial role in assimilating pollution due to their dynamic nature and self-purification capacity, also known as assimilative capacity [1]. However, it allows the river or stream to handle the pollution load to a certain extent. If the pollution load exceeds its carrying capacity, it has a serious impact on the river ecosystem and its survival. Therefore, it is important to measure the river's carrying capacity to ascertain the health of the river. A river health assessment requires periodic data on water quality, as well as the identification of parameters that affect and contribute to pollution. It is also essential to determine spatial and temporal variations in water quality to identify pollution sources, which helps in developing water quality management strategies and maintaining the river's health [2, 3]. Multivariate statistical analysis methods such as ANOVA, cluster analysis (CA), and Principal component analysis (PCA) aid in interpreting complex water quality data, describing spatial and temporal variations, identifying pollution sources, and pinpointing parameters that significantly influence water quality [4, 5]. This is a crucial first step in water quality modeling to estimate the river's carrying capacity. A wide range of water quality models is available that simulate changes in pollutant concentrations as they move from one location to another. These water quality models (WQMs) estimate the river's assimilative or self-purification capacity by modeling water quality along a designated stretch. They serve as effective tools for assessing pollution levels and long-term impacts, helping researchers evaluate related risks. The research study aims to simulate a model for assessing the pollution load and carrying capacity of the Sabarmati River by analyzing various water quality parameters and determining the river's self-purification ability to restore and maintain its water quality at different reaches, ensuring it meets the conditions needed for its intended use.

3.0 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 [6–9]. Therefore, this research was proposed to determine both spatial and temporal variations in the water quality of the Sabarmati River at various locations to identify the most important parameters for establishing pollution reduction goals. The study also involves the water quality modeling of different stretches of the river to examine the pollution load and self-purification capacity of the river. The research work provides the basis to ascertain the water quality of the river for intended use, and assists in restoring and maintaining the pristine nature of the water body.

4.0 Objectives

Based on the literature review and research gap identified from previous studies, this research study was framed considering the following objectives:

- 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.

5.0 Scope of the work:

The research includes a preliminary survey and study of the entire Sabarmati River to select and identify critical river 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 significantly affecting 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.

6.0 Original contribution by the thesis

The research study presents the spatial and temporal water quality variations of the Sabarmati River at 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. The application of the selected QUAL2Kw model is clearly outlined in the thesis. 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 their pollution load capacity and water quality management for its intended use. Finally, the proposed river water quality framework can be utilized as a basis and can be replicated in other similar research works for maintaining the river's health.

7.0 The methodology of research

The methodology was designed for systematic planning and execution of the research work to meet the defined objectives. Figure 1 shows the methodology adopted for the research study.

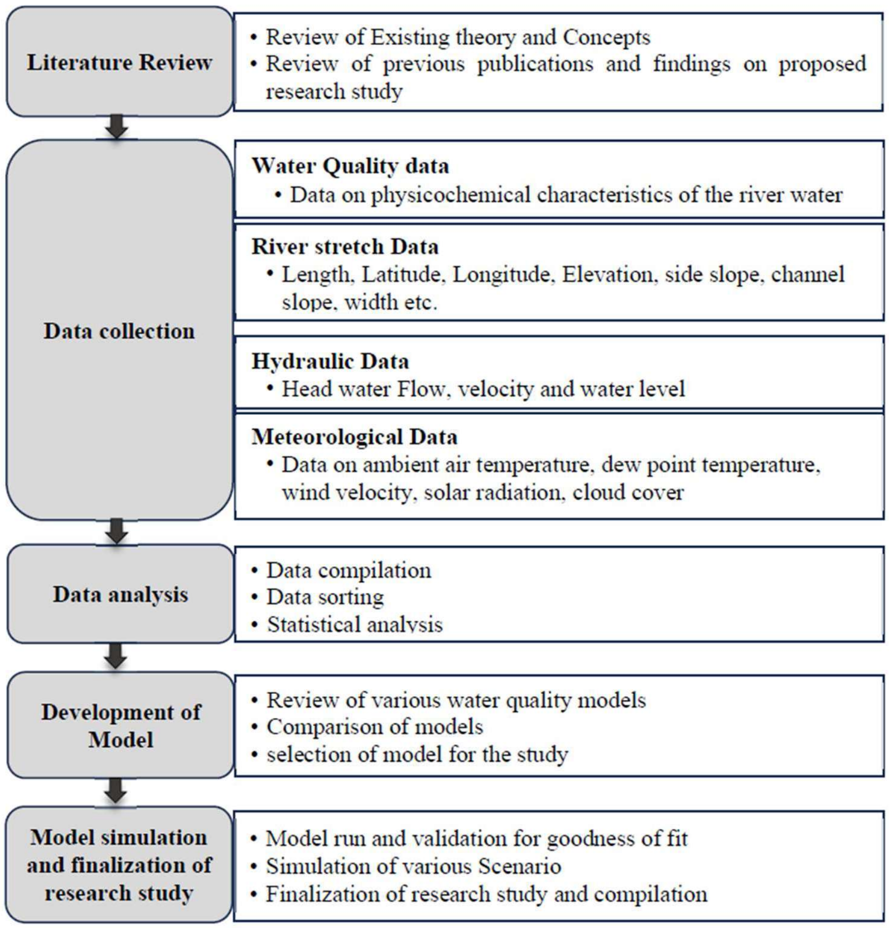


Figure 1 Research Methodology

8.0 Study area

Considering the inflow, pollution sources, and utility of the river water, three stretches of the Sabarmati River were selected for this study as shown in Figure 2, upstream (US-1 to US-4 starting from Dharoi reservoir), middle stream (MS-1 to MS-3 starting from Karai dam) which includes the riverfront, and downstream (DS-1 to DS-4 starting from Vasna barrage). 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 lower part of the basin and within the urban and rural areas, where sewage and industrial effluent discharges are prevalent [6, 10, 11].

