Integration of Surface River Water Quality Model Using QUAL2K, Water Quality Index, and GIS For Evaluating River Water Quality of Bhadra River System, India.

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by

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CERTIFICATE

It is certified that the work contained in this thesis, titled " Integration of Surface River Water Quality Model Using QUAL2K, Water Quality Index and GIS For Evaluating River Water Quality of Bhadra River System, India." by Himanshi Singh, has been carried out under my supervision and is not submitted elsewhere for a degree.

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Dedicated to

My Beloved Parents

Mr. Ram Ratan and Mrs. Mithlesh Singh

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Abstract

River water quality is a vital component of the ecosystem which is the main source for drinking, irrigation and more. In recent years, increasing urban growth and expansion have resulted in structural deterioration and functional degradation of river systems, resulting in significant volumes of harmful contaminants being discharged into the water. River pollution substantially impedes long-term economic and social growth and endangers human health. In order to enhance the water environment, it is essential to examine the reasons for water quality deterioration. River water quality modeling is the finest way to assess and monitor water quality. River water quality models are mathematical models that simulate the behavior of pollutants in surface water bodies used to predict the concentration of pollutants in the water and assess the overall river water quality. QUAL2K is a widely-used water quality model that can simulate water quality parameters, such as Dissolved Oxygen (DO), nutrients, and pH, in streams and rivers. However, simulation of many water quality parameters through water quality model does not assess the status and overall pollution extent of any river system. Single river water quality index is required for evaluation of overall pollution extent and to adopt necessary water quality control measures. Therefore, a holistic approach which can integrate river water quality simulation model and pollution extent characterization model is necessary. Thus, this study aims to develop an integrated, holistic model approach to estimate the pollution extent in terms of river water quality index utilizing various river water quality model parameters. Furthermore, the study aimed to analyze the spatial variability of river pollution extent using Geographic Information System.

In this present study, the river water quality model, QUAL2K, is used to assess the quality of Bhadra river stretch, one of the major tributaries of the Tunga-Bhadra River situated in Karnataka. The study stretch considered is around 27 km which is divided into three reaches with elements of 1km as 3,4,20 for each reach respectively. In this current study, we analysed the effects of wastewater discharge from the monitoring stations such as the Mysore Paper Mill (MPM), the Visveshvarya Industrial Steel Limited (VISL), and the Bhadravathi city to simulate the Dissolved Oxygen by varying the Biochemical Oxygen Demand (BOD) loads (25%, 50%,70%,100%) coming from different pollutant sources within the study stretch. The observed water quality parameter data from 2006 to 2017 for those monitoring stations has been obtained from Advanced Centre for Integrated Water Resource (ACIWR). The water quality parameters like flow rate and pollution point sources discharge are the highly sensitive water quality parameters for modelling the QUAL2K model. There must be a reduction of 25% of BOD effluent to reach the minimum standards set by the Central Pollution Control Board (CPCB). It is noted that a 75% reduction of BOD effluent from point sources will lead to an increase of 15% average DO throughout the study stretch.

The weighted Average Water Quality Index (WAWQI) method is used in estimating Water Quality Index (WQI) by using QUAL2K simulation results for the study stretch. QUAL2K model was calibrated from April 2006 to October 2013 and validated from November 2013 to March 2017. The estimated WQI values range from 92.35 to 112, indicating the quality classification ranges from very poor to unfit for consumption for the Bhadra river. It was observed that the quality status of Bhadra river water was very poor in upstream and downstream segments, while unfit for consumption in the middle segment indicating access to industrial and anthropogenic activities. For spatial analysis, Arc-Geographical Informal System (GIS) software and Inverse Distance Weighted (IDW) interpolation technique is used to generate water quality parameters concentration level and WQI maps. In context to this, it was found that the middle segment of Bhadra study stretch falls into the category of unfit for consumption due to the combination of effluents from industries like MPM and VISL and domestic effluents from Bhadravathi city. Overall, this study revealed that the MPM water quality station was a hotspot for river water quality degradation. Based on all these analyses, we provide a framework for the integration of the three components, i.e., QUAL2K calibration, WQI and spatial visualization for water quality management and policymakers to take decisions about water quality management in Bhadra river stretch .

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Abbreviation	Meaning
BOD	Biological Oxygen Demand
DO	Dissolved Oxygen
TDS	Total Dissolved Solids
TSS	Total Suspended Solids
CBOD	Carbonaceous Biochemical Oxygen Demand
NSE	Normalized Summation of the Excursions
QUAL2K	River Water Quality model
Ec	Electrical Conductivity
WHO	World Health Organisation
GIS	Geographical Information System
1D	One Dimensional
IDW	Inverse Distance Weightage
WQI	Water Quality Index
WA-WQI	Weighted Average Water Quality Index
WQM	Water Quality Models
SPI	Synthetic pollution index
MPM	Mysore Paper Mill
VISL	Visveshvarya Industrial Steel Limited
CPCB	Central Pollution Control Board

Chapter 1
Introduction

1.1 Background

Water quality is a crucial component of environmental health that affects both human and aquatic ecosystem health [1]. Rivers are essential suppliers of freshwater, and the quality of their water has substantial effects on the ecosystem and public health. River water quality can be influenced by various variables, including human activity, climate change, and natural processes. Monitoring and evaluating river water quality is essential for recognizing and mitigating perceived risks to human health and the environment. River water quality monitoring necessitates multifaceted techniques that involve identifying the origins and channels of contamination, reviewing and interpreting water quality data, and assessing possible threats to human health and aquatic ecosystems. Water quality simulation models and water quality index systems can be used to assess river water quality, identifying pollution trends over time and providing significant insights for developing successful river water quality management strategies.

1.2 Motivation

Rivers are a vital source of freshwater, and their health is essential for maintaining the quality of the precious resource. Maintaining river health is crucial for ecological equilibrium. A healthy river system may help to filter pollutants and toxins, making the water safe for humans, animals, and vegetation. In the modern era of urbanization, industrialization, and human activities, rivers globally have suffered unprecedented pollution and degradation. As a result, developing strategies for the integrated management of watersheds is essential to the oversight of water supply and the maintenance of river ecosystems by combining water quality simulation models, water quality index evaluation with GIS techniques. In order to understand the water quality of the river system, the present study integrates the water quality simulation tool with the water quality index to evaluate the overall current status of the river system. The proposed approach of river water quality management can provide guidelines for decision-making processes for improving water quality and conserving river ecosystems.

1.3 Introduction

Surface water quality is a vital component of our environment that not only affects aquatic life but also human health and well-being [2]. Hence, recognizing changes in water quality is one of the primary obstacles to the efficient utilization of water resources. As the quality of surface water has declined over the past few decades, a substantial decline has been noted [3]. It is due to the fact that surface water is prone to pollution from natural as well as human generated wastes, such as industrial effluents, household waste, and run-off from agricultural practices, which have resulted in a host of environmental disasters. Population growth and rapid industrialization have resulted in the generation of an uncontrollable amount of waste that is indirectly received by the rivers downstream and has caused both immediate and long-term damage to the water supply, which is essential for human survival.

One of the main causes of water-borne diseases in India is the constant dumping of untreated sewage from towns and villages into river water bodies. According to the data estimated by the World Health Organization (WHO) that about 80% of water pollution in developing countries is caused by domestic waste, most of which consists of biodegradable substances that affect the dissolved oxygen concentration and serve as a major indicator of polluted surface water [4, 5]. Due to the severe consequences of water contamination, immediate action is required to properly manage the polluted segment of the river.

River water quality refers to the suitability of water for various purposes based on its physical, chemical, and biological attributes [6]. Understanding and measuring water quality is essential as it directly impacts human consumption and health, industrial and domestic use, and the natural environment and aid in the development of effective river water quality management strategies to protect the river ecological stability.

1.3.1 River Water Quality Modeling

River water quality modeling simulates the behavior of contaminants and other water quality parameters in a river system using mathematical and computer models. The models mimic the rivers distribution and fate of contaminants using inputs including flow rates, climatic parameters, pollutant loadings, and other water quality parameters. An illustrated model of water quality is composed of a collection of formulations, each of which is meant to depict one of the physical processes that determine the location and movement of contaminants within the water body.

Mathematical water quality modeling is widely regarded as one of the most effective methods for estimating the current pollutant load, pollutant transfer, and emerging cause-effect relationships between various sources of pollution and water quality. Modeling water quality provides decision-makers and policymakers with the capacity to choose a very accurate strategy for managing water quality from among a multitude of viable possibilities. It is vital to have the models to discover more effective techniques for resolving challenges of sustainable water quality over the long run. The physical, chemical and biological properties of water have been used in assessments and models of water quality. Water system managers must understand the primary causes and processes that impact each local water resources water quality to make superior management decisions. Hence, practical knowledge gained through water quality modeling is essential for comprehending how the environment and water systems are contaminated and adopting valuable decisions and directions.

Water quality deterioration has become a pressing environmental issue over the past decades and can be resolved using river water quality models such as QUAL2K, AQUATOX, QUAL2E, WASP, CE-QUAL-W2, MIKE11, SWAT, and SIMCAT. River water quality models are important tools to assess water quality, understand pollutant transport, identify pollution sources, and estimate environmental impacts.

Stream water quality models can be categorized according to a variety of aspects, including model type, degree of detail and complexity, and intended application [7]. Some of the popular approaches to categorizing models of stream water quality are:

Empirical models are based on statistical relations between water quality parameters and environmental characteristics. These models utilize historical data to establish links between various water quality parameters and ecological conditions such as temperature, pH and DO levels. On the other hand, mechanistic models are based on fundamental laws of water quality, such as mass balance and reaction kinetics. These models integrate mathematical equations to describe the physical, chemical, and biological processes that regulate water quality.

Another factor to consider when categorizing stream water quality models is their level of complexity. Water quality is assumed to alter mainly along the length of the stream channel in 1D models. Variations in the cross-sectional shape of the stream channel are taken into consideration in 2D models. 3D models take into account the entire three-dimensional geometry of the stream channel.

In steady-state models, water quality parameters are assumed to remain constant across time. These models are useful for analyzing long-term water quality trends. In general, dynamic models simulate water quality changes over time. These models are useful for forecasting short-term changes in water quality resulting from variations in flow rates or pollutants loads

Process-based models mimic the physical, chemical, and biological processes that impact water quality. In contrast, statistical models forecast water quality based on historical data using regression analysis or other statistical methods. Although process-based models are more accurate, they require more information, whereas statistical models are simpler and require less information.

Depending on the study objectives for water quality assessment, QUAL2K model has been utilized to simulate the river water quality. QUAL2K is a dynamic, one-dimensional model that evaluates the water quality within a river system by simulating the movement and conversion of contaminants throughout the river length. The model comprises numerous physical, chemical, and biological processes, including as hydrodynamics, sediment transport, oxygen balance, the nutrient cycle, and pollutant fate and transit. The model can simulate several water quality attributes, such as dissolved oxygen, nutrients, organic matter, and many other contaminants. The model can be modified to incorporate the distinct characteristics of a particular river or stream. It can be used to quantify the efficacy of various pollution prevention and control techniques on water quality. Compared to other available water quality models, it is quite evident that QUAL2K is a reliable model as its user-friendly and intuitive interface makes it simple to input data, run simulations, and interpret results. The model provides accurate predictions of water quality parameters under different conditions. It can also be used to model various scenarios, from simple and direct point-source pollution to complex watershed-scale concerns. The QUAL2K model evaluates the effectiveness of different management strategies and identifies the most cost-effective solution.

While QUAL2K modeling has many advantages, it also presents a number of difficulties. QUAL2K does not account for spatial variability or the interaction of streams and rivers within a watershed. Furthermore, QUAL2K is essentially a steady-state model that assumes stable water quality conditions across time. This may not be accurate in dynamic, changing systems. QUAL2K is intended to simulate water quality parameters and does not consider the ecological or biological consequences of water quality changes. Also, model findings are always subject to some degree of uncertainty, mainly when the input data is incomplete or inaccurate.

Models can also be categorized according to their intended use, such as monitoring water quality, management, and prediction. For instance, water quality assessment models identify the causes of water quality challenges, whereas management models are used to analyze the effectiveness of various management strategies. The application of these models can provide a reliable means of predicting river water quality [8].

1.3.2 Estimation of Water Quality Index

One of the most pressing problems facing many countries is the degradation of surface water resources due to anthropogenic activities and the atmospheric deposition of pollutants [9, 10]. The river water quality is deteriorating primarily as a result of natural processes and as a consequence of human activities such as the release of industrial effluent, domestic wastewater, and agricultural drainage water into the river [11]. However, industrial effluent, residential sewage, and agricultural runoff water are the main pollutants contributing to river contamination [12, 13]. River water is the primary source of fresh water for humans to use for various purposes. It is prudent to safeguard and regulate rivers against pollution and have accurate water quality data for successful management. To prevent the degradation of the river water, it is essential to examine and assess its quality regularly [14]. Water quality evaluation includes collecting, processing, and interpreting massive amounts of data [15].

The Water Quality Index (WQI) is a simple approach to quantifying overall water quality that utilizes range of variables to convert large quantities of data into a single value, generally dimensionless, in a simple, reproducible manner [16]. It provides crucial information outlining the state of the overall water quality, which may be immensely helpful in selecting the appropriate water-treatment strategy for dealing with pollution challenges.

The water quality index is divided into four major categories [17]. First category is Public indices which do not consider the type of water consumption when evaluating water quality and are utilized for general water quality, for example National Sanitation Foundation Water Quality Index (NSFWQI) [18]. Second is Specific consumption indices which are dependent on the kind and application of consumption (drinking, industrial, etc.) for example Oregon and British Columbia Water Quality Index [19, 20]. Third is Designing or planning indices which is a tool to enhance decision making and planning in water quality control projects. And the fourth is Statistical indices which are employed to assess data and validate assumptions. Since different panels of experts assign different weights to the same variables, the expert opinion technique is subjective. Statistical methods may also be used to determine essential criteria in assessing the quality of a water body, as well as the level to which they are significant [21].

The Water Quality Index (WQI) is a valuable indicator for assessing water quality that can be acknowledged by both water resource supervisors and the general community. WQI can be utilized for the detection and prioritization of water quality problems and the evaluation of the efficiency of water management and pollution prevention strategies. In addition, the WQI can be utilized to support decisions regarding managing water resources, such as resource allocation for water treatment and pollution prevention.

1.4 Problem definition

The Bhadra River is an important water body, serving as a source for irrigation and drinking water for a significant portion of the population in the region. However, like many other rivers in the country, the Bhadra River is facing a range of water quality issues that threaten its ecological and human health values. The degradation of water quality is primarily due to anthropogenic activities such as untreated domestic and industrial wastewater discharge, agricultural runoff, and deforestation. As a result, the river has been subjected to high levels of pollution, including elevated concentrations of nutrients, heavy metals, and organic matter. In recent years, there has been a growing concern over the deteriorating water quality in the river and the need for effective measures to mitigate the pollution. The majority of research analyses and estimates water quality by employing water quality models and water quality index independently. However, using such a water quality index method to analyse the water quality was insufficient to depict the overall status of the river. The majority of researchers focused exclusively on data obtained from accessible water quality stations rather than considering the entire river stretch with limited parameters of water quality[22, 23]. Several studies have been conducted on the spatial distribution of individual parameters of water quality without using simulation results obtained from any water quality models [24, 25]. Water quality index maps were generated using GIS to interpolate the river classification and produce individual parameters. However, a more robust approach, such as an integrated methodology for reducing pollution through simulation tools, has received less attention by the researchers [26, 27]. The main objective of the study is to integrate the three components, QUAL2K simulation, WQI calculation, and spatial visualization, to simulate river water quality. The integrated approach proposed will be useful for the policymakers and stakeholders with valuable information regarding river water quality management and will enable them to make informed decisions regarding water resource management. Furthermore, integration of river water quality simulation models to simulate water quality parameters, evaluation of pollution extent in terms of water quality index and visualization of pollution maps using GIS technology has not been much explored in the literature.

Hence a holistic approach is required to evaluate the surface water quality using water quality simulating tools, pollution index tools and GIS visualisation techniques. QUAL2K is one of the water quality models that help to simulate the river water quality characteristics and analyse the health of the entire river or selected stretch. A key objective of the present study is to provide a comprehensive spatial and temporal analysis of water quality indexes, categorize them, and generate pollution index maps using integrated QUAL2K-GIS for the Bhadra river, based on simulation outputs from QUAL2K simulations. In the current study, due to simplicity and popularity among researchers, the Weighted Average Water quality index method was adopted to estimate the Water quality index using the simulation results from QUAL2K and to represent the spatial distributions of water quality indicators and index maps using Inverse Distance Weighted (IDW) interpolation techniques using ArcGIS program.

1.5 Thesis Organization

This thesis is organized into six chapters:

- Chapter 1 provides an introduction to the water quality modelling problem definition, motivation for examining the extent of river pollution and objectives of the study.
- Chapter 2 summarizes a detailed literature overview of the various studies related to water quality modelling and water quality index methods to assess surface water quality.
- Chapter 3 delivers an overview of the case study and the datasets utilized in the analysis of river water quality
- Chapter 4 presents the application of the QUAL2K model for water quality modelling of the Bhadra river stretch, India.

- Chapter 5 presents the assessment of river water quality using the QUAL2K model and water quality index using GIS techniques for the Bhadra river.
- Chapter 6 presents an overview of the thesis work, findings, and potential future research expansions.

Chapter 2
Literature Review

This chapter examined the prior studies conducted on river bodies to study river water quality. In addition, studies on river water quality models available for simulating water quality parameters are provided. In the next section, we addressed the studies on the water quality index used to evaluate river water quality. A summary of an integrated approaches of water quality models and water quality indices with GIS mapping developed for a better knowledge of the current water quality status are also discussed. Later a description of the research gaps between previous studies and the proposed research objectives of the thesis are presented. The integrated approach of river water quality simulation and water quality index modelling approach proposed in the present study can be used to bridge the gaps in existing models, and it also has the potential for improvement in water quality management.

2.1 Introduction

All human activities rely heavily on the freshwater that is supplied by rivers [28]. Rivers are unpolluted at their source, but as water flows downstream, the river encounters point and non-point pollution sources, resulting in detrimental effects on river water quality. Water resource deterioration has raised the necessity of establishing the ambient condition of water quality to indicate changes caused by human activity. Because of urbanization, increasing industrial activity, intensive farming, and the abuse of fertilizers in agricultural operations, the discharge of untreated wastewater and sewage outlets, surface water resources are being contaminated. Water quality gives information on the concentrations of several physical, chemical, and biological parameters at a certain time and location. Continuous monitoring of river water quality is crucial for identifying the status of river pollution. Evaluating river water quality is integral to managing and maintaining the riverine health system over the long term. This study uses the integration of the water quality model QUAL2K and the water quality index to measure the water quality in the Bhadra River stretch and utilizes an interpolation approach for producing water quality spatial distribution maps.

2.2 Surface Water Quality Models

Streams are important to ecology because they give people water to drink and give aquatic species a place to live. Organic and inorganic pollutants are dumped into waterways in vast amounts by farming, building cities, and making factories. As a result, there is an imbalance in the high-quality water required by ecosystems to function properly [29, 30]. There have been a number of cases where unconservative pollutants that may pose a threat to various water bodies have been discharged, which can be classified as conservative or non-conservative based on the nature of the pollutants. Because of the increased concentration of these numerous contaminants entering the water bodies, making the streams free of all pollutants is critical.

