A Water Quality Assessment and Modelling of the Indian River Tungabhadra

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***Abstract*—Every river gets polluted as it moves from its source to the end. Hence, the quality of the water requires investigation for the usability. In the present work 40.69 km stretch of the river Tungabhadra in the Davangere district of the Karnataka, India was chosen for testing the water quality. The samples' physical, chemical and biological characteristics were tested from eight sites for each month during pre-monsoon, monsoon and post-monsoon seasons from 2017 to 2019. A biochemical oxygen demand-dissolved oxygen (BOD-DO) equation was estimated using the de-oxygenation and reaeration constants. The results showed that the physical and chemical parameters were within the limits of the usability standards for all the sampling stations during all seasons. For the first 2.54 km of the River Tungabhadra, the biochemical oxygen demand (BOD) levels were categorized as class "C", implying the river water to be within drinking water standards. However, from 2.54 to 40.69 km stretch, the river was classified as class "D", making it unsuitable for drinking water. It was also shown that the river could be maintained class "C" if it flowed at 6m^3/s which can be achieved by releasing water from the Tunga and Bhadra reservoirs. Moreover, treatment of the municipal waste before spilling to the river would further reduce the BOD levels.**

***Index Terms*—Dissolved oxygen control, QUAL2KW, Tungabhadra River, water quality**

I. Introduction

A report released by UNESCO in March 2018, stated that India's impending water crisis will intensify all over India by the year 2050. With a decline of 40% of the renewable surface resources, central parts of India are already suffering from the water crisis. As more people are in need of groundwater for their daily requirements, the pressure on water supply increases.

India's population density implies a high need for human waste disposal systems. Since these systems are lacking, India counts the highest percentage of people without access to clean water, something that becomes even worse due to the mass emigration of people to cities. Aside from the lack of effective treatment and sewage removal of waste, poor urban planning and management have made the only form of waste disposal directly flushing faecal matters into the river Ganges, making it one of the most polluted rivers in the world.

Despite failing the World Health Organisation Sewage Pollution Standards for irrigation [1], the Ganges serves an important role in the country. Millions of people rely on its resources for food and fibre, it holds a spiritual significance for the Hindus during the Kumbh Mela and it serves as a source for irrigation for the population living along its catchment area. Only 15% of the population living along its catchment area has access to clean water. The rest of the population is using water that isn't even safe for bathing.

The sewage system and urbanisation are not the only culprits for the poor water quality in India, industries and agriculture too join the list. Most of India's rivers become victim of toxic waste water from the industry and intensive agriculture contributes to the declination of water quality of India's rivers. At the onset of the monsoon, traces of fertilizer and pesticides get washed up into the river system, creating indirect sources of water pollution [2].

To endorse laws and assess the effectiveness of water system management programs, the study of water quality has become important. Until now, the river Tungabhadra has not been subjected to water quality assessments. Due to the disposal of industrial and local waste, the river is under threat, emphasizing the importance of understanding the quality implications of water pollution on human and aquatic life to manage the polluted segment of the river effectively. Customized solutions can be made through the scientific modelling of various methods, giving a lot of opportunities for integration, analysis and evaluation of water quality issues, setting a guide for planners, policy makers and decision makers to quickly curb pollution problems.

This study was carried out in the Davangere district of the Kamataka state, on the 40.68 kilometer stretch of the Tungabhadra River. This river has two major tributaries, which are the Bhadra and Tunga. The town used in this case study is Harihara town, located on the bank of the river. It serves as a major industrial base for the textile and sugar industries and has a population of over 1.0 lakh. To study the seasonal variations in water quality, monthly samples were collected during pre-monsoon, monsoon and post-monsoon seasons for the years 2017 to 2019.