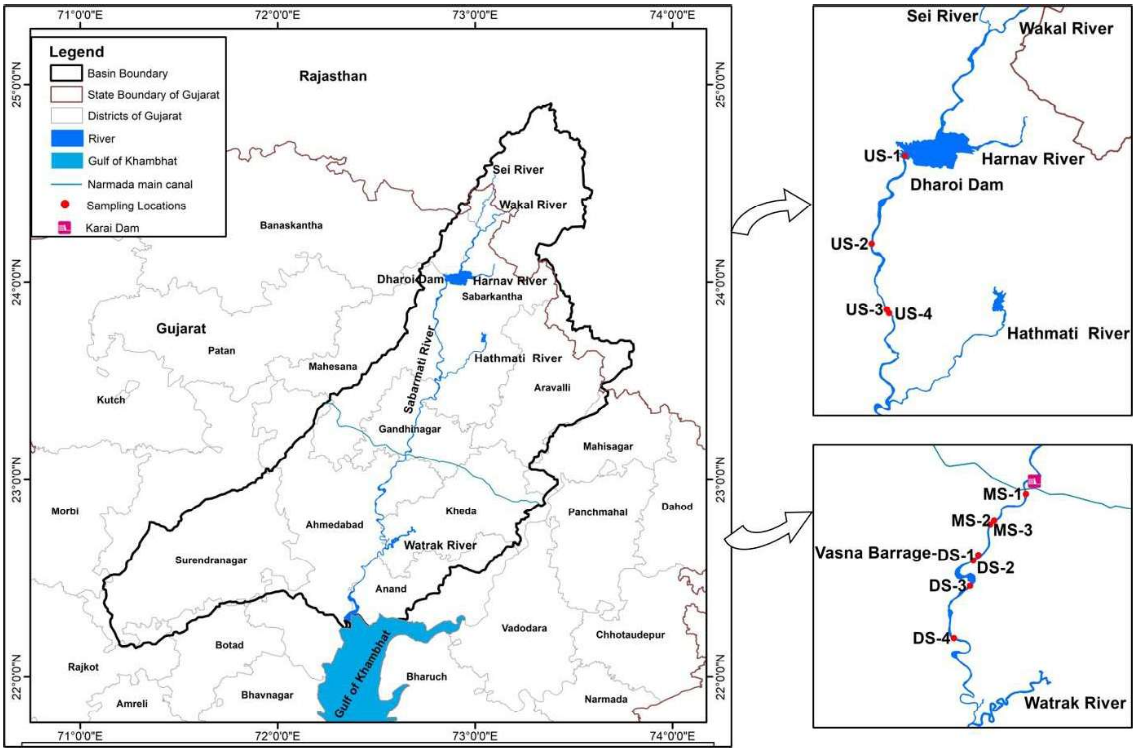


Figure 2 Study area

9.0 Materials and Methods

The methodology adopted for the analysis and interpretation of the data is shown in Figure 3 and described below:

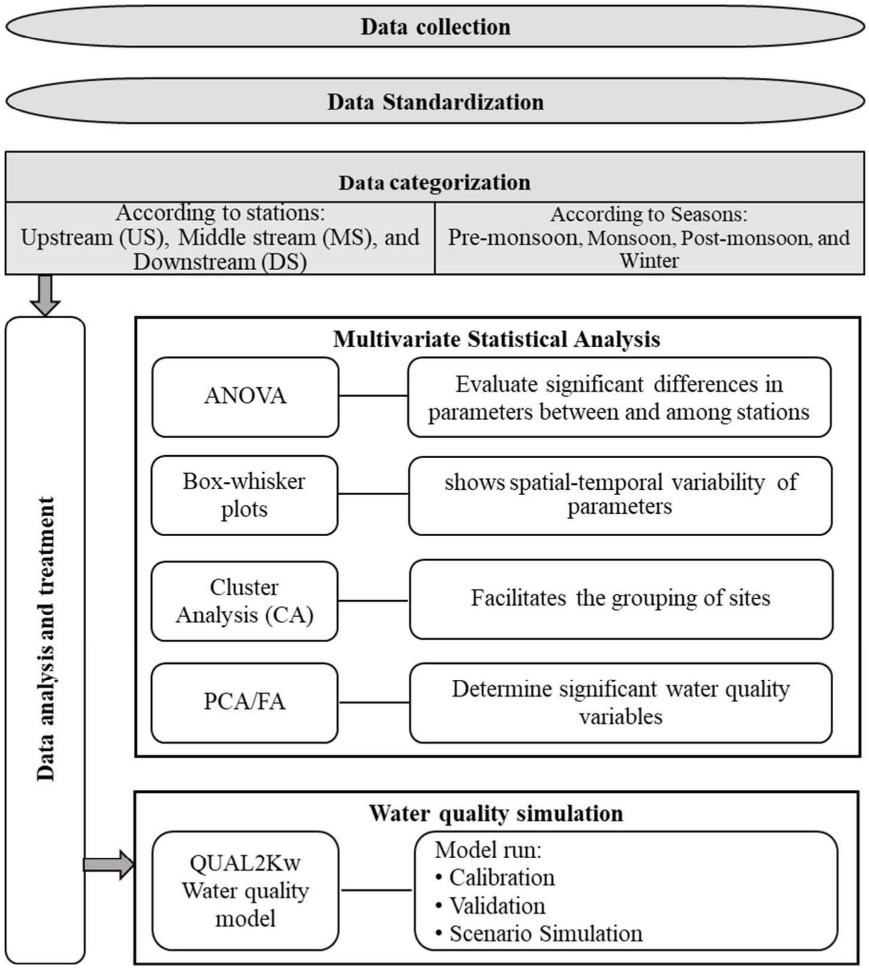


Figure 3 Methodology adopted for the data analysis and interpretation

10.0 Data collection and preparation:

The water quality data for the selected locations were obtained from the Gujarat Environment Management Institute (GEMI) [12]. Looking to 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 (NH3- 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 dataset contains yearly monitored data from 2012 to 2021, comprising 328 datasets. The data were checked 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 [13].

11.0 Multivariate statistical 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.

11.1 Box and whisker plots:

Box-whisker plots Figure 4 illustrate the temporal and spatial variation in the water quality parameters [14]. Seasonal changes in water quality parameters are evident through temporal variations. Pre-monsoon and winter seasons were found to be critical compared to others. Site-specific variations are apparent from the plots, showing the highest chemical pollution to the downstream sites.