According to [31, 32], Increasing levels of nutrient pollution entering water bodies have resulted in a sluggish process of eutrophication, causing algae to grow and, as a consequence, a decrease in the concentration of dissolved oxygen (DO). Stream water pollution has been one of the most critical environmental problems. The quality of freshwater has been severely damaged, and the number of aquatic organisms in bodies of water has decreased due to the drop in DO content in the water column [7, 33]. Because of the combined impacts of the diffusion and advection processes, streams serve as a transporter of contaminants that have been released and spread inside water bodies [34]. For the ecosystems integrity to be preserved and the number of pollutants dumped into streams to be minimized, an accurate evaluation of the DO and nutrients in the stream is necessary.

Monitoring and maintaining proper concentrations of nutrient essential for the existence of marine animals and humankind is vital for maintaining a healthy aquatic ecosystem. To anticipate contaminants in surface water, [35] demonstrated the value of developing water quality models. To simulate the evolution of contaminants within water columns and evaluate the hazards involved, decision-support systems called water quality models (WQM) are used [36, 37]. Pollutant estimation through monitoring is a challenging endeavor that necessitates the constant modification of current models and the establishment of an updated WQM for determining the quantitative transport of solutes. Streeter and Phelps (1925) study on water quality modeling was the first significant effort to simulate BOD and DO in the River system [7, 36, 38] WQM can be divided into the simulation model and optimization model categories [35, 36]

Basically, a simulation model is a mathematical representation of all possible deviations in water quality that can be mathematically predicted. It comprises all categories of deterministic mechanistic models. It is common practice to identify the least amount of alternative data prior to implementing a simulation model by using optimization models. Additionally, optimization models are typically utilized to locate the minimum possible alternative data before executing the simulation model. Also, simple models are preferable to complex ones when modeling the transport of solutes in water bodies, as the latter is more challenging to implement. The input data quantity and quality define the model complexity level to be utilized in simulating water quality parameters.

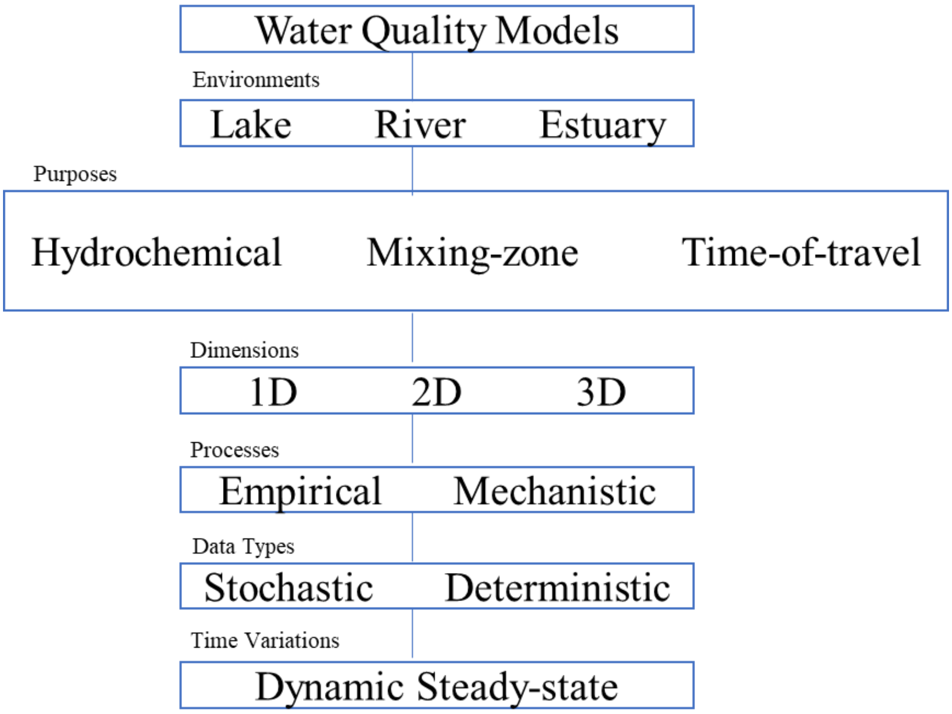

Figure 1. Commonly used water-quality model subdivisions (Cox, 2003)

Water quality modeling is regarded as a component of supporting water quality management choices, evaluating the efficiency of measures in restricting pollution sources for a defined use, and assessing the needs for satisfying water quality standards [39] as shown in Figure 2 . This modeling tool facilitates the assessment of multiple scenarios for a variety of management activities, thus improving water quality and water body management by evaluating the impacts of hydrological processes on water quality [40].

Many WQMs have been created due to continual progress and the necessity to examine specific water quality issues more scientifically. A wide range of WQMs are currently available based on the data availability and type of waterbody to be treated (e.g., Lake, Estuary, River). The assimilative capacity of the river system, which is determined by the degree of pollution and the self-cleaning capability of the river, serves as a foundation for each of the models. An understanding of the models application necessitates a comprehensive overview of the modeling procedures, factors influencing water quality, and significant parameters that impact water quality in a significant way. An appropriate model can be determined according to a variety of factors including the type of data, the size, the inputs required, in addition to the complexity and limitations of the model itself. It is essential to consider all of the WQMs already in use before choosing a model to address a specific water quality issue.

Rapid advancements in mathematical modeling have resulted in the adoption of several models. Mathematical models have been used to evaluate changes in water quality caused by wastewater discharge requirements. AQUATOX, WASP (Water Quality Analysis Simulation Program) , CE-QUAl-W2 (Corps of Engineers-Quality-Width Averaged), MIKE11, SWAT (Soil Water and Analysis Tool), and SIMCAT (Simulation of Catchment) are the promising water quality models available for evaluating surface water quality. [41] utilized the AQUATOX model to forecast the effect of eutrophication in the Braden River reservoir in Bradenton, Florida. It was depicted that a high proportion of nutrients in the water body was degrading the river quality. There is a limitation to these models as they are not capable of modeling metals, and they cannot be merged with hydrodynamic models. Moreover, there is no representation of the internal nutrients within algal bioenergetics. Additionally, that model assumes a unit volume of water in order to make the simulation of the changes in the concentrations of nutrients, chemicals, and sediments in the water body possible [42].

For qualitative analysis and assessments, the QUAL2E methodology based on USEPA (United States Environmental Protection Agency) is widely employed. QUAL2E model is the latest version of QUAL series. This model is one dimensional steady state model which can simulate DO and around 15 water quality parameters along the river and its tributaries. Paliwal and Sharma, (2008) explores the impact of discharge from various point loads on the river Yamuna for the period of low flow in Delhi, India, by using QUAL2E.

QUAL2K models are updated versions of QUAL2E, in which most equations are identical with the exception of those for Dissolved Oxygen, Biochemical Oxygen Demand, and Nitrates, which have been improved. In comparison, the QUAL2K simulation model has the most mathematical complexity, and this model is based on an automated calibration method that utilizes updated equations. QUAL2K is an advanced water quality modeling software that is widely considered one of the most comprehensive and sophisticated models currently available. Through its advanced capabilities and ability to deliver accurate and reliable results, QUAL2K has become an essential tool for researchers as well as water resource managers around the globe. QUAL2K is a water quality modeling software that is widely used for simulating water quality in rivers, with advantages like comprehensive modeling capabilities, an easy-to-use interface, flexibility, accuracy, and community support. Overall, QUAL2K is a powerful tool for simulating water quality and can be used to inform water management decisions and policies. By using the QUAL2K model the Temperature, BOD, and EC parameters were simulated for the Dez River (in the southwest of Iran) by [44]. In order to model DO, BOD, nitrate-nitrogen, and ammonia-nitrogen over a crucial time and evaluate the results against the approved water quality classification, [45] used QUAL2K for the Lam Takhong River in Thailand.

According to [46] studied the crucial attributes for deriving a quality model for the river Bhavani in Tamil Nadu using the QUAL2K model based on limited datasets and spatial variations for inorganic suspended solids and CBOD. According to the study [47], a water quality model QUAL2K was applied to develop a BOD-DO model and evaluate river stretch for Ghataprabha near Mudhol town in Bagalkot district Karnataka . An assessment of the effectiveness of the water quality model QUAL2K has been conducted to evaluate the water quality of the polluted segment of the river Yamuna, Okhla to Wazirabad [48]. Similary the water quality assement has been evaluated using QUAL2K model in Tungabhadra basin [49–57].

QUAL2K is a water quality modeling software that is widely used for simulating water quality in rivers, with advantages like comprehensive modeling capabilities, an easy-to-use interface, flexibility, accuracy, and community support. Study focuses on assessing the deterioration of the DO values relative to other parameters at various portions of the Bhadra river. According to the results of the simulation of the calibrated and validated model, it was revealed the water quality standards were not met at the downstream segment, which exhibited water quality of the fourth class and the appropriate DO concentration. 2.0 mg/L and BOD value, 4.0 mg/L.

The QUAL2Kw is an updated version of the QUAL2k model and modified version of QUAL2E. The model is a one-dimensional steady state model, the simulations are carried out in dynamic mode in order to simulate water quality kinetics and heat budgets [58].The QUAL2Kw model and Arc GIS were used by [59] to determine the level of pollution produced by the Karang Mumus River at the various points of its course. Using QUAL2Kw, which can be applied to small watersheds, the present study evaluates the impacts of wastewater loadings on Yamuna river water quality [60].

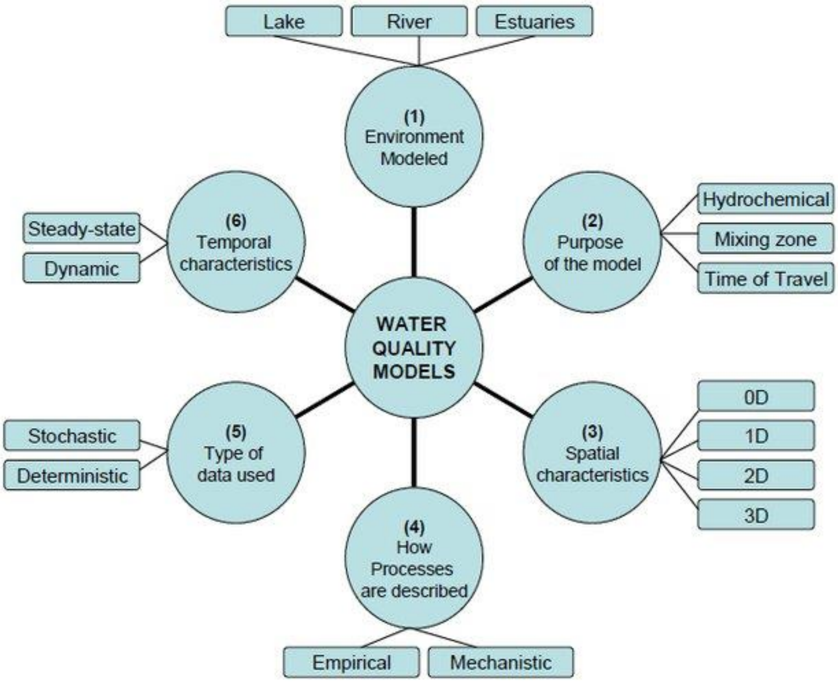

Figure 2. water quality model in common use [61]

In accordance with the literature, river classification was interpolated using GIS techniques in order to obtain individual parameters that can be used to create water quality maps. This method employed to analyze water quality using the simulation model was insufficient since the outcomes were given independently at each measuring or sampling locations. As a result, determining the overall river health is challenging. Most previous studies used integrated QUAL2K-GIS models to make individual water quality parameter maps, which may not be indicative of the broader health of the river system and its tributaries [62, 63]. Researchers have directed less interest to more reliable methods, such as integrated methodologies employing water quality modeling tools with a water quality index for assessing the surface water quality.

2.3 Water Quality Index Models

The water quality index (WQI) is a one of a kind rating that describes the overall water quality status in a single term and aids in the identification of appropriate treatment approaches to meet the respective concern standards [64]. In WQI models, data have been aggregationed through an amount of mathematical functions that enable the assessment of significant temporal and spatial variations within water quality datasets to generate a single value, that is the water quality index, which represents the quality of the water body [65]. A WQI typically consists of four steps [66]. Firstly, the required water quality parameters are identified. As a second step, water quality data is read and the concentrations for each parameter are converted into a single-value, dimensionless subindex that reflects the water quality of the water [16].

In the third step, each parameter that measures the water quality is given a weighting factor. Finally, an aggregation function uses every water quality parameter sub-indices and weighting factors to develop a single-value water quality index that summarizes the performance of all the parameters. [67]. Numerous WQI models have been introduced, each with its unique feature, set of included parameters and weightage, and ways of sub-indexing and aggregation [68, 69]. Many models are region-specific because most WQI model components were created based on professional opinions and local regulations [70].

Many researchers mention the uncertainty issues with WQI models [71]. Even while some degree of uncertainty is inherent in every mathematical model [72], the WQI four steps (Selection of parameters for water quality, generation of the parameter sub-indices, assignment of the parameter weight values and computation of the water quality index using an aggregation function) can each add to that uncertainty. Horton created the first WQI in 1965. [73] subsequently developed a WQI equivalent to the Hortons index in 1970. Brown WQI was renamed the National Sanitation Foundation Water Quality Index after obtaining support from the National Sanitation Foundation (NSFWQI). The NSF-WQI later became the foundation for various additional WQI models.

Numerous kinds of research are being conducted to assess water quality using different WQI models.[74] utilized the NSFWQI index in Mazandaran provinces encompassing three rivers (Siahrod River, Haraz River, and Babolrod River) with the conclusion that all the stations were under an unsuitable environment. The findings revealed that the worst conditions were found on the downstream side of the Siahrood River.

[75] conducted a critical evaluation of the NSFWQI use to determine how significantly the measure differs from its original form when users modify either the parameters (such as using orthophosphate instead of total phosphorous) or the units (using Fecal coliform (FC) based on the maximum probable number (FC-MPN) instead of the colony-forming unit (CPU)).[76] evaluated the water quality of the Al-Gjarraf river for drinking purposes using the Weighted

Average Water Quality Index. The results revealed that the water was unfit for consumption, demonstrating the total influence of environmental factors on surface water quality.

[77] analyze fourteen physicochemical parameters and the microbiological parameter of the Kaani and Kpean rivers using standard methods. These river water quality ratings will be determined by applying the results to the National Sanitation Foundation water quality index (NSF-WQI) and Weighted Arithmetic water quality index (WA-WQI). The Canadian Council of Ministers of the Environments (CCME-WQI) technique and discriminant analysis were used to assess the water quality. Using the CCME-WQI, the Coruh River Basins water quality was determined to be between 30.4 and 71.35, categorized as poor, marginal, and fair [78]. Water quality indices were compared to determine their ability to evaluate spatial and temporal variations in water quality in three Mediterranean intermittent rivers, the River Vène (France), the Oued Fez, and the River Sebou (Morocco). The CCME-WQI and BC-WQI indexes, which were developed for non-arid or semi-arid zones, provided appropriate water quality evaluations [79].

Al-Musawi (2018) uses the Bhargava method used to assess the water quality index for irrigation and drinking purposes. According to the findings, the water quality of the Diyala river was ideal for irrigation and safe for drinking at its beginning but poor for drinking and extensively contaminated in its middle. At the third location, the river water quality was adequate for irrigation but extremely polluted and unsafe for drinking [80]. The WA-WQI approach was extensively selected by multiple scientists among the various methods available for the estimation of WQI [42, 81–83, 83] which has been explained in chapter 5 section . For better visualization and analysis of the pollution extent, GIS techniques are used for the spatial distribution of water quality parameters in their respective area, thereby assisting water resource managers. Water Quality index (WQI) and Synthetic pollution index (SPI) are applied to the eastern stretch of the Ganga to assess water quality, which is integrated with GIS to illustrate the pollution status [84]. In order to attain acceptable water resource management and water quality, in accordance with the requirements of the framework for water management and other legislation related to water quality, the model outputs obtained from the water quality modeling, and water quality index are essential to integrate to create a valuable discussion and decision-making process.

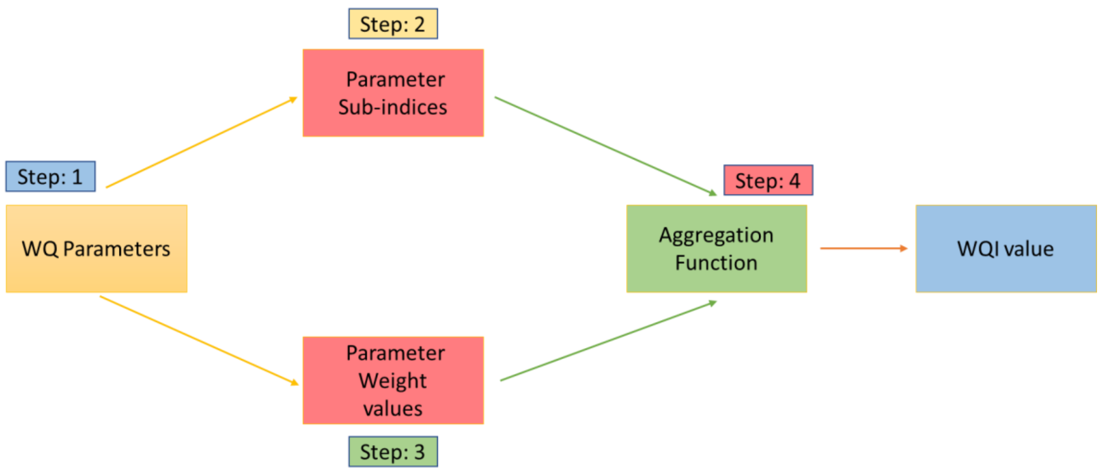

Figure 3. The overall framework of the Water Quality Index model (Uddin et al., 2021

2.4 Integrating Water Quality Models and Index with GIS mapping

Rivers, being an intrinsic part of the ecosystem, play an important role in maintaining the social economies continued and healthy expansion [2]. In recent years, increasing urban growth and expansion have resulted in structural deterioration and functional degradation of river systems, resulting in significant volumes of harmful contaminants being discharged into the water. River pollution substantially impedes long-term economic and social growth and endangers human health. In order to enhance the water environment, it is essential to examine the reasons for water quality deterioration and study the river water quality. Numerous studies have been carried out that concentrate on a specific kind of contaminant, such as untreated wastewater and industrial effluent [85], release from landfills, such as leachate [86], sediment [87], as well as effluent produced by sewage treatment plants [88].

Almost every researcher discusses particular pollutant concentrations in addition to their qualities, temporal patterns, and trends. In addition, spatial and temporal river water quality evaluations often require the collection of long-term, ascertainable data in order to identify trends or developments over a given time period. The majority of researchers employ statistical approaches to categorize rivers and identify key pollutants, such as multiple linear regression [87];[89] and multivariate statistical techniques [88] to classify the river.

The development of a more reliable strategy, incorporating an integrated system for the reduction of pollution by using technology to mimic water quality, has not garnered as much attention among researchers. There is relatively scarce research on river water quality evaluation utilizing the QUAL2K model [27, 90, 91] and the water quality parameters evaluated have been relatively constrained. For example, [91] focus only on three parameters: dissolved oxygen, biological oxygen demand, and ammonia. Despite the fact that these studies incorporate the QUAL2K model and GIS to map the spatial distribution of water quality, the inadequate water quality parameters may not effectively depict the status of the river. To assess the current status of the river water quality, water quality index is calculated using the simulation results of the water quality model, and the pollutants concentration is visualized using GIS software. The integration of water quality models and indices with GIS mapping offers unprecedented opportunities for analyzing water quality data spatially. This provides a more comprehensive understanding of water quality issues and the potential impacts of environmental factors.

2.5 Research Gap

Over the past few decades, water pollution has become a significant menace to natural and human ecosystems. As a result, monitoring changes in water quality is one of the most critical concerns for making the best use of water resources. Since distinct water quality models [92, 93] have been used for many years to analyze surface water quality at few selected check points with few water quality parameters. As a result, the water quality index was used to depict the river overall pollution condition. Most studies have used WQI estimates to classify river quality pollutant extent using minimal parameter data spatially.

Similarly, several researchers used GIS methods to visualize individual water quality parameters and water quality index (WQI) maps [62, 63, 94].

- However, earlier research has primarily focused on simulating the water quality model with constrained parameters for monitoring water quality at conveniently accessible stations.
- Previous rechargers concentrated on determining water quality indexes based on observable data rather than the entire river stretch using river water quality model simulations.
- Most studies concentrated on integrated mapping for only individual water quality parameters but did not investigated or evaluated the pollution extent with any numerical software or water quality simulation tool.

Overall, integration of river water quality simulation models to simulate water quality parameters, evaluation of pollution extent in terms of water quality index and visualization of pollution maps using GIS technology has not been much explored in the literature. Therefore, following objectives were defined in the present thesis, as follows:

2.6 Objective of the Thesis

This study aims to develop an integrated approach using river water quality simulation model to simulate water quality parameters, evaluation of pollution extent in terms of water quality index and visualization of pollution maps using GIS technologies. The study aimed to evaluate and analyze the surface water quality of the Bhadra River in terms of water quality parameters using river water quality models and GIS technologies.

- Developing river water quality simulation model QUAL2K to evaluate the surface water quality of Bhadra river stretch and assessing the model performance based on measured water quality data.
- Estimating river water quality index using the WA-WQI method by using QUAL2K simulations of river water quality parameters.
- Representing or mapping the WQI and water quality indicators using GIS visualization techniques.

Chapter 3
Study Area and Data

3.1 Introduction

This chapter gives a detailed description of the study area considered in the present study. A brief explanation about the input data, such as hydraulic, climatic data and river water quality parameters used to simulate water quality modeling for the Bhadra river, is provided. This chapter provides information on the data sources, the location of the study area, and the monitoring water quality stations used for assessing the water quality, which has deteriorated due to anthropogenic activities, and industrial and domestic effluents flowing into the river.

3.2 Study Area

The Bhadra River, which is located in Karnataka, India, presents as the case study for this research (Figure 4). The Bhadra is one of the tributaries of the Tunga-Bhadra which in turn is a significant tributary of the Krishna River. The Bhadra river is one of the most important rivers flowing through the Western Ghats, which is the primary source of drinking water in the districts of Chikkamagaluru and Hassan. The Bhadra river initially flows east, then changes direction to the north, and joins the Tunga River at Kundli latitude 75°40'32.61" E and longitude 13°59'43.75" N in Shimoga district.

The Bhadra is the third most important river in Karnataka after Kaveri and the Tunga-Bhadra. The river has a catchment area of about 4,000 km^2 and has an endless flow of about 3.5 million cubic meters per day. The river is highly seasonal in nature and flows during the monsoon season. The river is dammed to irrigate about 22,000 hectares of land and provide drinking water to millions of people. Bhadra Reservoir is constructed 50 kilometers upstream of Kundli, over the Bhadra River.

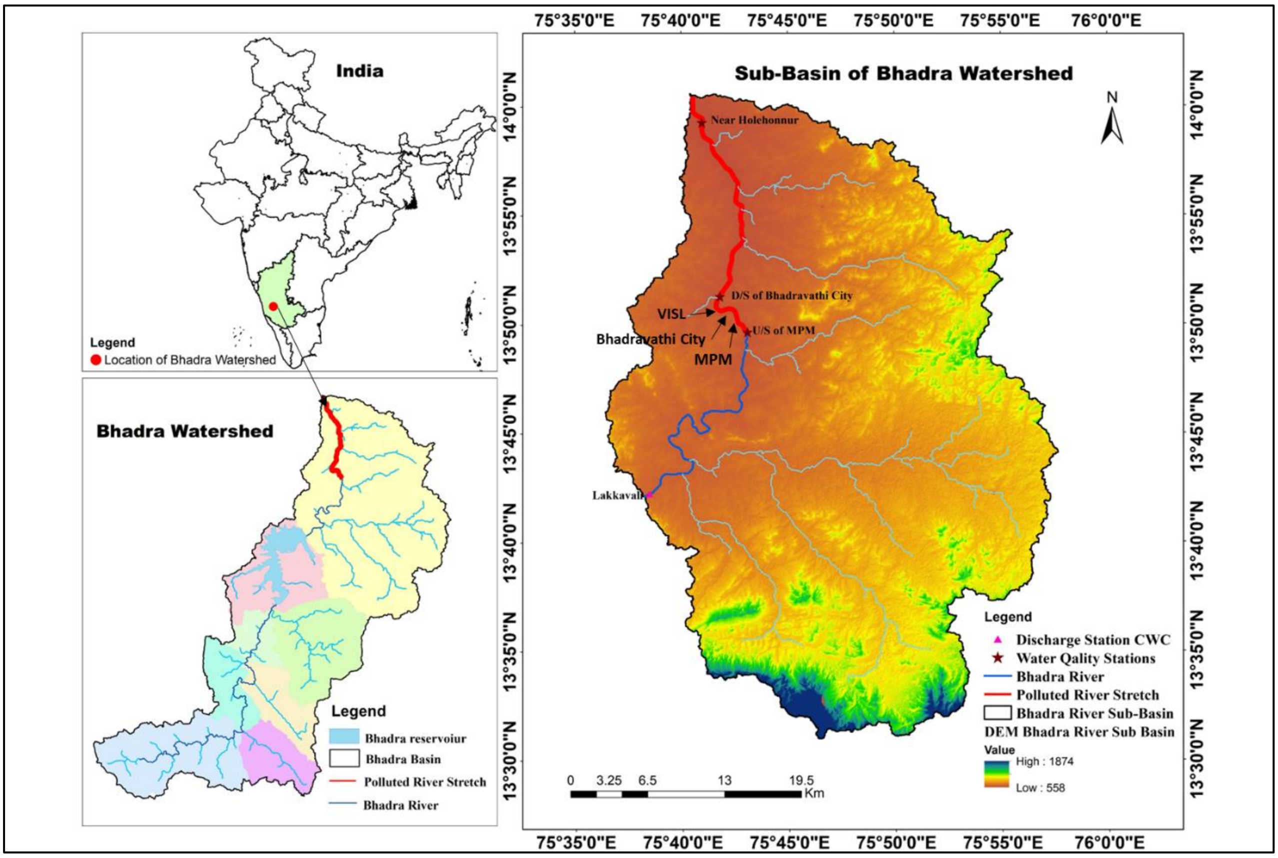

Figure 4. Study Area of Bhadra River Watershed

Bhadravathi City is traversed by the Bhadra river, where it is contaminated as a result of effluents from different industrial and household sources. Figure 1 shows the stretch of the river that was examined in the present research and its effluent drains. The Bhadra River receives untreated sewage and industrial effluents from viz. Mysore Paper Mill (MPM), Bhadravathi city, and Visveshvarya Industrial Steel Limited (VISL) [95] are located upstream and downstream, respectively.The following are the brief explanation about the three point sources :

1.Bhadravathi city-Bhadravathi is located at 75.42N latitude and 13.50E longitude. Bhadravathi is one of the most significant towns in Shivamogga District. Several points on the Bhadra River flow into it from the domestic effluents generated within the Bhadravati city limits. The paper and steel industries are the two largest industries scattered around Bhadravathi city and its surrounding areas.

2.MPM-Mysore Paper Mills Ltd (MPM) is located at latitude N-13.82760 and longitude E-075.70831. Mysore Paper Mills Ltd. is the only industry in the village for producing sugar and paper within the boundaries of Bhadravathi, and it has been in operation since 1903. MPM discharges a significant amount of treated trade effluent into the Bhadra River. The river is contaminated by domestic outfalls from the city.

3.VISL-Steel Authority of India, Visvesvaraya Iron and Steel Ltd (VISL), is located at the latitude and longitude of N-13.83788 and E-075.70084, respectively., The Visvesvaraya Iron and Steel Plant is the only primary industry located in Bhadravathi that manufactures mild steel and alloys.

The effluents from the MPM are characterized by high concentrations of pollutants, such as Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), Total Dissolved Solids (TDS), heavy metals, and color. Other than these drains, runoff from the surface from neighboring towns and farms is a non-point source that contaminates the 27-kilometer study stretch[96]. The Bhadra River stretch is identified as one of the most polluted rivers stretches of India by the Central Pollution Control Board (CPCB 2011). Therefore, there is a necessity to study the river water quality and mapping of contamination levels for Bhadra river under various municipal and industrial effluents.

3.3 Data Used

As state in Table 1 hydraulic data such as cross section (bottom width), channel slope and roughness coefficient; climatic data such as air temperature, windspeed and dew point temperature; and water quality data such as DO of the effluents, head water flows, point and non-point sources of effluents are required for water quality modeling to simulate the water quality for the Bhadra river. The river segment was divided into three reaches based on morphology, and each reach was further subdivided into 3, 4, and 20 elements[97] by considering each elements as 1 km of the study stretch .Hydraulic data taken into consideration from earlier research studies include the cross-section (bottom width) of 61.85 m, the channel slope of 0.00166, the roughness coefficient of 0.0492, and the side slope of 0.50 [97]. As the observed head water flow data was unavailable, the discharge was calculated using outflow data from the Bhadra Reservoir, which was set at 10.36 m^3/s for the period of 2014-2016 and 23.17 m^3/s for period between 2006-2017. The study stretch three-point sources (Mysore paper mills, Bhadravathi city, and VISL) had BOD loads of 399 mg/L, 15 mg/L, and 279 mg/L, respectively [97]. But for paper mills and domestic discharge, the CPCB has set a minimum BOD effluent limit of about 30 mg/L and 20 mg/L, respectively. The effluents from industrial and domestics sewage are hazardous and toxic by nature, causing the river ecosystem to degrade. Dissolved oxygen and BOD levels have been significantly altered due to the accumulation of toxic chemicals from industrial sources, sewage and agricultural run-off. Table 2 displays the details of effluent flow required to execute the models.

Table 1: Description of the data set used in the study.

Data Type	Year	Source
Observed water quality data (at headwater, point sources) • Temperature • Dissolved Oxygen • BOD • pH • Electrical Conductivity	2006-2017	Advanced Centre for Integrated Water Resource Management (ACIWRM)
Climate Data • Air temperature • Wind speed • Dew point Temperature • Cloud cover • Percentage Shade	2006-2017	Indian Meteorological Department (IMD) website
Hydraulic and hydrological data • Flow rates at headwater and point discharge • Dimensions for each river reach (reach length, bed width, bank slopes and bed slopes)	2006-2017	Advanced Centre for Integrated Water Resource Management (ACIWRM) (Rehana and Mujumdar, 2011)

Table 2: BOD loading and effluent flow for the three-point sources.

Water Quality Stations	**BOD Loads**	**Effluent flow (m^3/s) mean**
MPM	30 mg/L	0.8680
Bhadravathi city	20 mg/L	0.3080
VISL	30 mg/L	0.0579

Source of Data : Central Pollution Control Board (CPCB**),** S. Rehana and P. P. Mujumdar(2011)

3.4 Conclusions

The hydraulic, climatic and water quality parameter data were applied in river water quality modeling QUAL2K to simulate the water quality for the Bhadra river. The river water quality parameters simulated will be further used in the estimation of Water Quality Index (WQI) to visualize the contamination levels along the Bhadra river under various pollution scenarios as explained in Chapter 4 and 5. Further Geographical Information system was used in visualizing the spatial distribution of the water quality indictors and water quality index along the Bhadra river stretch .This holistic approach will help researchers and stakeholders to improve the water quality monitoring programs and management.

Chapter 4

River Water Quality Modelling of Bhadra River Stretch, India, using QUAL2K

4.1 Introduction

An important aspect of the present study is to provide a water quality model for the study area that can simulate water quality under different forms of pollutant discharge along the river. In this present chapter, the water quality model QUAL2K is used to assess the effects of wastewater discharge on the water quality of the Bhadra River stretch to simulate various parameters. To analyze the water quality of the Bhadra river, simulation of temperature, pH, DO, and Nitrate parameters with the help of observed data at three monitoring stations Mysore Paper Mill (MPM), Visvesvaraya Industrial Steel Limited (VISL) and the Bhadravathi city) were considered. The river water quality response was studied under various pollutant scenarios such as 25%, 50%, 75%, and 100% BOD effluent. The statistical error measurement of QUAL2K model performance was carried out utilizing root mean square error and R^2 for temperature, Dissolved Oxygen (DO), Nitrate, and pH. This chapter contains detailed information about the QUAL2K water quality model, which determines river water quality in order to predict the level of pollution and contamination to maintain the ecological balance in the river.

4.2 Water Quality Modelling

Concern about water source pollution, which consistently exceeds the threshold at which an aquatic system may self-purify, has increased globally as a result of continuing population expansion and economic development [99]. [100] study claims that the most obvious problem caused by human activity in the majority of developing nations is pollution and the problems it causes. Water pollution influences local biodiversity and raises wastewater treatment costs, rendering treatment economically unviable in many circumstances. As a result, pollution control has become an essential aspect of global economic management. River water quality models are crucial mathematical tools for efficient water management as they facilitate the analysis of management plans and help with decision-making by providing water quality simulations [101]. Additionally, these models minimize the water collection and analysis requirement, which lowers expenses in terms of resources and time [102]. Overall, river water quality models provide a reliable way to simulate, control, and analyze the effects of water pollution on local biodiversity. These river water quality models enable an estimation of the impact of different management scenarios on water quality and can be used to investigate the future state of a river. Therefore, with their ability to save resources and time while providing insights into the long-term consequences of different management plans, water quality models can be a powerful tool to help ensure sustainable water management practices for those seeking to protect and improve water quality. Water quality models come in many different varieties, including WASP, QUASAR, SWAT, MIKE 11, SIMCAT, QUAL2KW, QUAL2E, and AQUATOX. The selection of water quality model depends on a number of factors, including data accessibility, simulation capabilities for water quality, model complexity, kind of waterbody, availability of a suitable model certification, and ease of access to the software source code, model widespread use and accessibility of implementation and considering the cost factor. Some of the water quality models are described in further detail in the following sections

4.2.1 AQUATOX

United States Environmental Protection Agency (USEPA) created the model to forecast the fate of various toxins and their impact on aquatic ecosystems (Park et al. 2008). It is a mechanistic ecological model whose objective is to anticipate the impact of environmental pressures on a river ecosystem. It replicates several water quality characteristics, including nutrients, silt, and hazardous compounds. In addition, their effects on aquatic animals and flora are evaluated by the model [103, 104]. According to [42], the models algorithms are derived through the clean model utilized in the biological aquatic environment model. In addition, the model predicts about twenty water quality parameters simultaneously within the marine ecosystem, making it one of the finest water quality model. In addition, it has free public access, which can be coupled with watershed models, making it superior to other water quality models.

The AQUATOX model is exceptionally complex and compatible for predicting different contaminants in an environment with high levels of mixing. To assess the fate of pollutants in aquatic ecosystems, a model was constructed as a mechanistic model that incorporated spatial and temporal resolutions. It assumes that the river comprises distinct, well-mixed segments at each time step and utilizes average flow data in order to operate. In addition, the model equation was solved with Runge-Kutta integration algorithms of the fourth and fifth order. The response to the differential equation of the fifth order was utilized to rectify the mistake noticed based on the fourth order solution. As a result, the model may be used to examine the effect of different water quality characteristics on aquatic environments utilized the model to quantifiably characterize food webs and, subsequently, to comprehend the functioning of the ecosystem in the Po River, Italy. The model was used to forecast pollution fates (nutrients or pesticides) and reflect their possibility of accumulating in food webs along the Yangtze River in China [105].

4.2.2 Mike11

The model, which was created by the Danish Hydraulic Institute, Netherland, is a deterministic computer program designed to simulate irregularities in a water flow. It is used to determine the river flow, water level and water quality in streams. In addition, it may also be applied to simulate tidal sections of a water system as a hydrodynamic model, as well as a model of water quality in a tidal environment [106]. The model is capable of simulating more severe water quality issues, including DO, BOD, sediment exchange processes, the balance of nitrate and ammonium without denitrification, and coliform bacteria. The hydrodynamic model is based on the formulation of the Saint-Venant equations, which were solved using the implicit finite difference technique. It is applicable to both one-dimensional and two-dimensional unsteady flow in water columns. For its simulation, the model can apply kinematic, diffusive dynamic, and vertically integrated mass and momentum equations. Using the continuity and momentum equations, the hydrodynamic module is solved to obtain the water level and flow rate. The hydrodynamic module is necessary for the operation of the other modules in the model. To solve the mathematical equations utilizing the iteration approach, the result of the first iteration was used to solve the second time step. The Saint Venant equations were solved using the following assumptions: water is incompressible and homogeneous, wavelengths are enormous relative to water depth, the bottom slope is low, and flow is subcritical. The equations of advection and dispersion were solved, and the first-order decays of the contaminants were taken into account in order to obtain a dynamic solution. Researchers have made substantial use of MIKE 11, mainly for rivers and lakes.[107] employed MIKE 11-HD to model the unsteady flow of the Strymonas River and MIKE 11-NAM to simulate the process of rainfall runoff.

4.2.3 SIMCAT

A simulation model that simulates water quality indicators, such as dissolved oxygen within water bodies, is called Simulation Catchment (SIMCAT). The probabilistic model forecasts parameters affecting the quality of the river and the flow dynamics throughout the water column. The model was designed by Anglian Water in the UK (Warn 1987), and this model has been used to forecast both conservative as well as non-conservative levels of contaminants in rivers. This model is based on a stochastic process that operates using the Monte Carlo simulation method. It can be applied to determine how pollutant discharge influences water systems (Warn 2007).

The model utilized the concept of mass balances as the basis on which it developed its operations and represented river reaches as continuously stirred tank reactors in series (CSTRS) with a constant flow condition. By using the model, it is possible to simulate contaminants in freshwater without sediment-pollutant interactions. The residence time for each reach is computed using the flow velocity given by the velocity-flow relationship. It assumes that pollution is spread uniformly across each river reach. In order to calculate the concentration of contaminants entering the next river stretch, computation of solute concentration through first-order decays is utilized.

The implementation of the model relies on minimal data, and it is readily applicable in a watershed.[108] monitored the quality of the River Ribble watershed in the UK by determining the sources of pollution, either point or non-point sources, and estimating their effects on the quality of the river. It has been recognized that the model has the potential to be an effective tool for managing water quality.

4.2.4 SWAT

To predict the effects of management techniques on rural and agricultural environments, the United States Department of Agriculture- Agriculture Research Service developed the Soil Water Assessment Tool (SWAT) model, a distributed hydrology and water quality model. SWAT can simulate daily, monthly, and yearly timeframes, and is frequently employed in watersheds and massive river basins [109].

Additionally, SWAT has the capability to simulate the entire watershed, along with its sub-units, such as sub-basins, channel segments, waterways in the leading channel network, and point sources that could be relevant in the watershed. It is considered that the initial level of a sub-basin, which includes more than a single hydrologic response unit (HRU), tributaries and the main channel or range, or two kinds of dams, a pond, or wetlands, is the level of a sub-basin. Sub-basin delineation can be derived by grid cells and sub-watershed borders, preferably since they preserve routing reaches and topographic flow channels. The HRU, as mentioned earlier, comprises a part of the subbasin with distinctive land use or management or soil properties. According to [110], the model can be utilized in hydrographic basins to such continental levels and can produce a successful calibration in the lack of data. The model was also used in the San Joaquin Watershed, California, United States, to predict streamflow, silt, and pesticide.The model was utilized to estimate phosphorus and nitrate loads in the Vamanapuram River basin Kerala [111].[112] investigated analysis of water quality, using SWAT, for the mined watershed in Jharkhand, during the monsoon and pre-monsoon periods. An analysis using the semi-distributed hydrological model SWAT revealed a significant increase in nitrogen concentration in the subbasin of the Narmada watershed [113].Thus SWAT model has been utilized by many researchers [53, 114, 115].