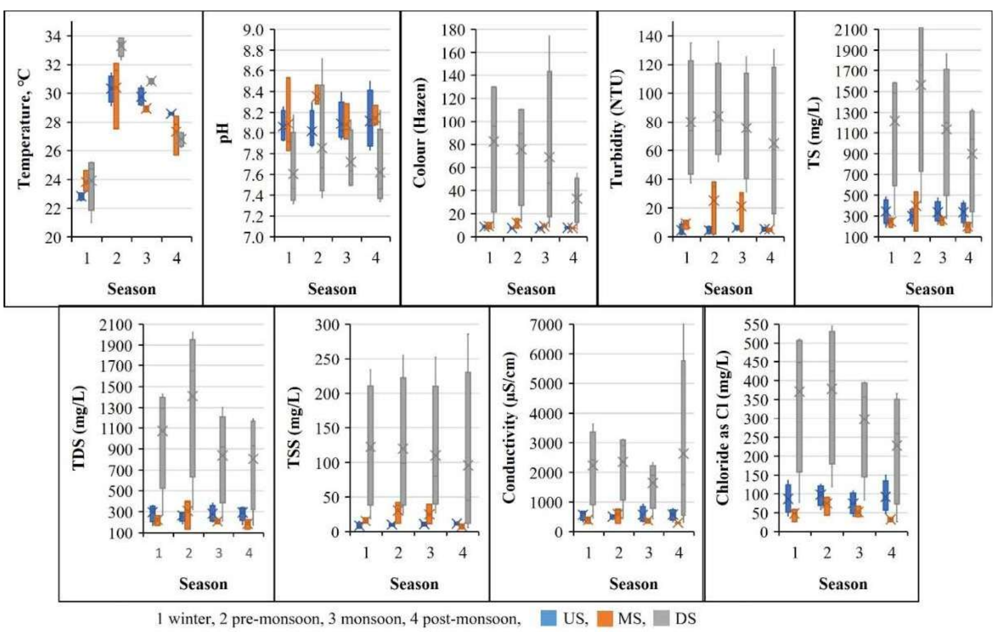


Figure 4 Box and Whisker plots

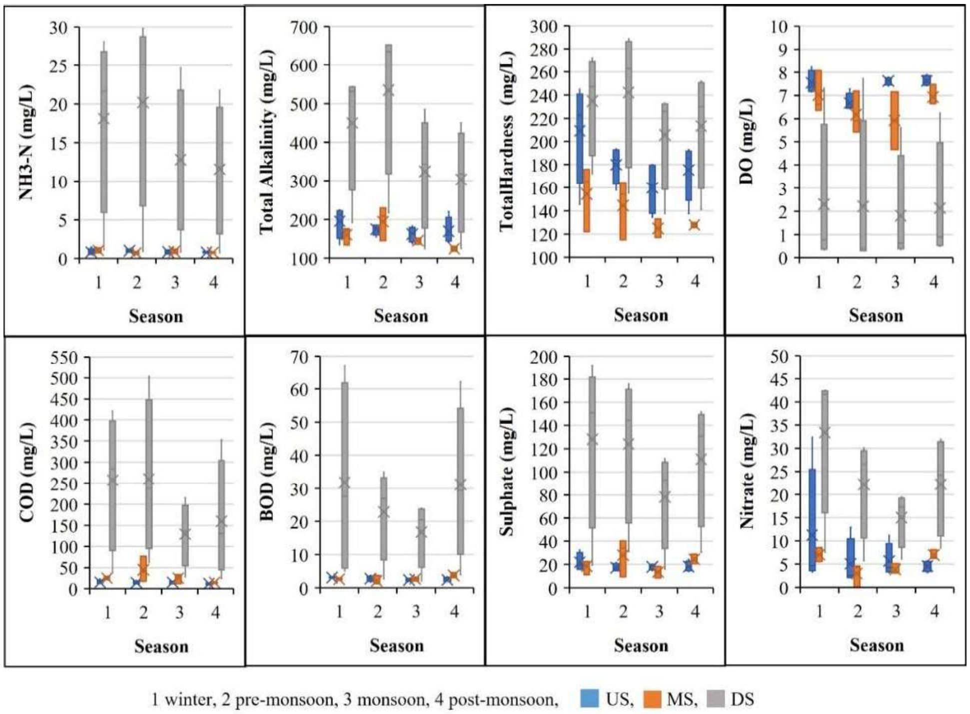


Figure 4 Box and Whisker plots continued

11.2 ANOVA analysis

The non-parametric "Kruskal-Wallis test was conducted to determine the significance of water quality parameters among the sampling points and seasons. Significant differences were found at $p<0.05$ [15, 16]. The results are summarized in Table 1.

Table 1 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	

- The test results indicate 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 ($p<0.05$)

11.3 Cluster analysis

The spatial variations in the water quality parameters were further assessed through cluster analysis. This analysis produced a dendrogram shown in Figure 5 that grouped the sampling sites into three statistically significant clusters, with a (Dlink/Dmax) X 100 ratio below 60 [17, 18]

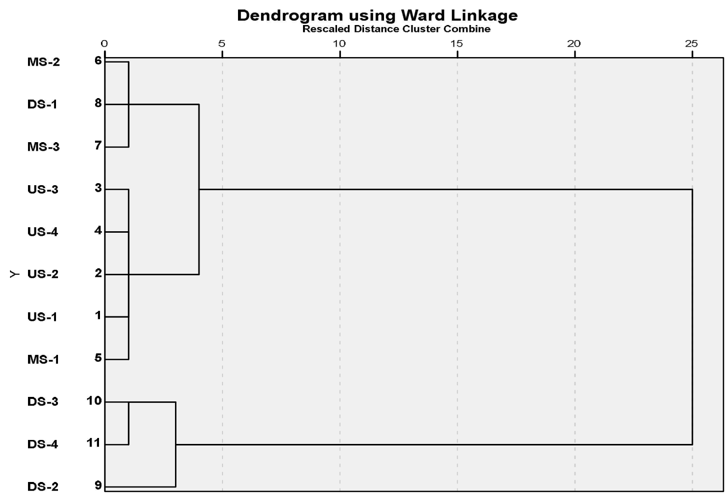


Figure 5 Dendrogram based on hierarchical cluster analysis

- **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 and 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 deterioration in the water quality at the sites is also reported in the previous study [7]. 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 [19]. Therefore, these sites are categorized as **highly polluted (HP)**.

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

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 because they are important indicators of pollution load and the river's carrying capacity. The normalized raw data, including sample temp., pH, TDS, NH3N, Chloride, COD, BOD, DO, sulphate, and nitrate was grouped for LP, MP, and HP sites and subjected to principal component analysis. 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, indicating the suitability of the data for PCA [2, 20, 21]. The components with eigenvalue greater than 1 are retained for further analysis. The load factor matrix for LP, MP, and HP sites is summarized in Table 2 to 4 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 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 absolute value of the load factor indicates the significance of the variables [18, 22–24]. 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 [22, 25]and summarized in Table 5.

Table 2 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 3 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 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

Table 5 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

12.0 About QUAL2Kw

Based on the review of various water quality models, **QUAL2Kw**, developed by USEPA was selected for the study[26–28]. The model was due to its easy accessibility, microsoft Excel interface, capability, autocalibration system and wide applications for major Indian rivers, including the Tapi, Godavari, Yamuna, Periyar, and Kshipra parameters [29–35].

From the significant water quality parameters and standard requirements, seven water quality parameters, Temperature, dissolved Oxygen (DO), CBODslow, CBODfast, NH_3-N, inorganic suspended solids (ISS), and pH, were selected, which are important for the carrying capacity and health of the river.