4.3 QUAL2K Model

The QUAL2K was the most widely utilized mathematical model for assessing the traditional pollution impact on the river and stream water quality. This model was created by the US Environmental Protection Agency (US-EPA) and had certain limitations (Hossain et al 2014). [116] updated it due to several limitations and created QUAL2K 2000, which featured new water quality interactions. Chapra and Pelletier refined it further in 2003 under the moniker QUAL2K 2003. [117] created QUAL2Kw, an updated version of QUAL2E, by altering the QUAL2K 2003. The QUAL2K model is a widely used technique for estimating river water quality.

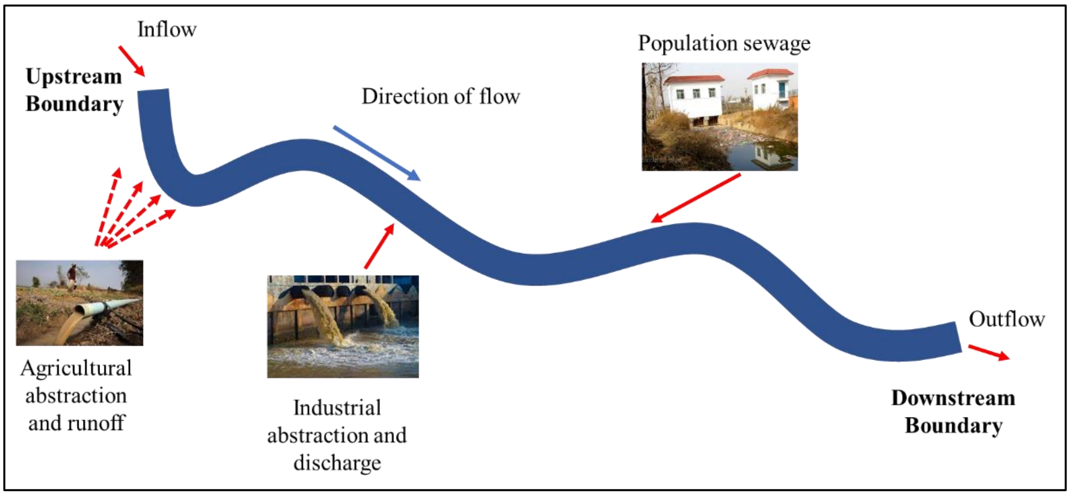

Figure 5. Typical inflows and outflows required for a river water quality model.

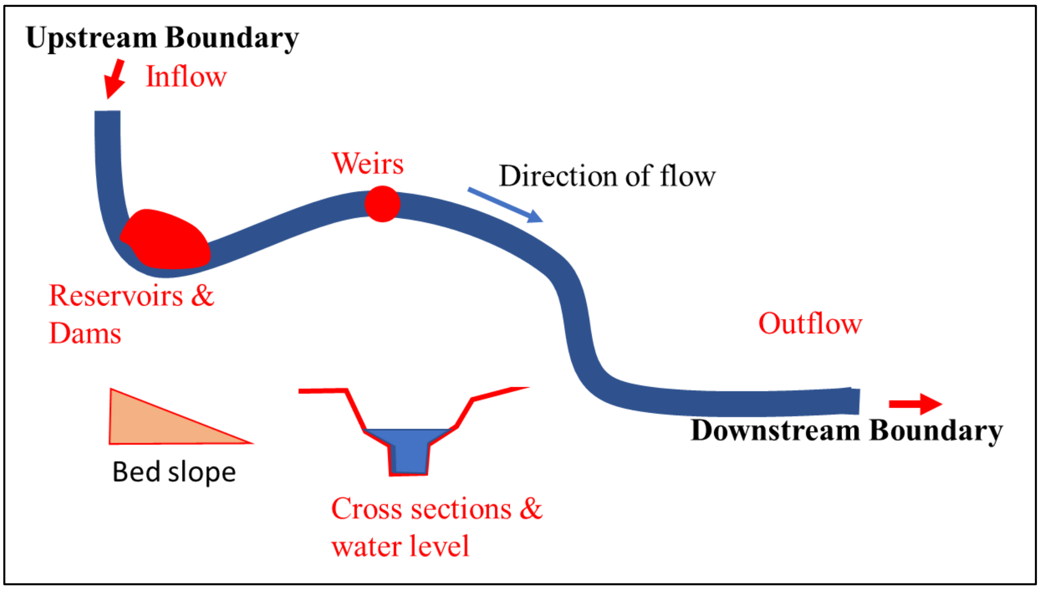

Figure 6. Hydraulic data required for a one-dimensional model

4.3.1 QUAL2K framework

The QUAL2K is a one-dimensional, time-variable model that simulates temperature, carbonaceous BOD, DO, phytoplankton, phosphorus, and nitrogen in each specified reach of the stream. It may also simulate river stream pH, alkalinity, inorganic suspended particles, pathogenic bacteria, and bottom algae. The ability to add hourly data into the QUAL2K model is a big plus. It may model a system stream with multiple tributaries and the main branch. This one-dimensional model simulates the effects of point and non-point pollution loading and is

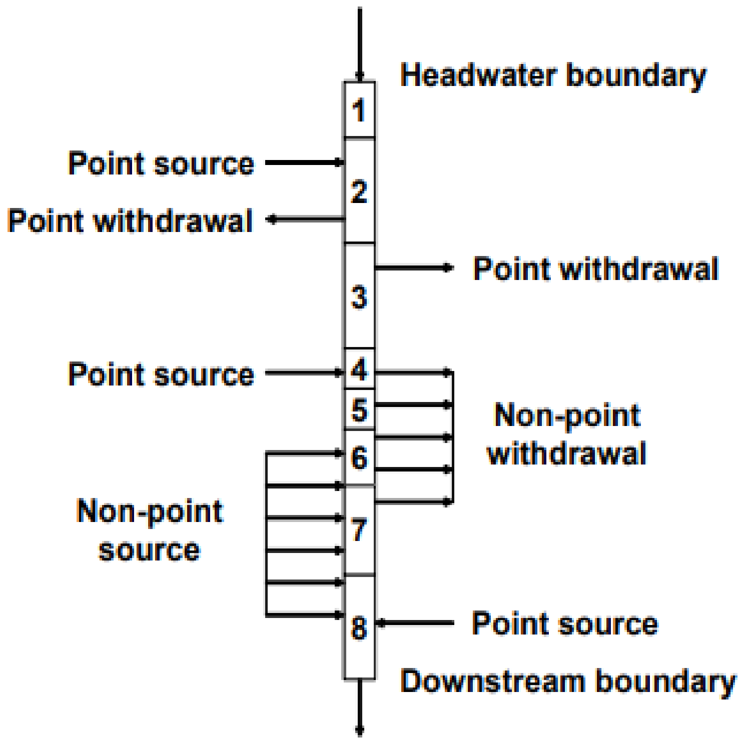

Figure 7. A general schematic segmentation of a river with no tributaries used in QUAL2K [118].

based on the principle that the channel is well mixed in both vertical and lateral directions. All hydraulic parameters presented in Figure 6 are modelled as a one-dimensional, steady-state flow with non-uniform flow, meaning water depth and velocity vary depending on channel location. Because the diurnal heat budget calculations are dynamic, the model incorporates diurnal changes as water quality dynamics, and the heat budget is calculated on a diurnal time scale. QUAL2K divides a river stream into reaches, which are then separated into elements, which are the fundamental computing units. Additionally, the model may also divide each reaches into an arbitrary number of components using a control volume (the model fundamental computational unit) in which each element has the same length and can change from element to element as presented in Figure 7.

4.4 Methodology

River water quality models are incredibly effective for replicating the natural state of a river system and, as a result, forecasting changes in the natural state under different situations. River water quality variables are influenced by (1) point and non-point pollution sources merging in a river length, (2) climatic circumstances, and (3) water quality and quantity at the river

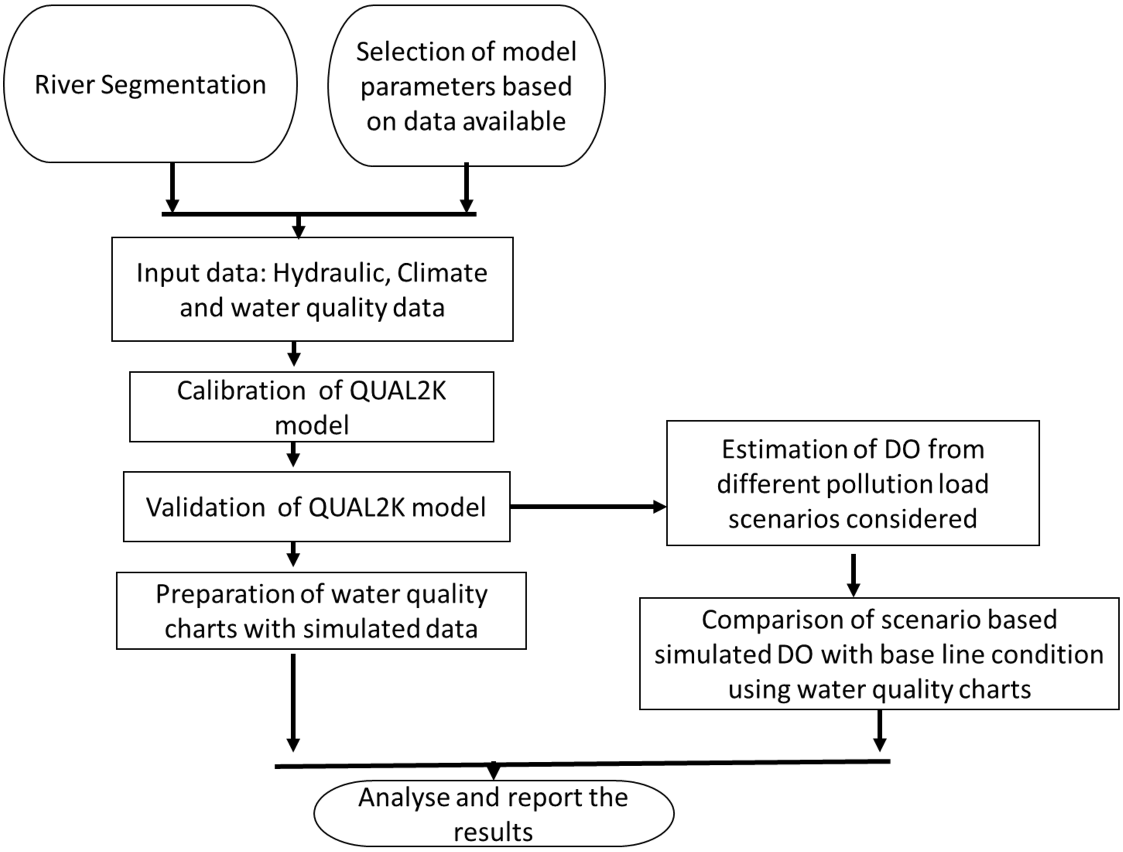

Figure 8. Flowchart of the proposed methodology in the present study.

headwater. Various pollutant load scenarios are explored for the modelling of DO to find the influence of wastewater loadings on the river health of the considered study stretch using water quality simulation model, QUAL2K. The steps involved in the current methodology are schematically depicted in Figure 8.

4.5 Development of QUAL2K model

The model users handbook contains a detailed description of the processes and mathematical representations of the interacting water quality model parameters and sources and sinks of constituents due to reactions and mass transfer mechanisms (Chapra and Pelletier, 2003). In order to evaluate the quality of river and stream water, the QUAL2K (or Q2K) model is used. It is an updated version of the QUAL2E model. QUAL2K possesses the following characteristics: (i) Diurnal water-quality kinetics and heat balance (the model simulates all water quality variables, temperature, and heat budget on a diurnal time scale); (ii) Mass and heat input (the model can simulate the point and diffuse loads and abstractions). The QUAL2K model divides the study river into multiple “reaches,” each of which is split into “elements”. These elements are the model shortest simulation portions.

4.5.1 The Flow Balance Relationship in the QUAL2K Model

The QUAL2K model uses the correlations between flow, temperature, and mass balance. To produce a steady flow for each element along the river, assuming complete mixing, following relationships are used:

$$Q_i = Q_{i-1} + Q_{in,i} - Q_{ab,i} \tag{1}$$

Here Q_i is the outflow from element i into element $i + 1$ (m^3/d), Q_{i-1} is inflow from the upstream element $i - 1$ (m^3/d), $Q_{in,i}$ is the total inflow into the element i from point and non-point sources (m^3/d) and $Q_{ab,i}$ is the total outflow from the element i due to point and non-point abstractions (m^3/d). Figure 6 depicts a schematic representation of the flow balance. Each elements outflow is computed, and the velocity and depth of the flow are determined by one or more of the following three methods: weirs, rating curves, and Manning equations. A trapezoidal channel appears to be ideal for each section of the river. The Manning equation can be used to represent a connection depth-flow under steady flow circumstances as:

$$Q = \frac{{S_o}^{1/2} {A_c}^{5/3}}{n\, P^{2/3}} \tag{2}$$

Here Q is flow (m^3/d), n = the Manning roughness coefficient, So is the bottom slope (m/m), A_c is the cross-sectional area (m^2), and P is the wetted perimeter (m) . The governing equation of QUAL2K is a one-dimensional advection-dispersion equation.

$$V \frac{\partial c}{\partial t} = \frac{\partial (A_c E \frac{\partial c}{\partial x})}{\partial x} dx - \frac{\partial (A_c U C)}{\partial x} dx + V \frac{dc}{dt} + S \tag{3}$$

In this formula, U stands for the average velocity (m/d), Ac is the area of cross section (m^2), E is the coefficient of longitudinal dispersion (m^2/d), c is the concentration (g/m^3), , x is the distance (m), and S represents the sources and sinks of the constituent as a result of reactions, mass transfer phenomena ($g/m^3/d$) ,V is the volume (m^3).

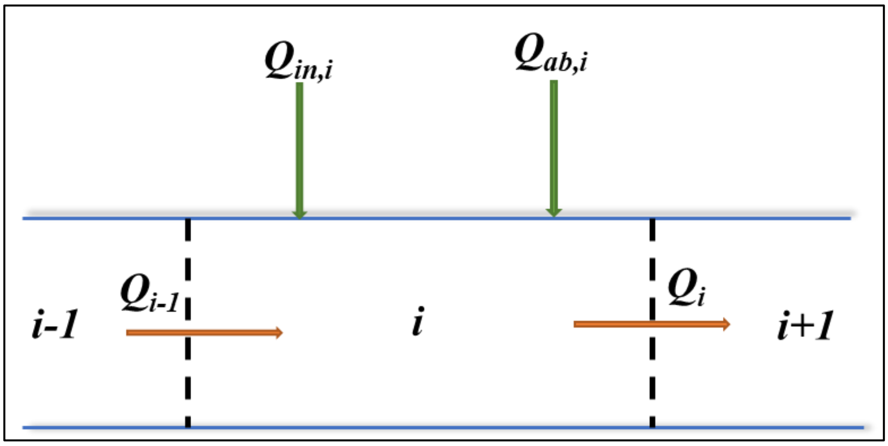

Figure 9. Flow balance for elements of the rivers [118]

4.5.2 Mass Balance Relationships in the QUAL2K Model

Mass conservation is one of the fundamental characteristics of water quality model formulation. The principal equation solved by the QUAL2K model is the one-dimensional advection-dispersion equation obtained for all parameters with the exception of marine algae according to equation (4).

$$\frac{dCi}{dt} = \frac{Q_{i-1}}{V_i} C_{i-1} - \frac{Q_i}{V_i} C_i - \frac{Q_{ab,i}}{V_i} C_i + \frac{E_{i-1}}{V_i} (C_{i-1} - C_i) + \frac{E_i}{V_i} (C_{i+1} - C_i) + \frac{W_i}{V_i} + S_i \quad (4)$$

Here *Ci* is the concentration in the variable element *i* (g/m^3), *Vi* represents the volume of the variable element *i* (m^3), *Wi* denotes the load of the constituent external to the variable element *i* (g/d or mg/d), *t* indicates the duration of the process (d), *Qi* is the outflow from the variable element *i* into variable element *i+1* (m^3/d), and *Ei* is the bulk dispersion coefficient between the elements (m^3/d).

4.5.3 Longitudinal Dispersion

Based on the hydraulics of the channel, the QUAL2K model used a hydraulics-based formula to internally compute the longitudinal dispersion for a border between two elements:

$$E_{p,i} = 0.011 \frac{{U_i}^2}{H_i} \frac{{B_i}^2}{{U_i}^*} \quad (5)$$

Here $E_{p,i}$ is the longitudinal dispersion coefficient between elements *i* and *i+1* [m^2 /d] , U_i is velocity [m/d], B_i is the width [m], H_i is mean depth [m], and ${U_i}^*$ is the shear velocity [m/d], and this, in turn, is linked to more basic features by:

$$U_i^* = \sqrt{g\ H_i S_i} \quad (6)$$

Here g represents gravitys acceleration, and S_i corresponds to the slope of the channel.

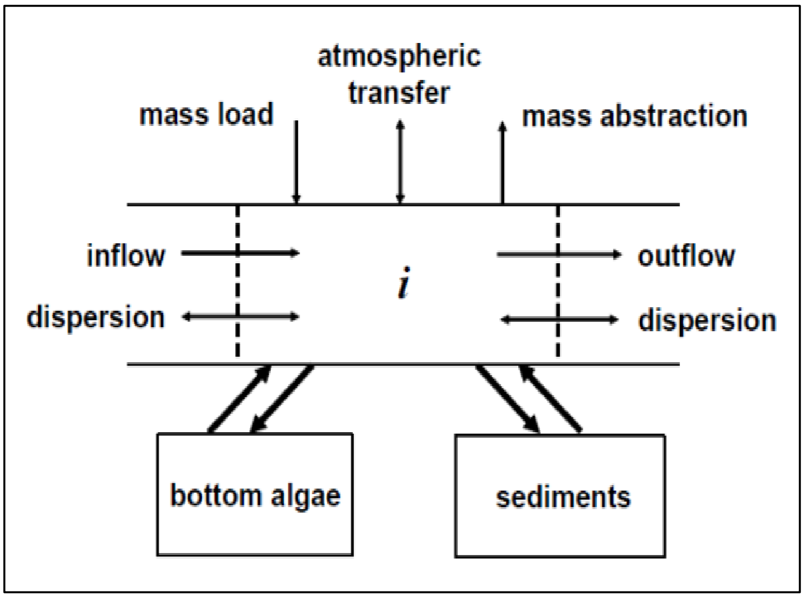

Figure 10. Processes involved in the modelling of QUAL2K general mass balance [118].

4.6. Results and Discussions

4.6.1 River Segmentation

The current study length of the Bhadra River is approximately 27 kilometers long, and the Mysore Paper Mill (MPM), the Visveshvarya Industrial Steel Limited (VISL) and the Bhadravathi city are the two industries and municipal effluents that pollute the river system. Non-point sources such as overland flow from surrounding towns and farmland contaminate the 27 km study area and these drains. Based on morphology, the current research stretch of the Bhadra River was split into three reaches, each of which was further divided into 3,4,20 elements presented in Figure 11.

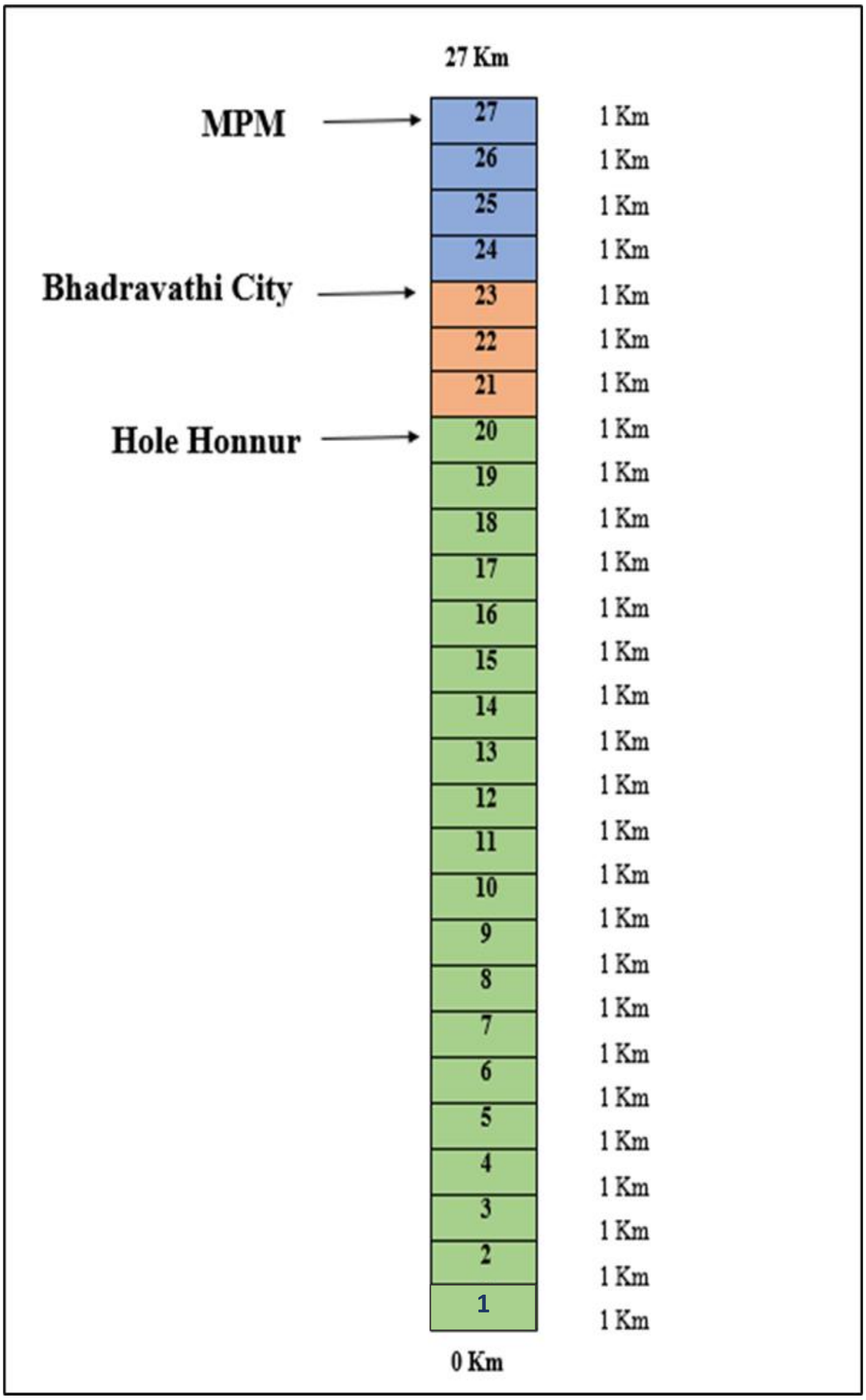

Figure 11. System Segmentation With the location of pollution Sources of the Bhadra River

4.6.2 QUAL2K model calibration and Validation

While calibrating the QUAL2K model, the objective function is to improvised the model performance using statistical error, i.e., R^2, MBE, and RMSE values that quantifies the goodness of fit between observed and simulated water quality data. The variables considered for calibration and validation were temperature, DO, nitrate, and pH. The calibration process strongly emphasized evaluating and optimizing the model performance concerning Dissolved Oxygen (DO) concentrations. The model was calibrated for the period of 12 months from April 2014 to March 2015 and validated for the period of 12 months from April 2015 to March 2016. There are several challenges associated with the QUAL2K model, particularly in regard to the availability of water quality data. Calibrating the model requires accurate estimation of parameters like reaction rate coefficients, settling velocities, and other water quality-related parameters. Figures (12 to 15) depicts the QUAL2K model calibration and validation results for parameters such as Temperature, pH, Nitrates, Dissolved Oxygen along the distance of the Bhadra river stretch respectively. Temperature, pH, and DO findings exhibit close fits to actual data over the calibration period. There was a notably smaller validation result for pH (Figure 13) and Nitrates (Figure 14) compared to the calibration period within the third reach. Because the observed pH value and the observed nitrates value for the validation time period are lower in intensity and concentration that can be due to may reason such as potential variations in the environmental conditions; for example, seasonal changes, fluctuations in upstream inputs, or local influences have influenced these differences. Three statistical error metrics (RMSE, MBE, and R^2) must be established to assess the model performance using Equations (6 to 8).)[119].

$$RMSE = \sqrt{\frac{\sum_{k=1}^{k}(X_k - Y_k)^2}{k}} \quad (6)$$

$$MBE = \frac{1}{k}\sum_{k=1}^{k}(X_k - Y_k) \quad (7)$$

$$R^2 = \frac{\sum_{k=1}^{k} x_k y_k}{\sqrt{\sum_{k=1}^{k} x_k^2 \Sigma y_k^2}} \quad (8)$$

Where:

X_K = observed values

Y_K = predicted values

K = the number of pairs of predicted and observed values of the parameters.

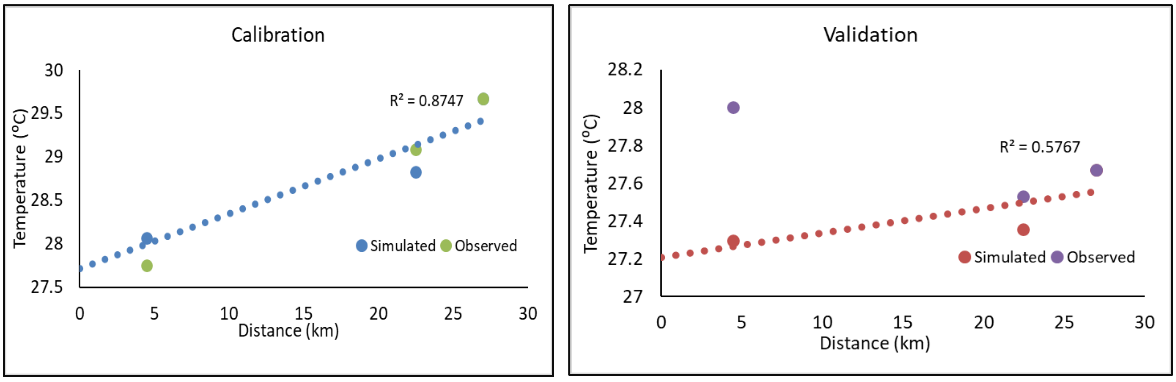

Figure 12. Calibration (April 2014 to March 2015) and validation (April 2015 to March 2016) results of Temperature for Bhadra River.

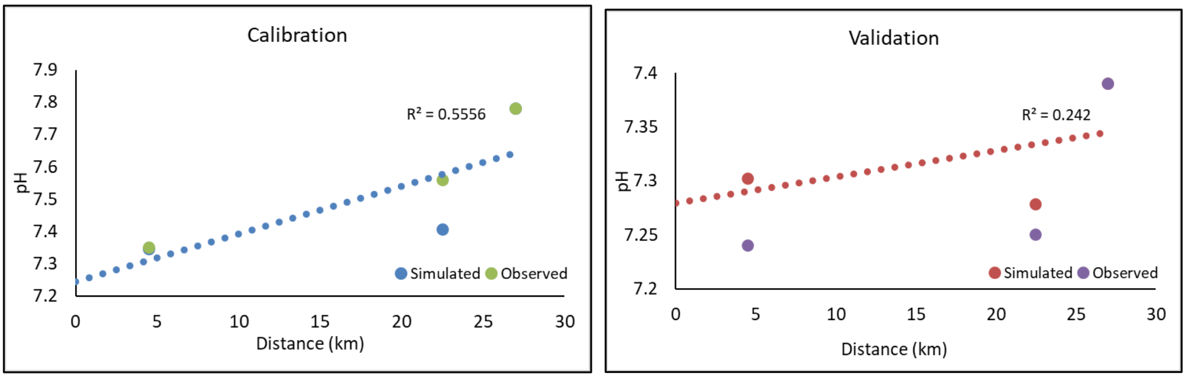

Figure 13. Calibration (April 2014 to March 2015) and validation (April 2015 to March 2016) results of pH for Bhadra River.

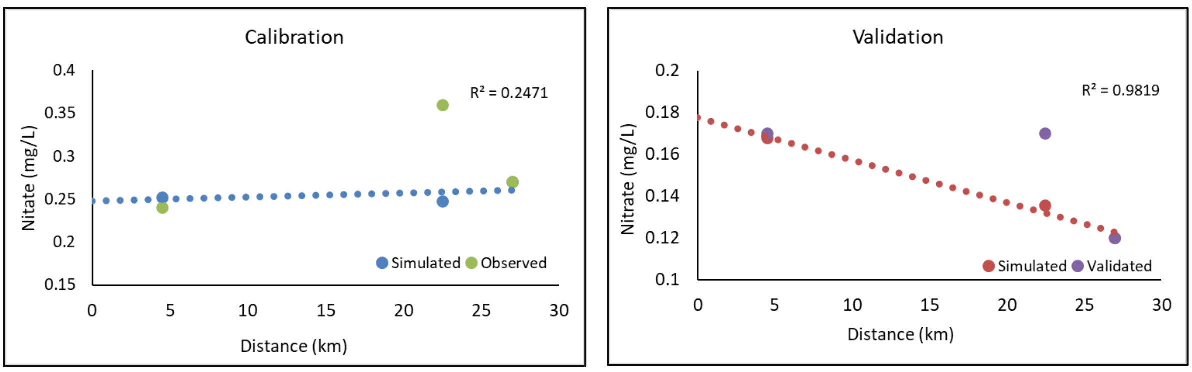

Figure 14. Calibration (April 2014 to March 2015) and validation (April 2015 to March 2016) results of Nitrates for Bhadra River.

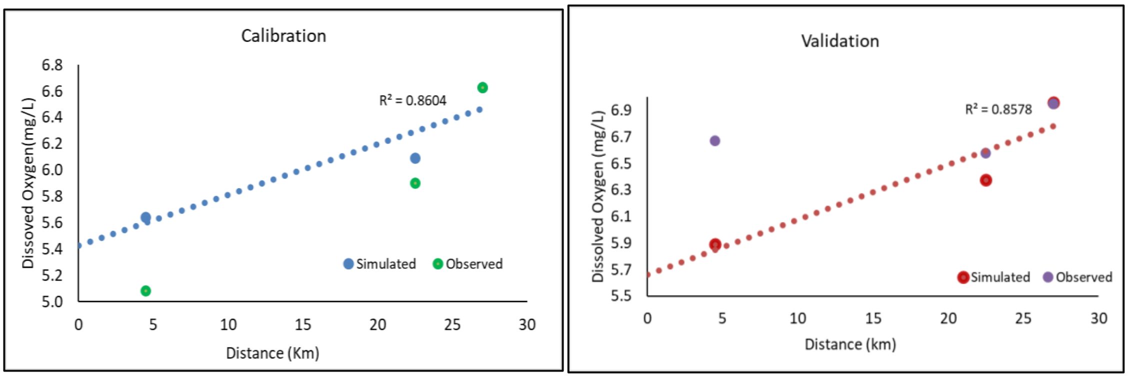

Figure 15. Calibration (April 2014 to March 2015) and validation (April 2015 to March 2016) results of Dissolved Oxygen for Bhadra River.

Table 3. Calibration parameters for the Bhadra River stretch water quality modelling.

Parameters	**Units**	**Values**		
		Reach 1	Reach 2	Reach 3
ISS Settling Velocity	m/day	0.35	0.35	0.35
Fast CBOD Oxidation rate	/day	0.1260	0.1360	0.01260
Organic N Hydrolysis rate	/day	1.5300	1.5800	1.2500
Organic N Settling Velocity	m/day	0.6500	0.6600	1.9600
Ammonium Nitrification	/day	0.3256	0.1530	0.0921
Nitrate Denitrification rate	m/day	1.9000	0.9213	0.1950
Sediment- denitrification transfer coefficient	m/day	3.1410	2.0000	1.0350

The calibration parameters, reaction rates, and coefficients of the water quality model are more important for the model performance during calibration. The ISS settling velocity was 0.35 m/day for all three reaches. The DO simulation is influenced by the fast CBOD oxidation rate, which varies from 0.0126 to 0.136 per day. Organic Nitrogen hydrolysis rate (1.25-1.58 per day), Organic Nitrogen settling velocity (0.65-1.96 m/day), Ammonium nitrification (0.09-0.32 per day), Nitrate denitrification rate (0.19-1.9 m/day), and sediment-denitrification transfer coefficient (1.03-3.14 m/day) were the calibration parameters used in the model. The calibration variable ranges are constructed using the maximum and minimum values of the model. The exact values of the calibration parameters used in the respective reaches of the study stretch are given in Table 3. As mentioned above, the model performance was evaluated using some statistical error parameters. R^2 values for Temperature, pH, and DO during model calibration are obtained as 0.87, 0.50, and 0.62, respectively, while RMSE values for Temperature, Nitrate, and pH are obtained as 0.23, 0.06, and 0.08, respectively. R^2 values for Temperature, Nitrate, and pH during the validation period are 0.56, 0.90, and 0.64, respectively, while RMSE for Temperature, DO, Nitrate, and pH are 0.42, 0.47, 0.02, and 0.03, respectively. The RMSE, MBE, R^2 values for the calculated and measured data during the calibration and validation phase are given in Table 4**.**

Table 4. Root mean square error (RMSE), Mean bias error (MBE) and R^2 for the simulated & observed water quality parameters for the entire river stretch; (C- Calibration & V- Validation) .

Parameters	**RMSE**		**MBE**		**R^2**	
	C	V	C	V	C	V
Temperature	0.23	0.42	-0.02	0.29	0.87	0.56
DO	0.34	0.47	-0.25	0.32	0.50	0.12
Nitrate	0.06	0.02	0.03	0.01	0.11	0.90
pH	0.08	0.03	0.05	-0.03	0.62	0.64

4.6.3 Estimation of DO from pollution load scenarios

Various pollution scenarios were created based on the availability of point source data. The BOD effluent from point sources (MPM and VISL – 399 mg/l and 279 mg/l, respectively) are obtained from Rehana and Mujumdar [97]. Because BOD load is one of the influencing factors for the overall DO condition of the river stretch, the pollution scenarios with reduction of 25%, 50%, 75%, and 100% BOD effluent were investigated for DO modelling. Figure 16 compares and illustrates the fluctuation in DO throughout the study stretch for various pollution scenarios. Based on the examination of the simulated DO, it was revealed that a decrease of 25% BOD effluent results in an increase of 8% average DO across the study stretch. Similarly, during the investigation process, 11.5 % of average DO increase for a 50% reduction in BOD effluent and 15% of average DO increase for a 75% drop in BOD effluent.

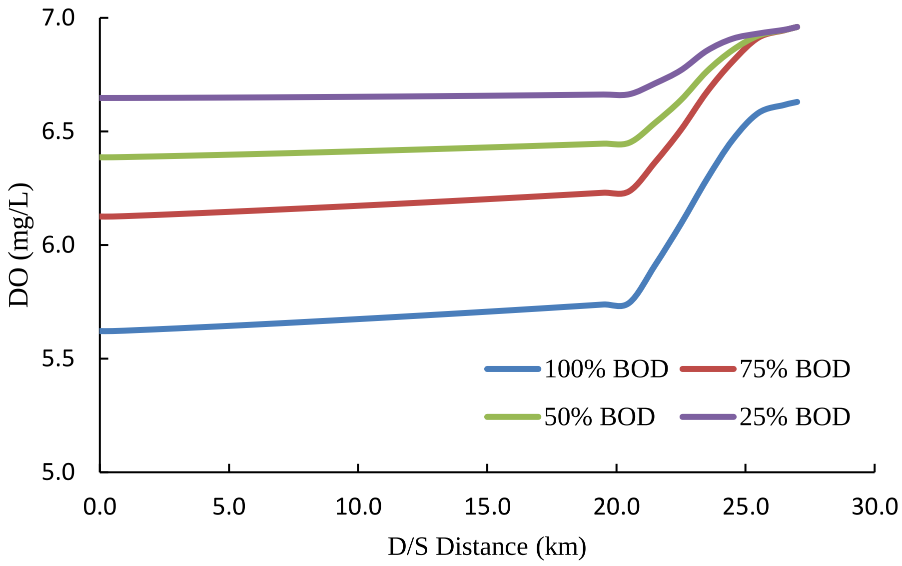

Figure 16. Variation of DO for different pollution scenarios of BOD load

4.7 Conclusions

In this study, the water quality model QUAL2K was utilized to assess the river water quality in order examine the level of pollution and contamination in the Bhadra river stretch by simulating the DO by varying the BOD loads coming from different pollutant sources within the stretch. The following conclusions can be drawn from this research:

(i) The QUAL2K model was used to simulate Temperature, Nitrate, pH, and DO parameters for the Bhadra River stretch, and the model calibration and validation for a period of 24 months were successfully completed.

(ii) The model performance was evaluated using statistical error parameters, i.e., RMSE, MBE and R^2. It has been observed that the RMSE for Nitrate and pH parameters is very satisfactory, while for temperature and DO parameters is good.

(iii) The results revealed that the Bhadra river stretch was highly polluted due to effluents coming from the industries, mostly MPM & VISL present in the study stretch. There must be a reduction of 25% of BOD effluent to reach the minimum standards set by the CPCB.

(iv) Under diverse contamination scenarios, the validated QUAL2K river water quality model is successfully employed to forecast DO. There is a 15% rise in average DO throughout the study stretch due to a 75% drop in BOD effluent from point sources.

(v) The water quality model, QUAL2K, was the most sensitive to calibration parameters like rapid CBOD oxidation rate, and nitrification rate for modelling dissolved oxygen.

(vi) The QUAL2K can be used to successfully simulate various pollution management scenarios with reduced effluent loading, allowing the river DO to be restored to levels above the permitted limit with minimal effort.

Using the QUAL2K model, the water quality of the Bhadra river was evaluated. This study focuses mainly on the concentration of certain pollutants at monitoring sites receiving effluent from industry and domestic discharge, which was insufficient to assess the overall status of the water quality. Furthermore, the visualization of contamination levels along the river stretch can help the river water quality managers to provide thresholds on the effluents for better quality control. Therefore, the use of an integrated approach that incorporates GIS techniques can help to improve the accuracy and comprehensiveness of water quality models, and provide decision-makers with the information they need to make informed decisions about water quality management. Integration of river water quality simulations from QUAL2K model with GIS interface to visualise the contamination levels in terms of pollution index has been explained in Chapter 5.