Parameter name as per QUAL2Kw	**Parameters considered**
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 – NH_3-N
pH	pH
	(Ref. : Sarda & Sadgir 2015, Metcalf and Eddy as medium strength water, Lestari et al. 2019)

Water quality data, head water flow data and meteorological data were collected from the concerned dept. for 2012-2021. Further, the reach length, latitude, longitude, elevation, channel width and slope data were also collected as per the model's input requirements [36]. The 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 [37]. Global rate parameters were used for the model calibration. The rate parameters considered for the study are: CBODs - hydrolysis rate and oxidation rate, CBODf- oxidation rate, Inorganic suspended solids - settling velocity, ammonium – nitrification. Model was calibrated by auto-calibration method [33]. 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 data of water quality [30]. Weights for the water quality parameters were determined to reduce the error between measured and model-predicted parameters. 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 [37–40].

12.1 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. Figure 6 shows the grouping of data input to the model for the upstream stretch. 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.

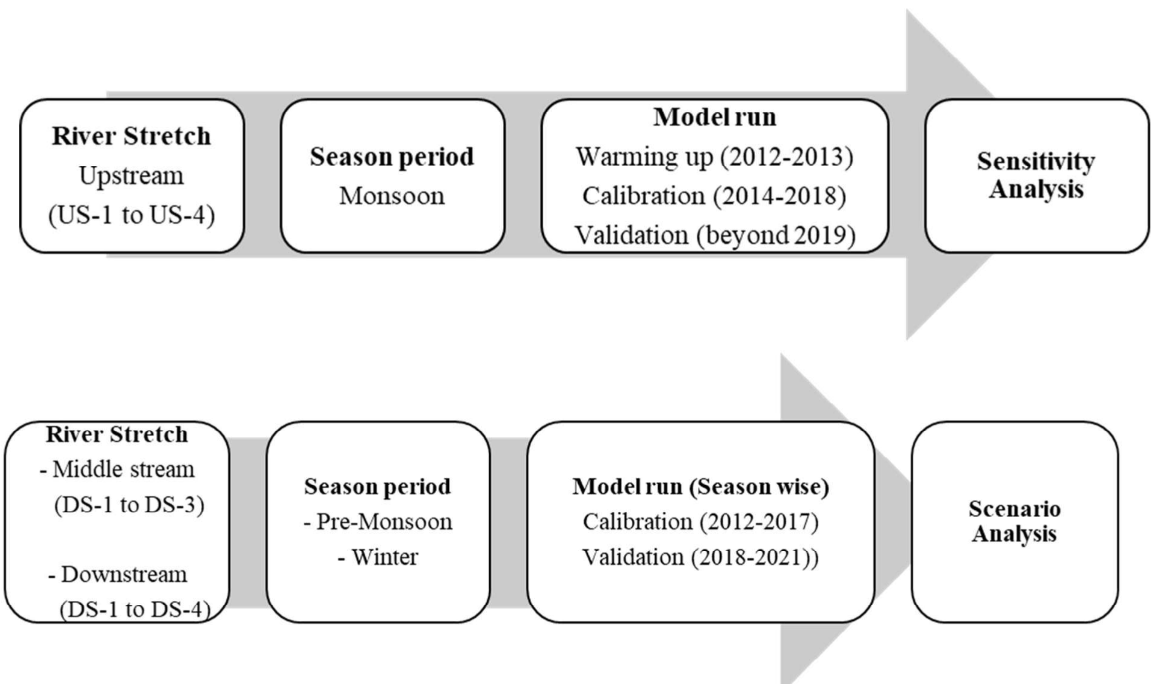


Figure 6 Application of QUAL2Kw model

13.0 Model run and sensitivity analysis for Upstream stretch

13.1 Calibration and validation of the model:

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 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.

The model was calibrated for the monsoon season data 2014-2018 with the auto calibration method for the selected rate parameters. The calibrated model performance was checked by considering 2018-2021 for validation. Table 6 shows the normalized RMSE values of the simulated calibrated and validated output. The results indicate the RMSE value in good parity between the calibrated and validated data for DO, BODs, and NH3-N. While the difference was large for ISS, CBODf, and pH. However, the overall performance of the calibrated model with a fitness value of 6.29 is found satisfactory, with the validated model with a fitness value of 5.65.

Table 6 Model fitness and RMSE value for upstream stretch (monsoon)

	ISS	DO	CBODs	CBODf	NH3-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

13.2 Sensitivity Analysis:

A sensitivity analysis was conducted to quantify the 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 [41–43]. The calibrated model was used for sensitivity analysis, and the impact of one parameter was tested by increasing and decreasing its value by 20% while keeping all other parameters constant. The impact on the simulated output was checked for changes in each parameter. From the sensitivity analysis, the model was highly sensitive for headwater flow, hydrolysis rate for CBODs, oxidation rate for CBODf, and depth coefficient. These parameters were optimized further for calibration to obtain best-fit model.

14.0 Model run for Middle stream stretch

The middle stream stretch was simulated for the critical season of winter and pre-monsoon seasons. The inflow from the Karai dam was taken as a headwater flow for the simulation run. The water level data of CWC at the Subhas Bridge was taken as a reference in hydraulic calculations. The water quality and meteorological data were averaged for the winter and pre-monsoon seasons

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 the Naranghat location 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 head water flow, contribution 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