Chapter 5

Assessment of River Water Quality Using QUAL2K Model and Water Quality Index for the Bhadra River, India

5.1 Introduction

Water quality is a complex and dynamic issue that requires an integrated approach for effective management and protection. Various tools and methods have been developed to simulate and analyze water quality in different contexts to address the challenge of water quality. This chapter focuses on integrating the Water Quality Index with water quality modelling and GIS mapping to analyze water quality in the Bhadra river stretch. Water Quality Index (WQI) is a numerical index that summarizes the overall water quality status of a surface water body such as a river, lake, or stream. It is calculated based on the concentrations of multiple water quality parameters, such as Biochemical Oxygen Demand (BOD), Dissolved Oxygen (DO), Electrical Conductivity (EC), Nitrate (NO3), pH, and Temperature. The parameters are weighted based on their relative importance to water quality and human health and combining into a single score ranging from 0 to 100. WQI is categorized into different classes based on the score range, each of which represents another water quality status, such as “Excellent,” “Good,” “Poor,” “Very Poor,” and “Unfit for consumption.” The estimation of the water quality index has been evaluated using QUAL2Ksimulation. This chapter demonstrates the value of an integrated approach for water quality management by combining the strengths of these tools to provide a more comprehensive understanding of water quality. WQI is a valuable tool for summarizing the overall water quality status of a surface water body and for communicating water quality information to decision-makers, stakeholders, and the public. The categorization of WQI into different classes helps to identify areas where water quality is poor and where improvement is needed and provides a basis for prioritizing action to improve water quality.

5.2 Water Quality Index

River water is regarded as one of the vital natural sources for human persistence and activities associated with development [120]. It is more vulnerable in terms of pollutants mutually from natural and anthropogenetic sources like domestic and industrial wastewater effluents, urban and agricultural runoff, a persistent decline in the river water quality has been detected over the past few decades [121, 122]. For sustainable growth and the protection of human well-being, it is decisive to preserve the excellent state of river water quality [123].

Management of water quality necessitates the grouping and analysis of enormous datasets on water quality, which can be complex to analyze and synthesize. The analysis of water quality data has been carried out using a variety of techniques, one of which is the Water Quality Index (WQI) model. WQI models can be defined as the collection of aggregation functions, which allow the analysis of substantial temporal and spatial variations in water quality datasets to generate a single value, i.e., the water quality index, which represents the quality of the water body [65]. They transform detailed water quality information into a single value measure of water quality in a way that is simple to grasp, which makes them appealing to water management/supply organizations.

A WQI usually consists of four steps, or elements. Initially, the parameters that are relevant to the water quality of interest are selected. In the second step, the data on water quality is read and for each water quality parameter, the concentrations of the constituent components are transformed into a single-value, dimensionless sub-index based on the water quality data. A third step is to establish a weighting factor for every parameter of water quality. Finally, the final single-value index of the water quality is computed utilizing each water quality parameters sub-indices and weighting factors. On the basis of the aforementioned four phases, several WQI models have been developed. Numerous models are region-specific due to the fact that the majority of WQI model components were created based on expert opinions and local norms [70].

In 1965, the first WQI was developed by Horton (1965) by grouping 10 parameters of water quality that were considered relevant to a wide range of waterbodies. Brown et al. (1970) later created a WQI that was comparable to the Hortons index in 1970. After receiving assistance from the National Sanitation Foundation, Brown WQI was renamed as the National Sanitation Foundation Water Quality Index (NSFWQI), which is served as the foundation for several other WQI models.

The Scottish Research Development Department (SRDD), in 1973, established their own SRDD-WQI, a model somewhat resembling Brown's model, which was used to evaluate the water quality in rivers. Later variants of the SRDD-WQI include the Dalmatian Index (Stambuk-Giljanovi'c, 2003), House Index (1986), and Bascaron Index (1979). For the purpose of evaluating the water quality in the ecosystems of the Great Lakes, [124] later created the Environmental Quality Index model.

Another significant advancement was the British Columbia Water Quality Index (BCWQI), which was created by the British Columbia Ministry for Environment, Lands, and Parks to assess the water quality corresponding to a wide range of waterbodies located in the province of British Columbia, Canada[125]. According to [126] , BCWQI ratings have been consistently shown to be the most sensitive in terms of sample design. In addition, they are the most dependent on the precise implementation of water quality standards and goals. Different WQI models have been developed as of late by several countries and/or organizations to assess surface water quality globally. The following sections will provide an overview of some water quality index models.

5.2.1 National Sanitation Foundation WQI (NSF-WQI)

In 1965, Brown developed the NSF WQI as an adaptation of Horton's original model [127]. The NSF index provided five groups of 11 water quality characteristics, including physical, chemical, microbiological, nutritional, and hazardous parameters. Most other WQI models ignored hazardous factors, but Brown et al (1970) suggested adding the parameter group of toxic parameters. The parameter sub-indexing values ranged in value from 0 to 1, with the number 1 indicating that the measured value was within the allowable guideline range and 0 indicating that the value was outside of the permissible range. This model uses unbalanced parameter weight values that sum to 1 in order to calculate the parameter weights.

Table 5. The original NSF model weight values for water quality parameters [65]

Water Quality Parameters	Sub index weights
DO	0.16
FC	0.16
pH	0.16
BOD	0.10
Nitrates	0.10
Total Phosphate	0.10
Turbidity	0.08
Total Solids	0.07

In the same way, this model also took into account the environmental implications associated with water quality parameters when deciding how much weight to give each parameter. The multiplicative function illustrated in the equation (1) was the alternate aggregation function that Brown presented in 1973 to estimate NSF WQI (Brown et al., 1973).

$$WQI = \prod_{i=1}^{n} s_i^{w_i} \tag{1}$$

Where S_i = sub index value that corresponds to parameter *i*,

W_i = weight value of a specific water quality parameter *i*

n = total number of parameters.

The estimated index for water quality was a number between 0 and 100, with 0 representing the least desirable possible water quality and 100 representing the best possible water quality. It was classified into five classes as shown in Table 6.

Table 6. Classification scheme of NSF-WQI

Water Quality Status	WQI index value
Excellent	90-100
Good	70-89
Medium	50-69
Bad	24-49
Very Bad Quality	0-24

5.2.2 Scottish Research Development Department (SRDD) Index

The Scottish Research Development Department has been continuously improving the SRDD model since 1970 in order to assess the quality of surface water [70]. The SRDD model is used by the majority of temperate and tropical/subtropical nations due to its adaptability and regional suitability. While choosing the parameters for the water quality, this model such as used the Delphi method which can be define as "a method for structuring a group communication process so that the process is effective in allowing a group of individuals, as a whole, to deal with a complex problem”[128] An important characteristic of the technique is the anonymity of individual responses, the refinement of feedback over time, as well as the statistical analysis of responses [129]. Eleven criteria related to water quality were suggested. The model parameters are divided into four distinct classes based on water purity. Temperature, conductivity, and total suspended solids belonged to the physical group; DO, pH, and free and saline Ammonia to the chemical group; Total Oxide, Nitrogen, and Phosphate to the organics group; BOD and Escherichia coli to the microbial group (E. coli).

The Delphi method was used to acquire values for the models parameter sub-indices [130]. There is a wide range of possible values for the sub-index, from 0 to 100. To compute sub-indices, the technique of rating curves was utilized; the curves were based on the judgments of experts. Parameter weight values were determined using the Delphi method they are fixed, uneven weightings that must add up to 1.

Table 7. SRDD model proposed weight values for water quality parameters.

Water Quality Parameters	Sub index weights
DO	0.18
BOD	0.15
Free and saline ammonia	0.12
pH	0.09
Total oxidized nitrogen	0.08
Phosphate	0.08
Suspended solids	0.07
Temperature	0.05
Conductivity	0.06
E.Coli	0.2

This modified additive function is used for aggregation in the SRDD model.

$$SRDD - WQI = \frac{1}{100}\left(\sum_{i=1}^{n} S_i W_i\right)^2 \quad (2)$$

For the parameters sub-index and weight values, the model suggested a multiplicative aggregation approach (Eq. (3)).

$$WQI = \prod_{i=1}^{n} s_i^{w_i} \quad (3)$$

Where S_i = sub index value of parameter *i*, W_i = weight value for particular water quality parameter and *n* = total number of parameters.

The model presented a seven-tiered grading system that could be used to assess water quality, with the calculated WQI having a possible range from 0 to 100 which is shown in Table 8

Table 8. classification scheme of SRDD index model.

WQI index Status	Water Quality Level
Clean	90-100
Good	80-89
Good without treatment	70-79
Tolerable	40-69
Polluted	30-39
Several Polluted	20-29
Piggery Waste	0-19

5.2.3 Canadian Council of Ministers of the Environment (CCME) WQI

British Colombia WQI Model (BCWQI) provided the foundation for the CCME model development in 2001[127]. A broad variety of surface water bodies have used the CCME WQI model worldwide [16]. It is rather extensively used since it is simple to use and offers versatility in selecting water quality factors for utilization in the model. At least four water quality parameters must be used as inputs to the CCME WQI model, although there is no requirement that dictates which parameters must be included [125].

There is no sub-index calculation part in the CCME model as compared to other models, which is considered as the significant flaw in this one. The weights of the parameters are not needed to get the final WQI. The CCME employs a unique aggregation function, which is not seen in competing models. It is written as follows:

$$WQI = 100 - \left[\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1\cdot 732}\right] \quad (4)$$

Where:

F1 is the scope value, which represents the proportion of all parameters that do not satisfy the defined criteria.

$$F1 = \left[\frac{number\ of\ failed\ paramters}{total\ number\ of\ paramters}\right] * 100 \quad (5)$$

F2 is the frequency value, which represents the proportion of all test that do not satisfy the defined criteria.

$$F2 = \left[\frac{number\ of\ failed\ test}{total\ number\ of\ test}\right] * 100 \tag{6}$$

F3 is the amplitude value, which can be viewed as a way to measure how much a test value does not achieve its objectives. An asymptotic function is used to determine the amplitude, a number between 0 and 100, which is proportional to the Normalized Summation of the Excursions (NSE) based on the values in the test set, which represent the levels towards the objectives.

$$F3 = \left[\frac{NSE}{0.01(NSE)+0.01}\right] \tag{7}$$

The test values excursion is computed as follows if it is less than the target value:

$$excursion_i = \left[\frac{failed\ test\ value\ i}{objective\ i}\right] - 1 \tag{8}$$

On the other hand, if the test value is more than the objective value, the excursion value is determined as follows:

$$excursion_i = \left[\frac{objective_i}{failed\ test\ value_i}\right] - 1 \tag{9}$$

The total deviation between the values of each of the individual tests from conformity with one another is represented by the NSE, which is calculated by aggregating all variances from each tests objectives and dividing by the total number of tests.

$$NSE = \left[\frac{\sum_{i=1}^{n} excursion_j}{total\ number\ of\ test}\right] - 1 \tag{10}$$

The CCME model classified water quality status presented in the Table 9

Table 9. Classification scheme of CCME-WQI index model

WQI Value	WQ status
95-100	Excellent
80-94	Good
65-79	Fair
45-64	Marginal
0-44	Poor

5.2.4 Fuzzy Interface System (FIS)

FIS has been used extensively in the field of environmental risk assessment since fuzzy logic first appeared in the 1960s. Similar to WQI components, there are four main steps involved in the development of FIS models: fuzzy sets and membership functions, fuzzy set operations, fuzzy logic, and interference rules.

Parameter selection for FIS technique is not able to provide precise water quality parameters for evaluating the water quality, set functions theory, and logical principles were employed in selecting parameters for the model. To establish a connection between parameters, theoretical and statistical methods are used. Normalization of water quality parameters is achieved by using FIS, which allows a numerical value to be enforced and transformed into a qualitative value. FIS logic functions are used to generate weight values for the parameters. To aggregate WQ parameters, fuzzy logic interface rules are employed. A defuzzification process of the FIS is conducted to obtain the final water quality score [65, 131].

5.3. Methodology

The qualitative changes in the Bhadra River have been analysed using the river water quality simulation model, QUAL2K. For future qualitative forecasts of the Bhadra River, the models coefficients have been calibrated and validated. With the validated model findings, WQI was estimated using the WA-WQI method and represented spatially over the study stretch. Figure 17 shows a schematic representation of the workflow that makes up the current study.

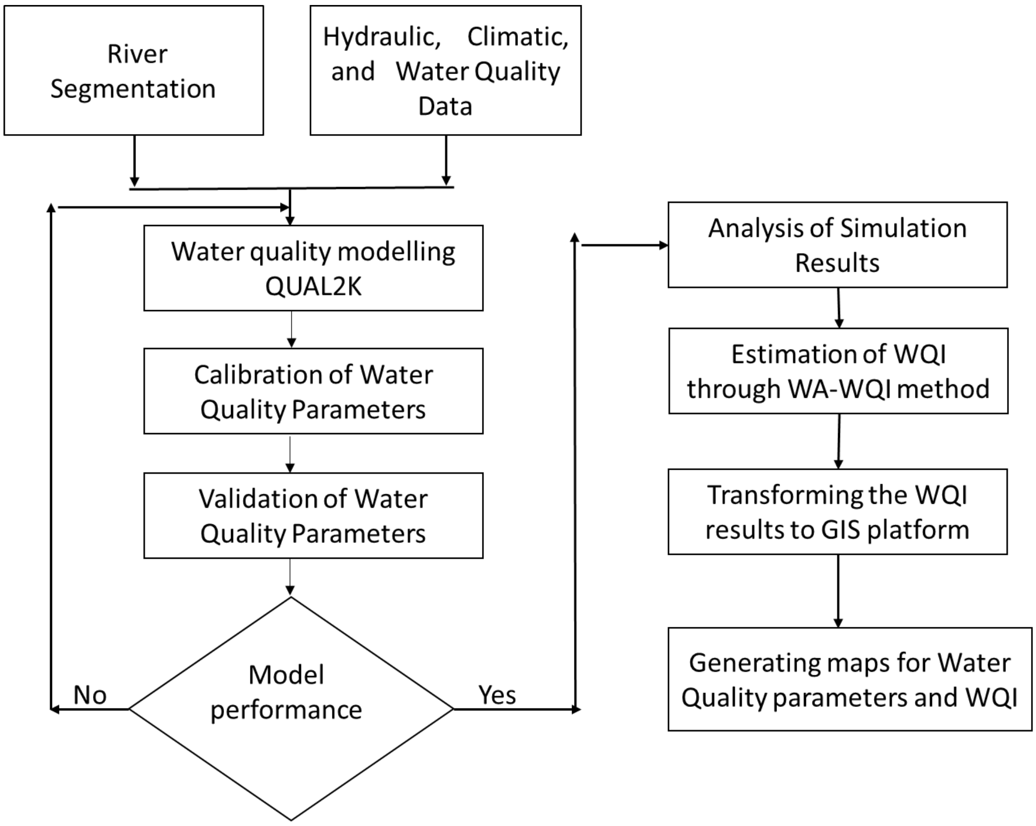

Figure 17. Flow chart representing the steps involved in work flow of current study

5.3.1 Water Quality modelling using QUAL2K model

To evaluate the effects of several pollutant releases along the Bhadra River, a simulation of water quality was done utilizing the QUAL2K model. The model is capable of simulating the movement and specification of a wide range of different water quality parameters, comprising DO, temperature, BOD, nitrates, ammonia, alkalinity, sediment oxygen demand, organic phosphorus, inorganic phosphorus, total phosphorus, phytoplankton, and algae. Pollution loads associated with both a point source and a non-point source were also considered.

The Bhadra River is divided into 3 reaches, and each reach is further divided into 3, 4, and 20 elements. Calibration and validation of the model were conducted at the beginning of the water quality modeling exercise using the QUAL2K model on the basis of the various parameters, i.e., DO, BOD, NH3, NO3, pH, and Ec. A validation process was conducted based on the hydraulic parameters which were used during calibration. A comparison between the observed data and the simulated water quality indicators was made. Whenever water quality parameters from the QUAL2K model are found to be satisfactory when compared to observed data, the hydraulic parameters can be considered accurate. Similar to the calibration process, the second data set was utilized to validate and assess the QUAL2K model performance irrespective of altering the hydraulic parameters. The calibration procedure must be repeated if the model performs less than adequately. Once the QUAL2K model had demonstrated satisfactory mutual performance in the calibration and validation phases, these processes were terminated.

5.3.2 Calculation of WQI using WA-WQI

The WQI is a ranking system that illustrates the combined contribution of various water quality parameters to the overall quality of the water. WQI is a well-known technique and one of the finest tools for expressing pollution extent of a waterbody. It provides policymakers and concerned individuals with information about water quality in a primary, reproducible unit of measurement. The recommended standards for the respective parameter are inversely related to the weights for the different water quality parameters.

One of the core benefits of WQI is that it integrates statistics from several water quality metrics into a scientific equation that quantifies the state of water quality with a single number (Brown et al., 1970). In this study, the weighted Average Water Quality Index (WA-WQI) method is used with water quality indicators such as water temperature, BOD, DO, Electrical Conductivity (E_C), Nitrate, and pH. The Weighted Arithmetic Water Quality Index method (WA-WQI), first suggested by Horton (1965) and developed by Brown et al. (1972), was utilized to calculate the overall WQI using the following Equation (11).

$$WQI = \frac{\sum Q_n W_n}{\sum W_n} \tag{11}$$

According to Brown et al. (1972), the following equation generates each parameters quality rating scale (Q_n).

$$Q_n = 100 \times \frac{(V_n - V_o)}{(V_s - V_o)} \tag{12}$$

Where V_n = mean concentration of n^{th} parameter, V_o = Actual value of the parameter in pure water, V_s = common desirable value of i^{th} parameter. Except for pH and dissolved oxygen, all ideal values (V_o) are assumed to be zero. The optimal pH value is 7.0, while the ideal dissolved oxygen level is 14 mg/l.

The following Equation (13) is used to calculate the unit weight, which is inversely proportional to the recommended standard (V_s) for each water quality parameter.

$$W_n = \frac{k}{V_s} \quad (13)$$

Where Wn denotes the unit weight of the proportionality constant k.

$$k = \frac{1}{\Sigma v_s} \quad (14)$$

Unit weight factors should be equal to unity on the summation of all the selected parameters. The range of the WA-WQI category value is 0 to 100. If the index value is low then it indicates the better river water quality. The index value range is then assigned to one of the following categories of water quality which are given in Table 10.

Table 10. Classification schemes of the WA-WQI index [59].

Water quality index level	Water quality status
0-25	Excellent
26-50	Good
51-75	Poor
76-100	Very Poor
>100	Unfit for consumption

5.3.3 Spatial distribution of Water Quality index using GIS techniques

Visualising analysis of the spatial variation in water quality parameters such as Temperature, pH, DO, BOD, Ec, Nitrates and the WA-WQI has been conducted using ArcGIS geographical software and inverse distance weighted (IDW) interpolation technique. It is crucial to visualize the spatial distribution of water quality parameters in order to identify areas where water quality can be improved through remediation efforts. Using a regular analysis of water quality parameter concentrations over time, trends and potential problems can be detected and tracked. In this study the inverse distance weighting (IDW) method is used to interpolate the water quality data over the entire study stretch. The IDW offers a basic and uncomplicated deterministic interpolation method based on the idea that sample values obtained closer to the prediction location have a greater impact on the predicted value over values obtained farther away [132]. Several watersheds worldwide have used the IDW for research on water quality management [133–135].

As a part of the analysis, Arc-GIS (Geographical Information System) is emerging as a powerful tool for managing spatial information in a holistic manner, while preserving the spatiotemporal variability that is critical to assessing water quality. This technology predicts the values of the sample data points within the area of each processing by averaging their values. The water quality modelling simulation results and estimated water quality index was imported into ArcGIS software and digitized values at unknown locations were interpolated using IDW method. The general equation of IDW is given as follows;

$$D = \frac{\sum_{1}^{n} \frac{z_i}{d_i^p}}{\sum_{1}^{n} \frac{1}{d_i^p}} \tag{15}$$

In this equation *D* denotes the predicated distance, *n* here denotes the number of neighbouring points that are nominated for the prediction, z_i here denotes the distance between the known points of the *ith* observation, and di indicates the distance between unknown and known points.

5.4 Results and Discussion

The QUAL2K model was setup for the 27 km length of Bhadra study stretch to assess the river water quality. The model was calibrated over a 91-month period (April 2006 to October 2013) and validated during a 41-month period (November 2013 to March 2017). The simulated results along with the available observed values of the monitoring stations are shown in Figures from 17 to 22.

5.4.1 Calibration and Validation of Water Quality Modelling QUAL2K

The calibration, and validation outcomes for water quality measures over the Bhadra river length is illustrated in the Figures from 18 to 23. The statistical error measurement developed to evaluate model performance was R^2. During calibration, the R^2 value for Temperature, Ec, DO, BOD, Nitrate and pH are noted as 0.98, 0.86, 0.72, 0.28, 0.65 and 0.57, respectively. During validation period, the R^2 value for Temperature, Ec, DO, BOD, Nitrate and pH are 0.58, 0.99, 0.83, 0.86, 0.26 and 0.52 respectively as shown in Table 11. The Temperature, Conductivity and DO values are very much satisfactory due to an excellent match with the observed data during the calibration and validation period. While BOD, Nitrate and pH are satisfactorily matched with the observed data.

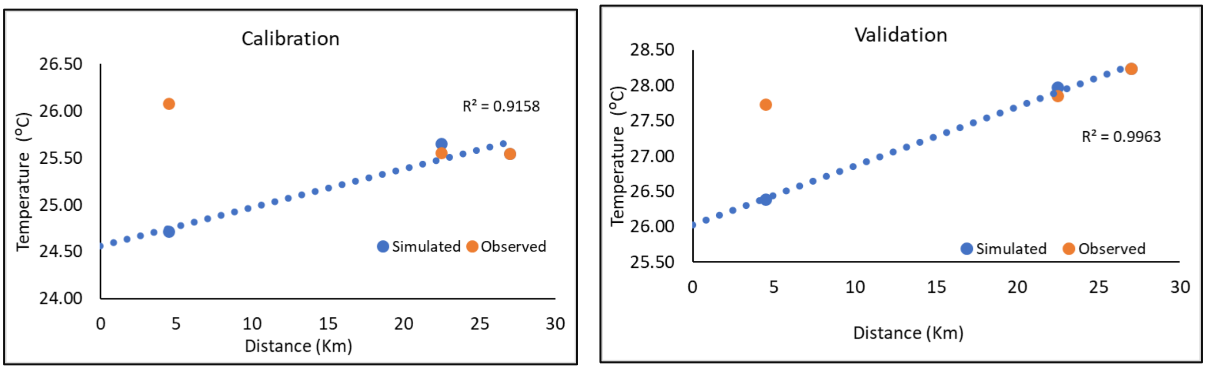

Figure 18. Calibration (April 2006 to October 2013) and validation (November 2013 to March 2017) Results of Temperature for Bhadra River

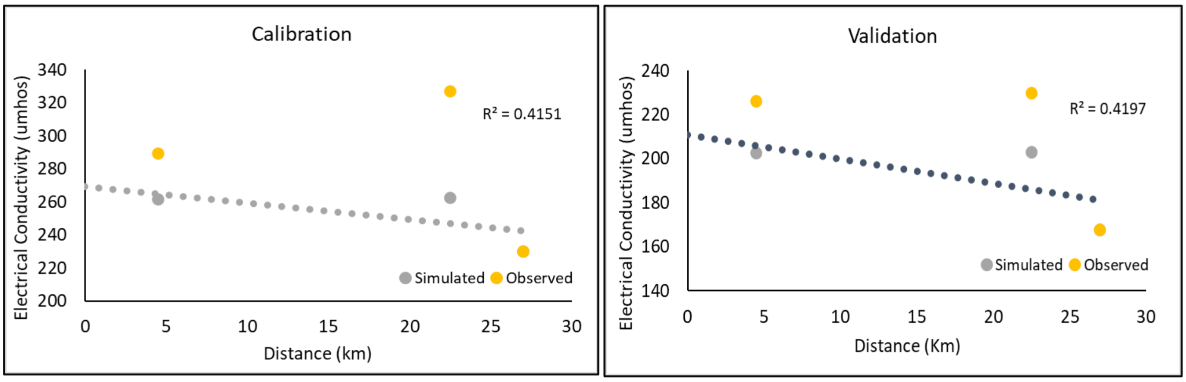

Figure 19. Calibration (April 2006 to October 2013) and validation (November 2013 to March 2017) Results of Electrical Conductivity for Bhadra River

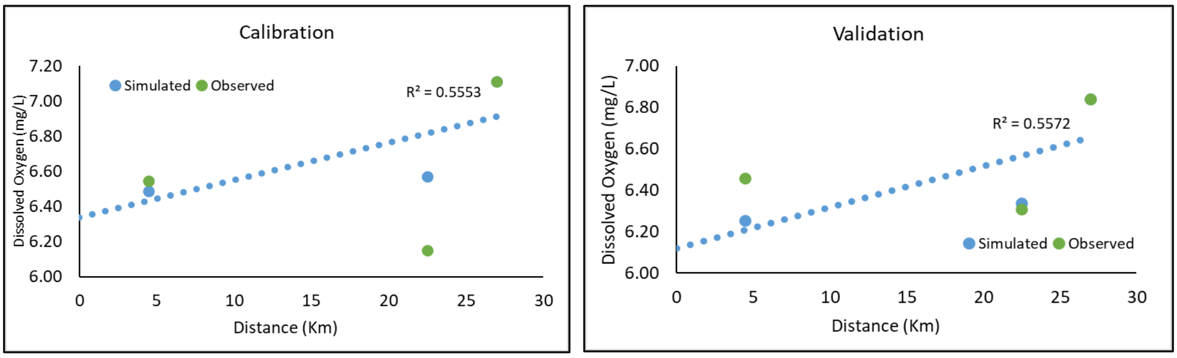

Figure 20. Calibration (April 2006 to October 2013) and validation (November 2013 to March 2017) Results of Dissolved Oxygen for Bhadra River

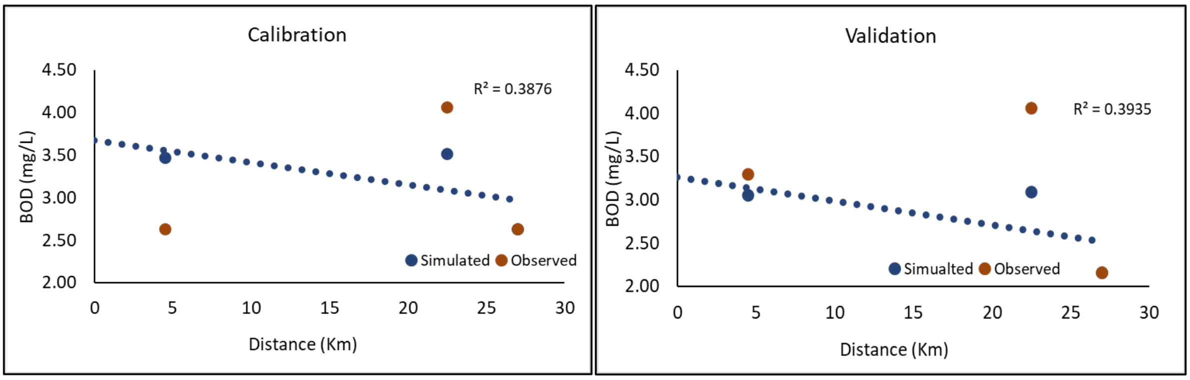

Figure 21. Calibration (April 2006 to October 2013) and validation (November 2013 to March 2017) Results of BOD for Bhadra River

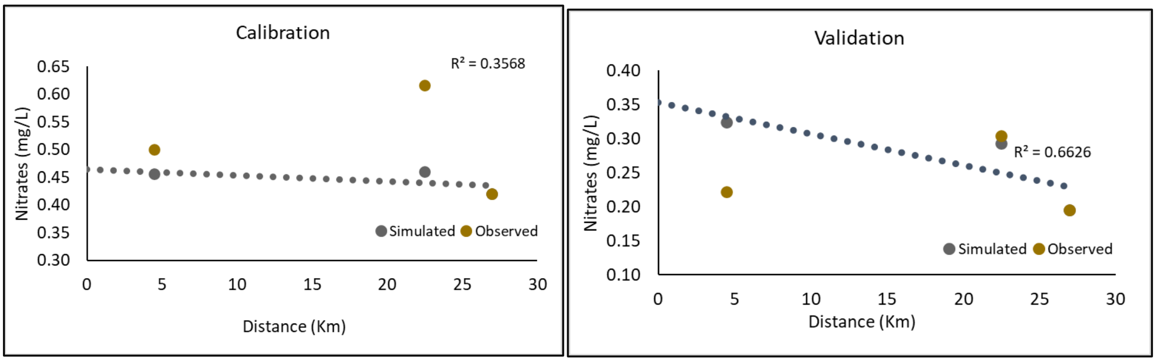

Figure 22. Calibration (April 2006 to October 2013) and Validation (November 2013 to March 2017) Results of Nitrates for Bhadra River

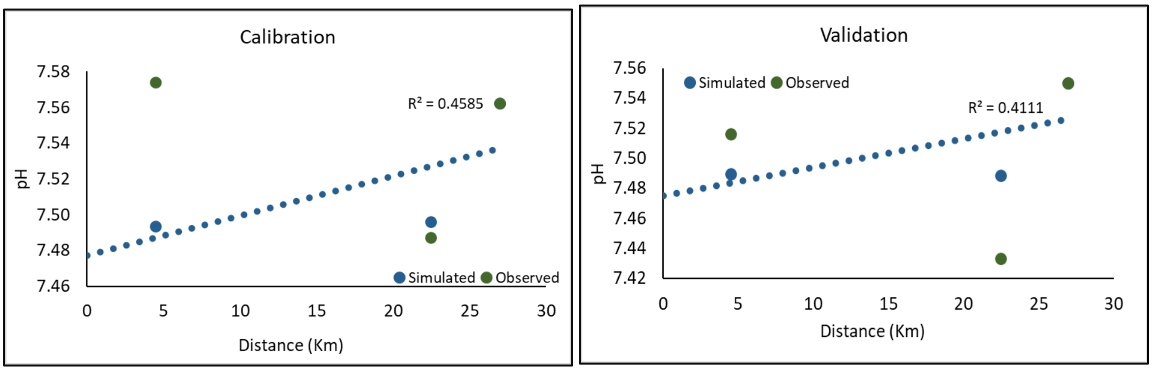

Figure 23. Calibration (April 2006 to October 2013) and validation (November 2013 to March 2017) Results of pH for Bhadra River

Table 11. Model performance value R^2 for simulated and observed water quality parameters.

Water Quality parameters	**R^2**	
	Calibration	Validation
Temperature	0.98	0.58
Electrical Conductivity	0.86	0.99
Dissolved Oxygen	0.72	0.83
BOD	0.28	0.86
Nitrate	0.65	0.26
pH	0.57	0.52

5.4.2 Mapping of Water Quality indicators used for WQI

To map the water quality parameters over the entire study, stretch the interpolation techniques are used in this study. The use of interpolation technique such as inverse distance weighting (IDW) method is most often utilized approaches for modelling spatial distribution based on point data [132]. In this work, IDW was used to prepare the several theme layers for water quality data. The IDW in the research region was calculated using the river designated watershed.