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

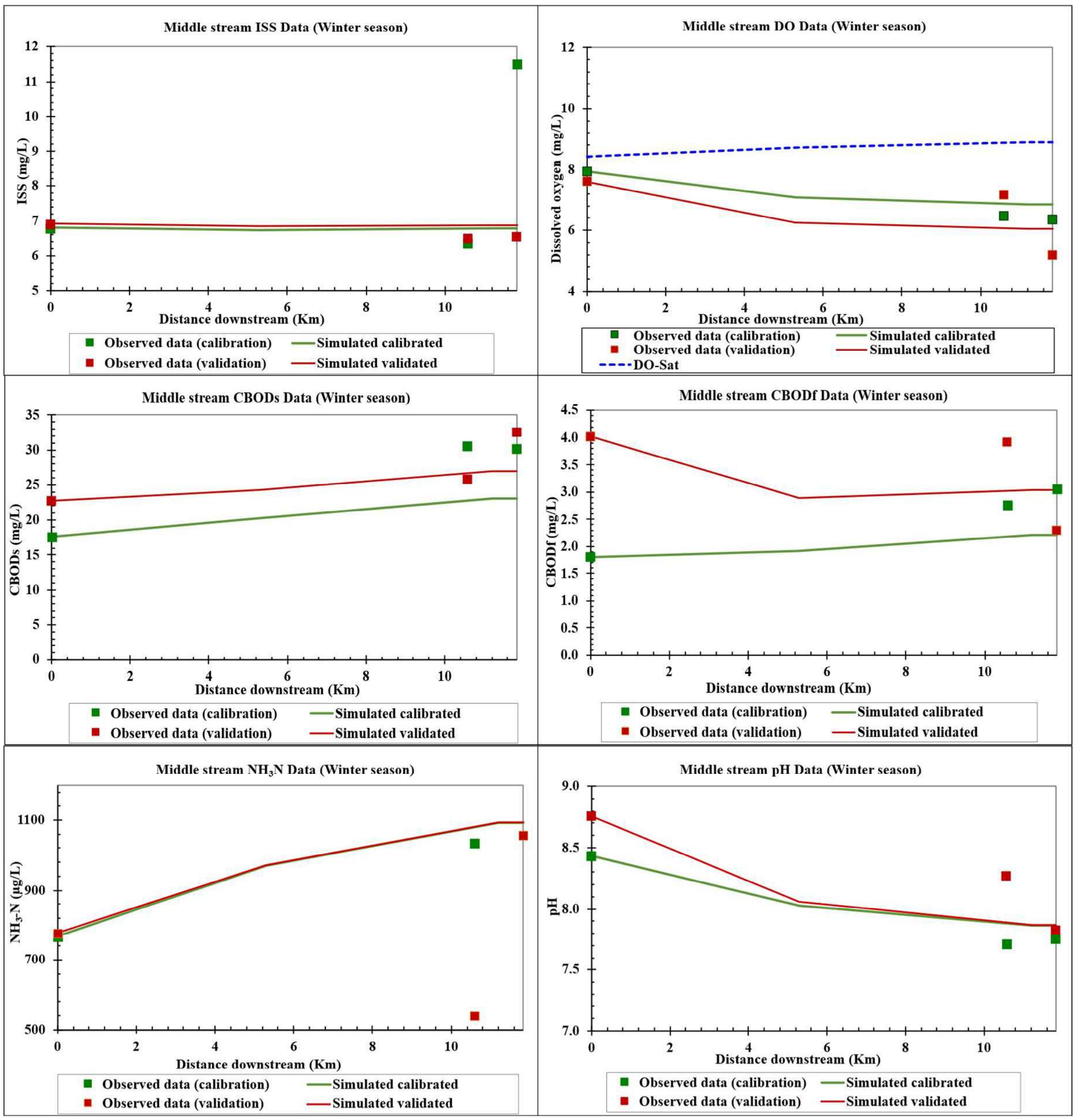
14.1 Model output for Middle stream stretch:

Winter season:

The simulation run output for the winter are presented in Graph 1 and RMSE values are depicted in Table 7. The graphs show that CBODs, CBODf, and NH3-N increase with the distances downstream due to the input of point sources within the stretch. As a result, the DO value was found to decrease continuously as the distance increases, but it was almost constant beyond 10 km, with the value of about 6.5 mg/L indicating good water quality. There is not much difference between the simulated and observed inorganic suspended solids. The predicted values of pH are also in good conformity with the observed data. High differences in RMSE values were observed for ISS, DO, CBODs and NH3-N because of the variations in the observed water quality data during the calibration and validation stage. The data represents the impact of the point source load on the water quality at the MS2 and MS3 locations.3 However, the calibrated model with fitness 7.06 was found to explain the relationship between the simulated and observed data with fitness of 5.77 in validation, indicating satisfactory output.

Pre-monsoon season:

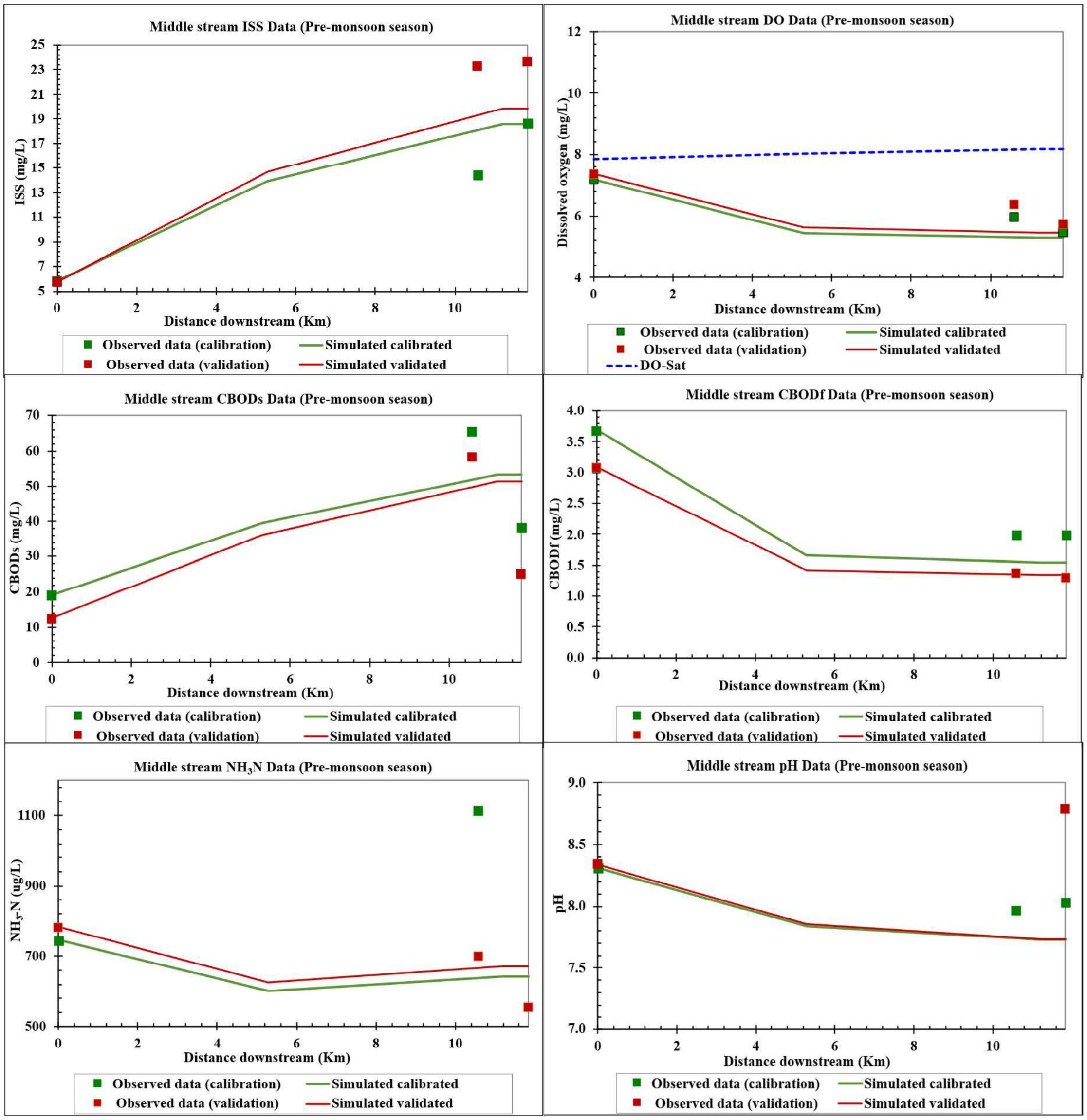
The simulation run output for the pre-monsoon are presented in Graphs 2 and RMSE values are depicted in Table 8. Graphs show that the concentration of ISS and CBODs increases with distance downstream from the headwater flow, indicating input from the point sources. CBODf decreases continuously as the distance from the headwater increases, representing the oxidation of the organic compounds. NH3-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 satisfies the minimum DO requirement of 4.0 mg/L. The differences in RMSE values for CBODs, CBODf, NH3-N, and pH between calibration and validation can be attributed to changes in water quality caused by anthropogenic activities during the two periods.



Graph 1 Model output for the middle stream stretch (winter season)

Table 7 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



Graph 2 Model output for the middle stream stretch (pre-monsoon season)

Table 8 Model fitness and RMSE values for the middle stream stretch (Pre-monsoon season)

Parameters	ISS	DO	CBODs	CBODf	NH3-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

14.2 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 CPCB's designated best use water quality classification. It also helps understand the pollution load capacity and the river's health. The scenarios were simulated considering two criteria, 1.) Modifications in river inflow and 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 9 and 10 for the winter and pre-monsoon seasons, respectively.

Middle stream (winter):

- A minimum flow of 10 m^3/s is required to maintain the water quality to satisfy 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 criteria.
- 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.

Middle stream (pre-monsoon):

- An increase in headwater flow by 50% i.e. 28.10 m3/s showed improved water quality but remained within class B criteria.
- 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 m3/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.

Table 9 Summarized results of 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
SC2	Reduction in flow condition	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
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

Table 10 Summarized results of 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	2.3	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
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

15.0 Model run for the downstream stretch

The Vasna Barrage, taken as a head point of the downstream stretch, holds the 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 from 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. Hence, the flow in the river is calculated as 236 m^3/s. The model was simulated considering the minimum calculated flow for winter and pre-monsoon season.

The Sabarmati River downstream of the Vasna barrage receives the discharges from STPs and CETPs located in the surroundings. The outfalls beyond Vasna barrage into the river have been taken from the GPCB action taken report 2023 [44]. The pollution load data for the selected data set 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 shown in Table 11.

Table 11 Point source data for the downstream stretch

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
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

15.1 Model output for the downstream stretch:

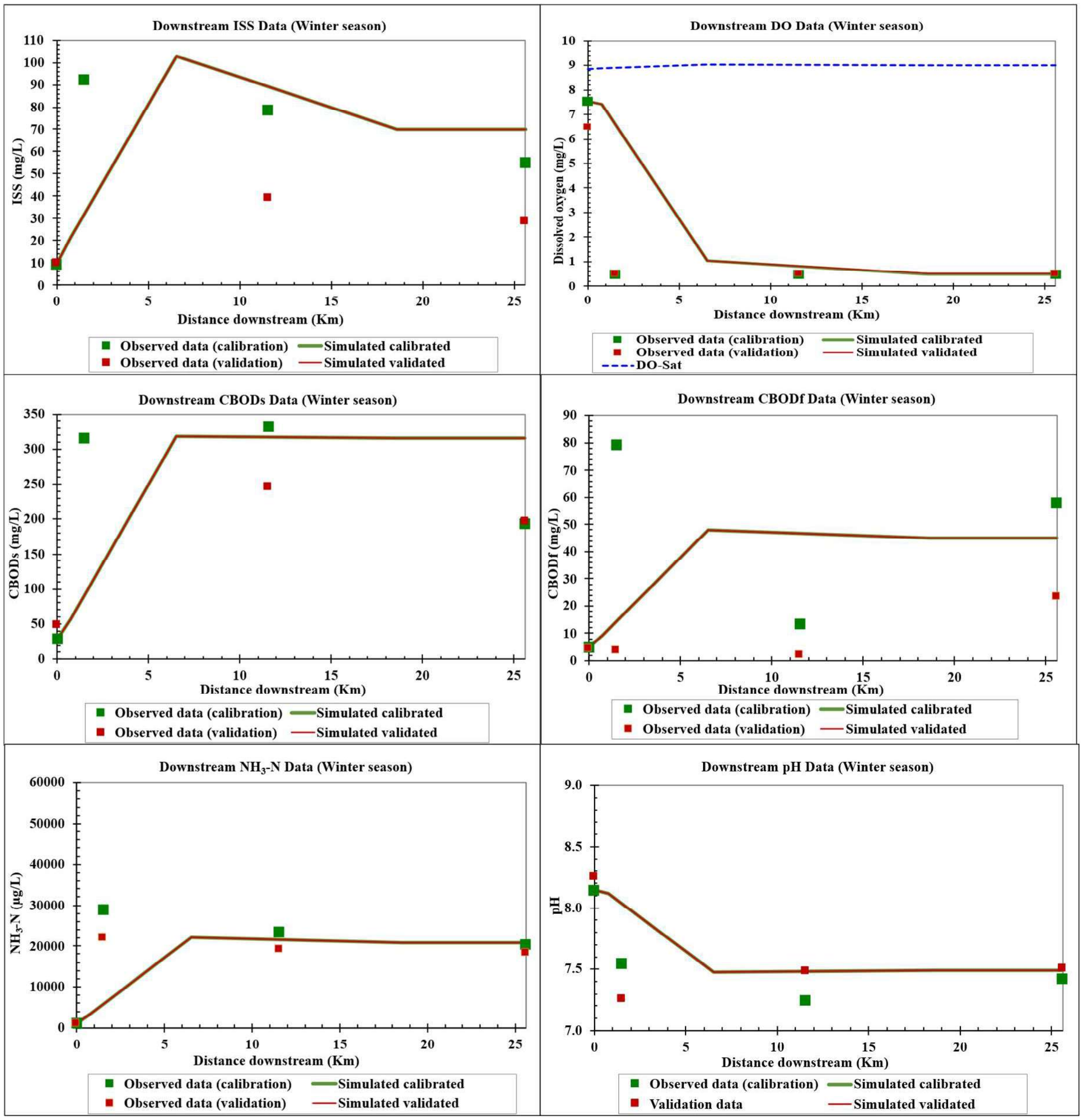
The model for the downstream stretch was simulated for the minimum calculated flow of 236 m^3/s. Hence, the simulated data for winter and pre-monsoon season showed a similar trend for water quality parameters, following the same system hydraulics as shown in Graphs 3 and 4. The simulated data of the calibrated model shows a sudden increase in ISS, CBODs, CBODf and NH3-N concentrations downstream of the Headwater up to 6.5 km, indicating the high pollution load input within the stretch. The trendline 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 NH3-N follow only a slight decreasing trend from 6.5 to 25.6 km. ISS concentration increases from headwater concentration 9.4 mg/L to 102.88

mg/L at 6.5 km, decreasing to 69.97 mg/L and remaining 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.