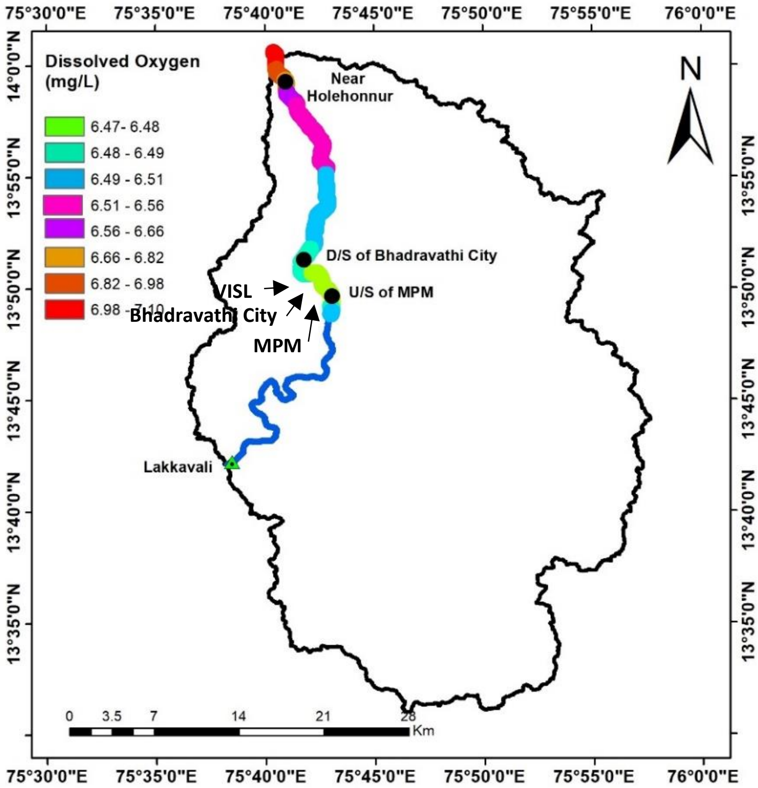

Figure 24. Spatial Distribution of Dissolved Oxygen for Bhadra River

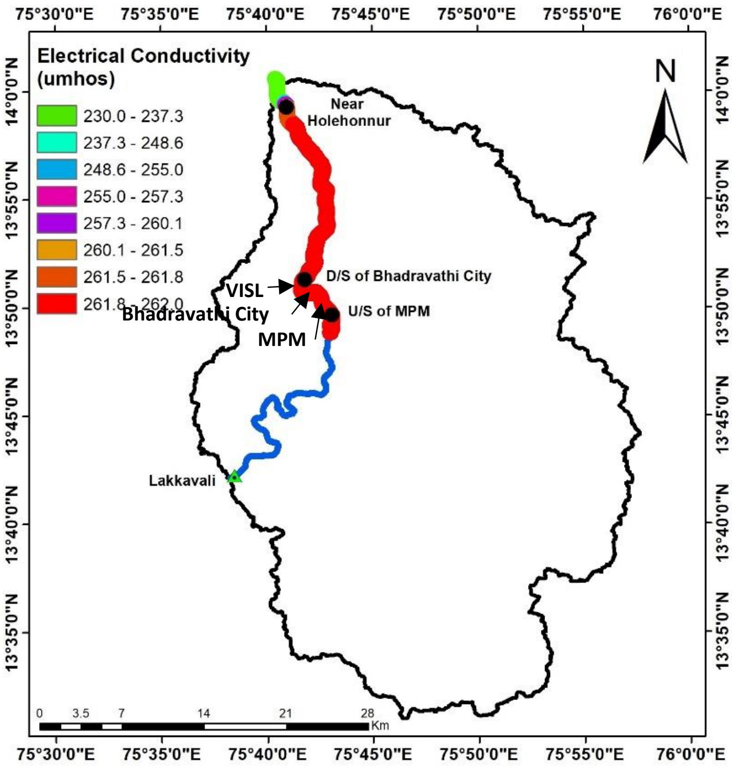

Figure 25. Spatial Distribution of Electrical conductivity for Bhadra River

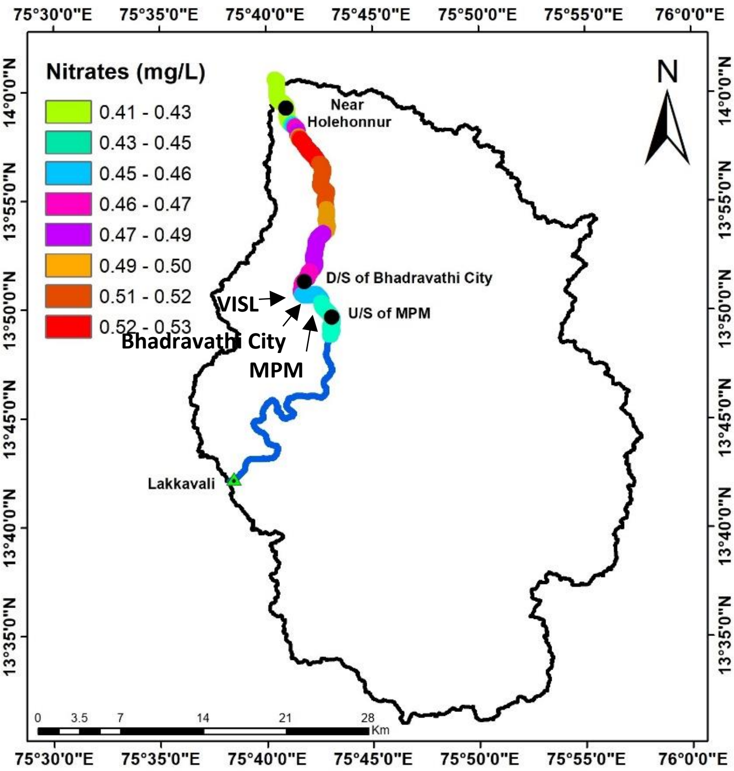

Figure 26. Spatial Distribution of Nitrates for Bhadra River

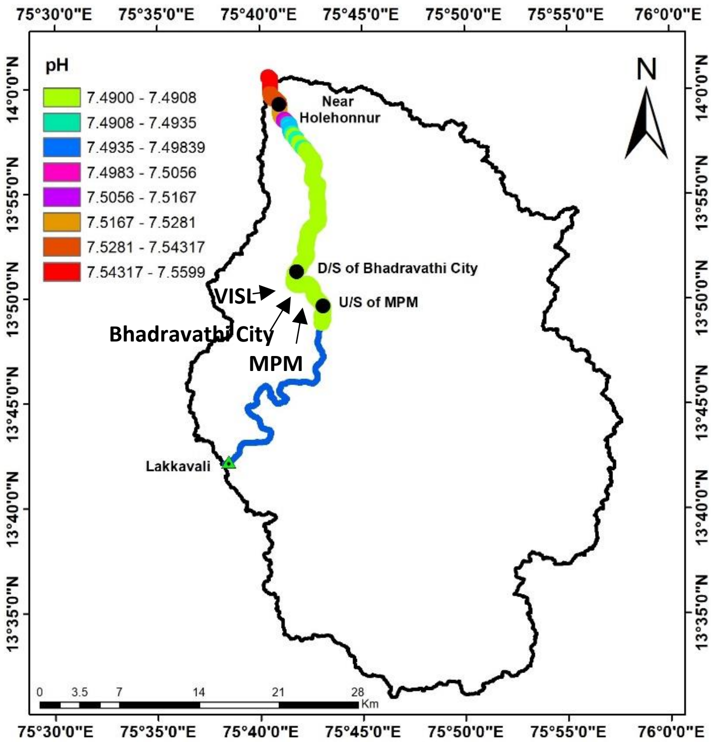

Figure 27. Spatial Distribution of pH for Bhadra River

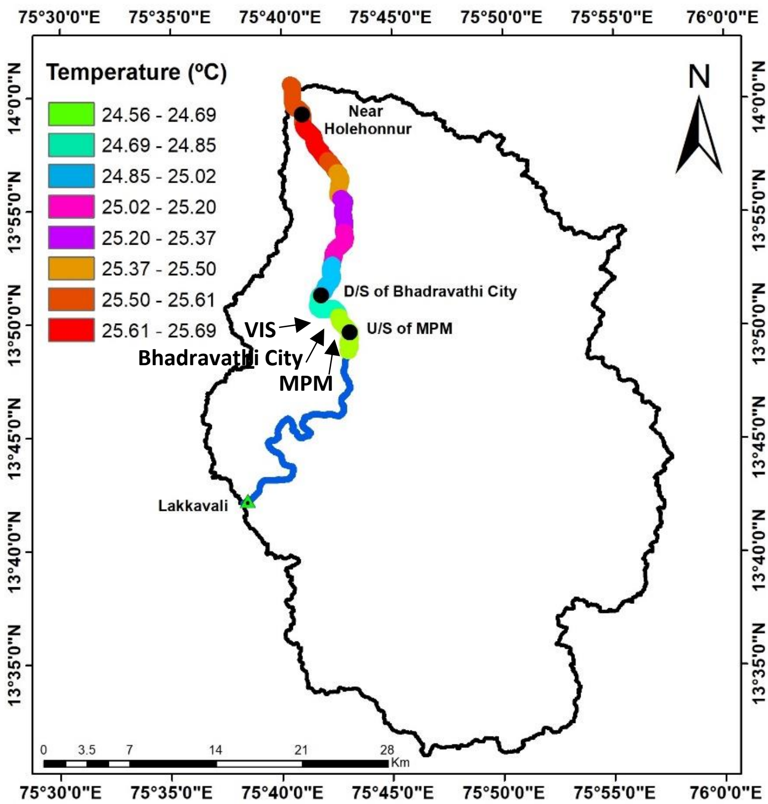

Figure 28. Spatial Distribution of Temperature for Bhadra River

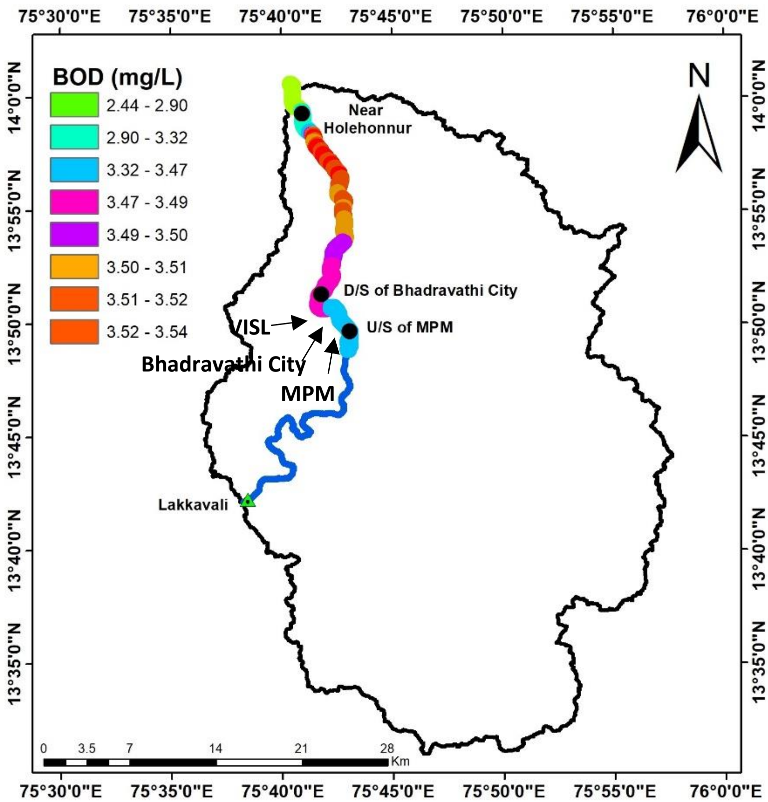

Figure 29. Spatial Distribution of BOD for Bhadra River

Figure. (24 to 29) depicts the interpolated maps illustrating the spatial distribution of the studied water quality indicators in the Bhadra river. According to the results of the analysis, the concentrations of DO decline from the upstream sampling site to the downstream sampling site, while the concentrations of BOD decreased from the upstream sampling site to the downstream sampling site, indicating the domestic effluent came from the sampling station. Bhadravathi city (Figure 24 and Figure 29). The water pH remained mostly alkaline, ranging from 7.49 to 7.55 for all monitoring stations (Figure 27). There was no uniformity in the water temperature between the sampling stations and the temperature decreased from upstream to downstream as they moved along the river system, ranges from 24.56 ^{0}C to 25.69 ^{0}C (Figure 28). Higher levels of electrical conductivity were found in lower and medium segments imprinting the untreated domestic effluent from Bhadravathi city (Figure 25). The spatial distribution pattern for Nitrates was found uniform, with a range of 0.41 mg/l to 0.53 mg/l, which is relatively low and within the permissible limit (Figure 26).

5.4.3 Estimation and Mapping of WQI using WA-WQI method

The estimation of WQI using WA-WQI method is based on the unit weights of the individual water parameters and these can be estimated using Equation 11. The standard values for the parameters used in estimation of WQI and the calculated unit weights are given in the below Table 12.

Table 12. BIS standards and unit weights of the WQI parameters

Parameters	**Units**	**BIS Standards**	**Unit Weight**
pH	unit	8.5	0.048
Dissolved Oxygen	mg/L	4	0.1022
Electrical Conductivity	µs/cm	300	0.007145
Nitrate	mg/L	45	0.0091
Temperature	°C	25	0.01636
BOD	mg/L	30	0.0137

The water quality status for the Bhadra River was evaluated using WA-WQI, and the score of WA-WQI for each of the surface water quality stations is presented in Figure 30. In contrast, the spatial distribution of the interpolated WA-WQI values has been shown in Figure 31. Very poor status of water quality was found for the upstream surface water quality station of MPM with a WQI score of 92.35. Similarly, the subsequent station demonstrated very poor water quality status at Bhadravathi city with a score of 98.38 and unfit for consumption status for Holehonnur with 102.04 score. In order to further support this argument, spatial distribution analysis was used to visualize the interpolated WA-WQI score (Figure 31). The score of WA-WQI indicates that the rivers water quality was in very poor status due to untreated domestic and industrial effluent, which continues to flow on the downstream side of the study river stretch. Due to lack of acceptable flow to attain the self-purification of river stretch the WQI values are in an increasing trend from upstream segment to downstream segment of the study stretch. According to the findings, the MPM water quality station was a hotspot for river water quality degradation. It was also noticed that the river quality was majorly deteriorated near the Bhadravathi segment where urbanization was more and sewage and industrial effluents are entering into the stretch. Thus, water quality has been severely impacted due to the effluents and waste dumped in the river at its prevailing scale.

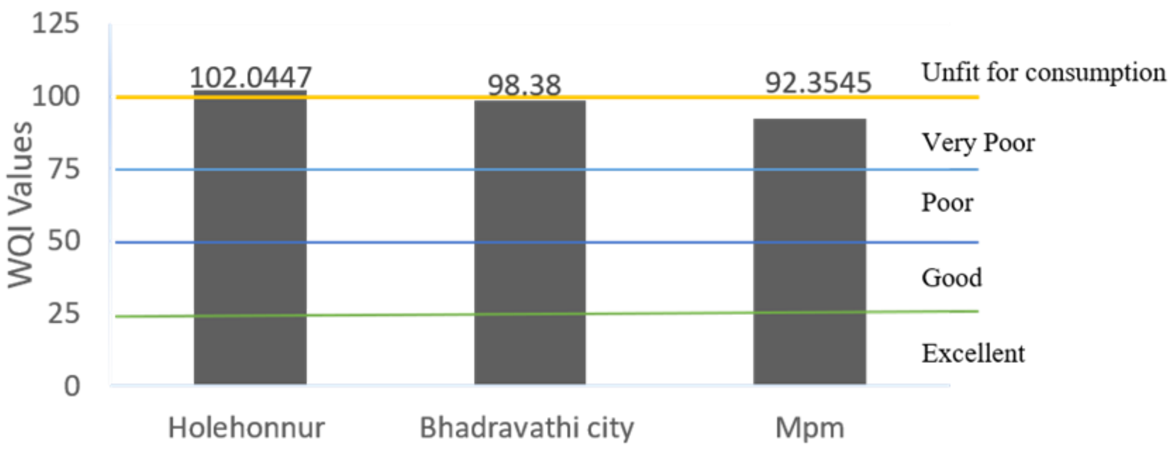

Figure 30. Water quality index values for three monitoring stations along Bhadra River Stretch

The IDW findings were used to map the pollution hotspots, and the results showed that the middle segment (Bhadravathi segment) of the study river stretch has the most severe pollution hotspots. The upstream segment and downstream segment fall under the very poor category but the middle segment i.e., Bhadravathi segment comes under the Unfit for consumption category (Figure 31).

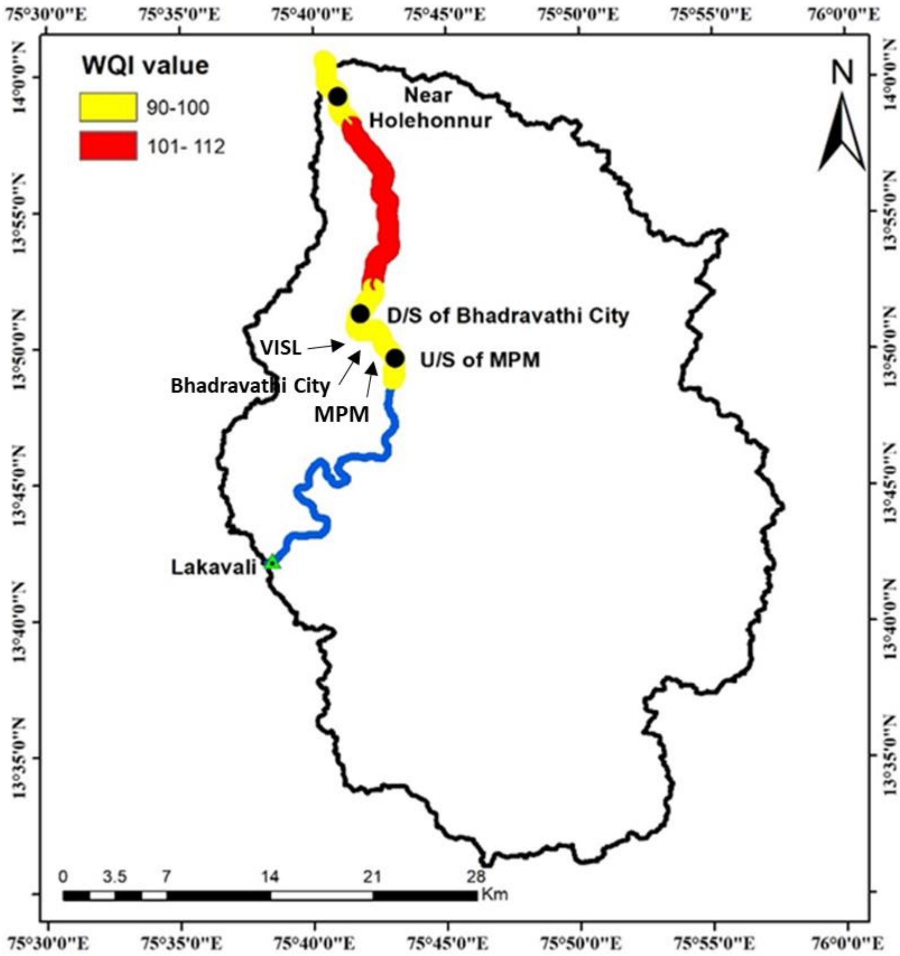

Figure 31. Spatial distribution of Water Quality Index for polluted River Stretch

5.5 Conclusions

In this research, surface water quality data from monitoring stations, climate and hydraulic data were used to setup the QUAL2K model to assess the pollutant distribution in the Bhadra river stretch. The WQI was estimated using the WA-WQI method by considering the QUAL2K findings and IDW spatial interpolation technique is used to create the spatial distribution water quality maps. The research findings of the study found that the upstream segment of the Bhadra River had significantly degraded water quality using GIS and WA-WQI models and important to detect pollution hotspots. The findings agreed with those of earlier investigations on the same case study. Considering this, the combined WA-WQI and GIS indicated that the majority of the water quality parameters in the Bhadra river were above the permissible limits, prompting the creation of immediate action plans and efficient river water quality management systems. Industrial and domestic waste are the major causes of Bhadra river pollution, and these wastes often flow into nearby rivers. The findings may thus be used to make the following conclusions:

- The river water quality simulation model, QUAL2K was calibrated and validated to simulate the water quality over the Bhadra river study stretch. The river pollution extent was studied using WQI with various river water quality parameters simulated using WA-WQI method.
- The estimated water quality index values for three monitoring stations are ranges from 92 to 102. The maximum WQI score about 102.04 attained for the Holehonnur station which falls under unfit for consumption category.
- The WA-WQI readings at monitoring stations show that the water quality at MPM and Bhadravathi stations is very poor, while the water quality at Holehonnur with a 102.04 score is unfit for consumption state. This demonstrates that there is not an adequate flow to achieve the river stretch self-purification.
- According to the WQI map produced using the IDW interpolation approach, the middle segment of the study stretch fall into the category of unfit for consumption because of the combination of effluents from industries like MPM and VISL and urban effluents from Bhadravathi city.
- The current study methodology for identifying pollution hotspots and formulating rules and regulations for river water quality management can provide advisory and guidelines for stakeholders, water quality maintenance agencies, and decision-makers.

Chapter 6

Summary and Conclusions

River water quality is becoming more crucial due to the excessive pollution that is being released from various sources, such as industries and domestic sewage discharges. For riverine health systems to be managed and sustained for future generations, an assessment of the river water quality is an essential component of evaluating their effectiveness. In this current study, river water quality has been assessed by integrating water quality modelling and water quality index with GIS techniques. The 1D-dimensional steady-state hydraulics, non-uniform steady flow model QUAL2K is employed to simulate the water quality conditions and cause of impairment and to predict the changes in watersheds and their environment. Using the parameters of water quality, this model has the capacity to simulate a wide range of branching stream scenarios that will mix laterally and vertically based on the characteristics of the streams.. The study examined different plausible pollution scenarios of Biological Oxygen Demand (BOD) effluent for modelling Dissolved Oxygen (DO). Using the QUAL2K simulations, the river water quality index was estimated using the Weighted Average Water Quality Index (WA-WQI) method. The river water index measures the overall quality status of surface water based on several factors. It is a single value that indicates the quality of river water based on an aggregation function that enables the analysis of large, temporally, and spatially varying datasets of water quality parameters. For spatial visualization and analysis of concentration distribution water quality indicators in the study area, the Arc-GIS (Geographical Information System) software and Inverse Distance weight (IDW) spatial interpolation methods have been considered in this study. The research findings of the study revealed that the upstream segment of the Bhadra River has significantly degraded the surface water quality; hence important to detect the pollution hotspots. This study has yielded the following research findings, which are summarized as follows:

- The study systematically formulated the river water quality model, QUAL2K, which was calibrated and validated to simulate the water quality parameters over the Bhadra river stretch.

- According to the results, the Bhadra river stretch is highly polluted because of effluents from industries in the study area, primarily MPM & VISL. To achieve the CPCB minimum standards, BOD effluent must be reduced by 25%.

- This study demonstrates that the validated QUAL2K river water quality model is capable of reliable forecasting DO under a variety of contamination scenarios. It is found that the average DO levels have increased by 15% across the entire study stretch because there has been a 75% reduction in BOD effluent from point sources.

- In this study water quality index was estimated using QUAL2K simulation results using WA-WQI, which revealed Holehonnur station with a maximum score of 102.04, representing the water quality status as unfit for consumption.

- According to the spatial distribution map of WQI generated using the IDW spatial interpolation approach, the middle segment of the study stretches falls into the category of unfit for consumption due to the combing effluents from industries like MPM and VISL and urban effluents from Bhadravati city

- The study suggested that the flow in the downstream river which is mainly contributed by the inadequate release from the reservoir in addition to the river to achieve self-purification as the water quality stations MPM and Bhadravati city fall under poor water quality status

- Overall, the results showed that the integrated approach was effective in assessing and managing water quality in the river basin. The QUAL2K model was able to simulate the water quality parameters accurately, and the WQI provided a comprehensive assessment of water quality. The GIS techniques allowed for the spatial distribution of water quality indicators, which helped in identifying the hot spots that needed immediate attention for water quality management authorities.

In this study, we have demonstrated the integration of water quality modelling with water quality index and spatial distribution using GIS techniques. We have explored the potential of these techniques to provide a comprehensive understanding of water quality and its spatial variability. As a result, it is imperative to note that these results are limited by a few several underlying factors which contribute to their limitations. A significant amount of errors and uncertainties can be phased out when simulating the QUAL2K model, including data uncertainties, parameter uncertainties, model structure and complexity, model calibration, boundary conditions and model limitations, and process representation such as oxygen demand and nitrogen nitrification. Errors can occur if these processes are not adequately represented or if there is not enough data to support their accurate estimation.A realistic understanding of the models capabilities and limitations is essential to addressing uncertainties within QUAL2K. This will be achieved by improving data quality, refining the model, and calibrating and validating the model.In this study, headwater discharge was employed as a method of analysing reservoir storage without considering other water usage and distribution mechanisms. Future studies might be able to incorporate direct measurements of headwater release, the analysis of remote sensing data, or the development of hydrological models as alternative strategies. In conclusion, future investigations should explore the effects of climate change in order to improve the assessment of water quality. In this study, the water quality was assessed using limited water quality data, but some key water quality parameters like nitrogen and phosphorus were not considered. Due to a lack of data for other parameters in the water quality modelling process, the current study primarily used DO values as the primary indicator of water quality since the majority of the riverine health system relies on DO levels. For future work, this study can be the basis for generating climate change scenarios and flow variation scenarios for predicting river water quality. Other water quality parameters like turbidity, sediment flux and nutrients could also be integrated into these studies for forecasting river water quality. The proposed holistic approach can be used by policymakers and water resource managers to make informed decisions about water quality management in the Bhadra river basin.

Related Publications

- Mummidivarapu, S.K., Rehana, S., Singh, H., (2023) Application of QUAL2K Model for Water Quality Modeling of Bhadra River Stretch, India, 978-981-19-9150-9, 526459_1_En, (Chapter 46), Lecture Notes in Civil Engineering, Vol. 314, P. V. Timbadiya et al. (Eds): Fluid Mechanics and Hydraulics, DOI: 10.1007/978-981-19-9151-6.

- Singh H., Rehana S., Kumar, M.S., (2022). Assessment of River Water Quality Using Qual2k Model and Water Quality Index for the Bhadra River, India 27 the International Conference on Hydraulics, Water Resources, Environmental and Coastal Engineering (HYDRO 2022 INTERNATIONAL) at Punjab Engineering College Chandigarh, India during December 22 -24, 2022.

- Kumar, M.S., Rehana S., Singh H., (2021). Application of QUAL2K model for water quality modelling of Bhadra river stretch, India. 26th International Conference on Hydraulics, Water Resources, and Coastal Engineering (HYDRO 2021 INTERNATIONAL) SVNIT, Suraj, Gujrat December 2021.

- Application of Water Quality Modelling QUAL2K in Bhadra River Stretch Karnataka. Indo –US International Bilateral Workshop on Water and Air Research Initiative for Societal Health (WaRISH) Poster Presentation. SRM Institute of Science and Technology, Tamil Nadu. Virtual Workshop 24-25 August 2021.

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