While 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. NH3-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.

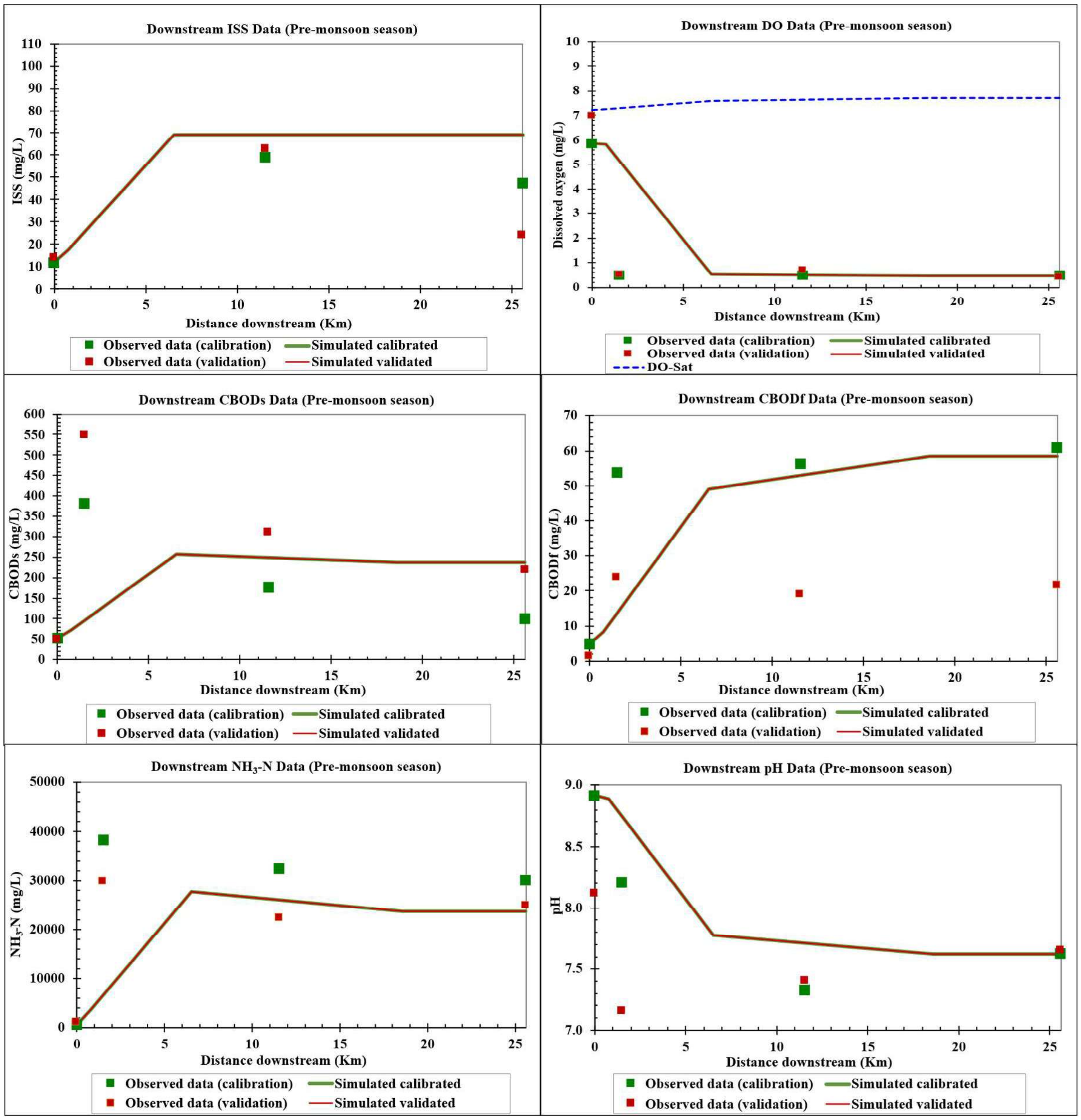
Significant differences in RMSE values were observed between the calibration and validation stages, reflecting the influence of point source loading on the river's water quality, as shown in Tables 12 and 13. Such variability was expected as the downstream stretch is affected by heavy point source discharges 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.



Graph 3 Model output for downstream stretch (winter season)

Table 12 Model fitness and RMSE values for the downstream stretch (winter season)

Parameters	ISS	DO	CBODs	CBODf	NH3-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**



Graph 4 Model output for downstream stretch (pre-monsoon season)

Table 13 Model fitness and RMSE values for the downstream stretch (pre-monsoon season)

Parameters	ISS	DO	CBODs	CBODf	NH3-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

15.2 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. 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 by considering three criteria: 1.) Reduction in pollution load, 2.) Increase in River inflow and 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 14 and 15 show the summarized results of scenario analysis run for the downstream stretch winter and pre-monsoon seasons, respectively.

Downstream (winter):

- 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.
- Even by reducing the current pollution load by 50% and increasing the river inflow by 70% i.e. 401.08 m^3/s, the DO of the river increases to 2.4 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.

Downstream (Pre-monsoon):

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

Table 14 Summarized results of scenario analysis for the downstream stretch for (winter season)

		Sr. No.	Scenario	Flow in river, m^3/s	ISS mg/L	DO mg/L	CBODs mg/L	CBODf mg/L	NH3-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	1.2	50% reduction	235.93	37.20	1.22	170.11	23.97	9803.16	7.51
SC2	River inflow modifications	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
SC4	Pollution load and river inflow modifications	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
SC5	Wastewater flow and pollution load modifications	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	6.4	50% reduction in wastewater flow, 50% reduction in pollution load and 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 15 summarized results of scenario analysis for the 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	NH3-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	1.2	50% reduction	235.93	40.15	1.31	138.92	30.85	9340.16	9.34
SC2	River inflow modifications	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	3.3	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
SC4	Pollution load and river inflow modifications	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
SC5	Wastewater flow and pollution load modifications	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

		Sr. No.	Scenario	Flow in river, m^3/s	ISS mg/L	DO mg/L	CBODs mg/L	CBODf mg/L	NH3-N ug/L	pH
SC6	River inflow, Wastewater flow and pollution load modifications	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

16.0 Achievements with respect to objectives

- The detailed literature review helped define the study area, select stretches of the Sabarmati River, establish the methods, choose a water quality model, and frame the study's methodology.
- The multivariate statistical analysis revealed critical locations of the river and significant parameters affecting water quality variations as defined in the second objective. The analysis was further followed by water quality simulations.
- The river water quality modeling, defined in the last objective, was successfully implemented by QUAL2Kw. The scenario analysis identified various water quality management scenarios to restore and improve the health of the river.

The study's findings thoroughly fulfilled the objectives and outcome with a river water quality management framework, which can be replicated for similar studies focusing on river health management.

17.0 Conclusions

The study revealed the importance of multivariate statistical techniques in assessing river water quality and identifying the primary pollutant sources affecting it. From the review of various water quality models, the QUAL2Kw model was found to be the best fit to meet the objective of the study.

Multivariate statistical analysis:

- ANOVA analysis indicated a significant variation in all water quality parameters ($p<0.05$) except for temperature among the sampling sites. Temperature, colour, NH3N, Chloride, and Nitrate were found to correlate with the seasons ($p<0.05$), highlighting the impact of seasonal phenomena.

- Box and whisker plots reveal that water quality deteriorates with increasing distance downstream. It showed the highest chemical pollution in the downstream stretch, largely due to wastewater discharges.
- Pre-monsoon and winter seasons were found to be critical due to higher chemical loads.
- Hierarchical cluster analysis grouped the 11 sites into three clusters based on similar characteristics: less polluted sites (LP) with minimal anthropogenic influence, moderately polluted sites (MP) affected by recreational and anthropogenic activities, and highly polluted sites (HP) burdened by external pollution loads.
- PCA analysis revealed that 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, while other chemical parameters (pH, NH3-N) were significant for MP and HP sites.

Water quality simulation by QUAL2Kw modeling:

QUAL2Kw was found effective in simulating the water quality of the Sabarmati river of the selected stretches for the varying conditions. The auto-calibration of the model help achieve best fit of the model. The calibrated model was found in good conformity with the validated model. The scenario analysis depicts the following conclusion to maintain the carrying capacity and health of the river and to further improve the water quality for the intended best use.

Middle stream:

- For winter, a minimum flow of 10 m^3/s is required to maintain class B water quality outdoor bathing criteria with the existing pollution load. An increase in the headwater flow by 50% or a reduction in the existing pollution load by 20% improved the water quality to class A criteria.
- For Pre-monsoon, a minimum flow of 13.11 m^3/s is required to maintain water quality within class B criteria for the existing pollution load. An increase in headwater flow by 50% or a reduction in the existing pollution load by 20% improved the water quality but still remained within class B criteria.

Downstream:

- For winter, the standard discharge limits for CBODs and CBODf can be met with a river inflow of 235.93 m^3/s, and with a 50% reduction in the existing pollution load, but the DO remained around 1.0 mg/L. DO value above 4.0 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.

- For pre-monsoon, the standard discharge limits for CBODf can be met either with a river inflow of 235.93 m^3/s and with a 50% pollution load reduction or with a river inflow of 353.90 m^3/s m^3/s and with a 30% pollution load reduction, but the DO remained around 1.3 mg/L. DO value above 4.0 mg/L can be achieved by reducing the current wastewater flow and pollution load by 50% and increasing the river inflow by 50% i.e. 377.50 m^3/s.

18.0 Proposed water quality modelling framework for river health

From the study, the framework shown in Figure 7 has been proposed for water quality modelling to ascertain the river health. The proposed framework can also be utilized for the other study for assessing and maintaining the river's health.

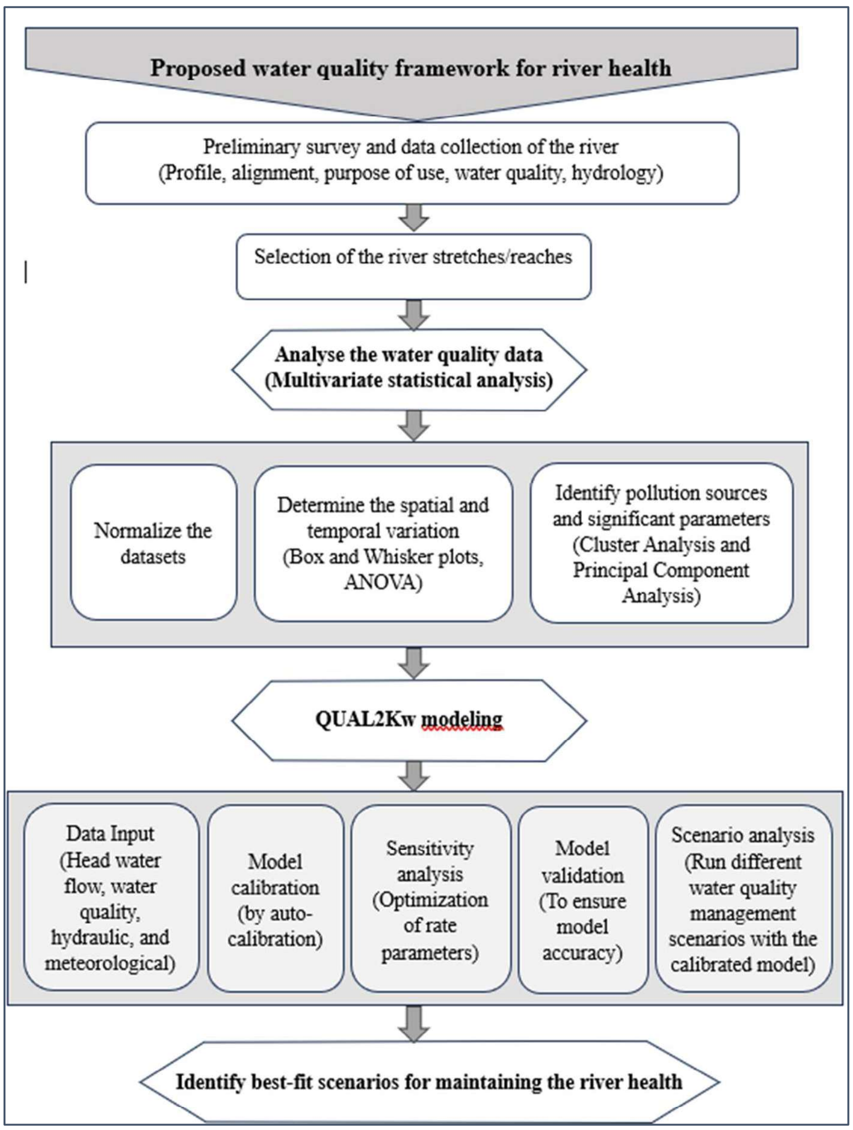


Figure 7 Proposed water quality modelling framework for river health

19.0 List of publications arising from the thesis

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
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20.0 References

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