The objectives of this study are:

- To identify and analyse sources of pollution, assessing the water quality of the Tungabhadra River in terms of various physico-chemical and biological parameters
- To study the variations of the water quality parameters in different seasons and develop suitable water quality indices
- To develop a comprehensive BOD-DO model by determining the kinetic parameters, such as biochemical oxygen demand (BOD) loss rate, de-oxygenation constant, sediment oxygen demand and the reaeration constant

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- To evaluate a predictive equation of the reaeration constant by error statistics using the measured data of the reaeration constant
- To develop an appropriate refined predictive equation for the reaeration constant and evaluate the performance of this equation in comparison to previous reviewed predictive equations
- To measure hydro-geometric parameters (e.g. flow, channel slope, side slopes, etc.) and characteristics of waste inputs at various reaches of the river required to execute the QUAL2KW model
- To calibrate and validate of the QUAL2KW model
- To compare the results predicted by the model with the actual measured values and evaluate the performance of the model by using statistical analysis
- To simulate the validated QUAL2KW model to generate alternative scenarios and suggest approaches to achieve the desired levels of river water quality.

II. The Indian River Water Quality

There are nine major rivers, that together with their tributaries form the Indian river system, offering a means of transportation, electricity, irrigation, and making the lives of many people over the country easier. The Bengal Bay is where almost all the rivers pour their water. However, several rivers flow through the country’s western region towards the eastern region of the state of Himachal Pradesh into the Arabian Sea. Water usage in India is classified as abstractive and in-stream usage. Examples of abstractive water usages are irrigation, domestic and industrial uses, whereas in-stream usage is classified as fishery, washing, hydropower, navigation, and community health.

A nationwide network called the Water Quality Monitoring Network was developed by the Central Pollution Control Board (CPCB) in association with The State Pollution Control Boards (SPCB). A network of water quality monitoring systems was established, made up by 4022 units in 28 states and 6 union terrains. The National Water Monitoring Program and River Basin Studies is generating water quality data since 1980, observing a declinein the water quality levels in the river system and water bodies. Water bodies that do not meet the water quality criteria are identified as polluted river stretches or water bodies. In association with the CPCB, the various stages of pollution in rivers have been set out and according to the organic pollution the limitations are: highly polluted (BOD > 6 mg/L), moderately polluted (BOD 3−6 mg/L), and relatively clean (BOD < 3 mg/L). Because of the release of untreated domestic waste water from urban centres, the levelof bacteria and organic contamination is extreme in water bodies. From 1995 to 2012, 13–19% of the water bodies had BOD levels higher than 6 mg/L, with a 19% peak observed in 2001 and 2002.

The major source of water pollution in India is the discharge of domestic sewage from towns and cities. According to the tenth plan document from the Indian planning commission, sewage alone constituted 80% of the total water pollution in the country [2]. Generation of sewage in cities (Class 1) and towns (Class 2) towns is estimated to be 29,129 MLD. Water pollution in the industrial sector is concentrated within a few sectors, especially for organic pollutants and toxic waste. Chemical processing is a large contribution to the pollution of the river system. In addition to effluents from industries, the total waste discharged into the rivers is over 3 billion litres of daily waste. The amount spent on different clean up measures is approximately 20 billion Rupee.

III. Study Area

The Tungabhadra is a major tributary of the River Krishna, which is also the second largest Peninsular river that flows into the Bay of Bengal. The other rivers that contribute to the River Tungabhadra include the rivers Tunga, Bhadra and Vedavati. The Tunga and Bhadra originate at Gangamula at the Varaha Peak at Lat 13, 15'N, 75, 14'E long of the Western Ghats in Chikamagalur District. The Tunga passes down the deep valley which is situated between the fragmented chain of hills. After sliding away from the Ghat section, the Bhadra flows past the industrial town of Bhadravati and joins the river Tunga at Kudali at an elevationof 610 meter, a relatively flat area. The River Tungabhadra moves through high banks of red loamy soils of subsequentlysmall streams before it falls into the unified River Krishna. The Tungabhadra travels for around 550 km from Kudali in the general northeaster course where it joins the stream Krishna at Sangameshwar in the Mahabubnagar region of Andhra Pradesh at an elevation of 264 metre as shown in Fig. 1.

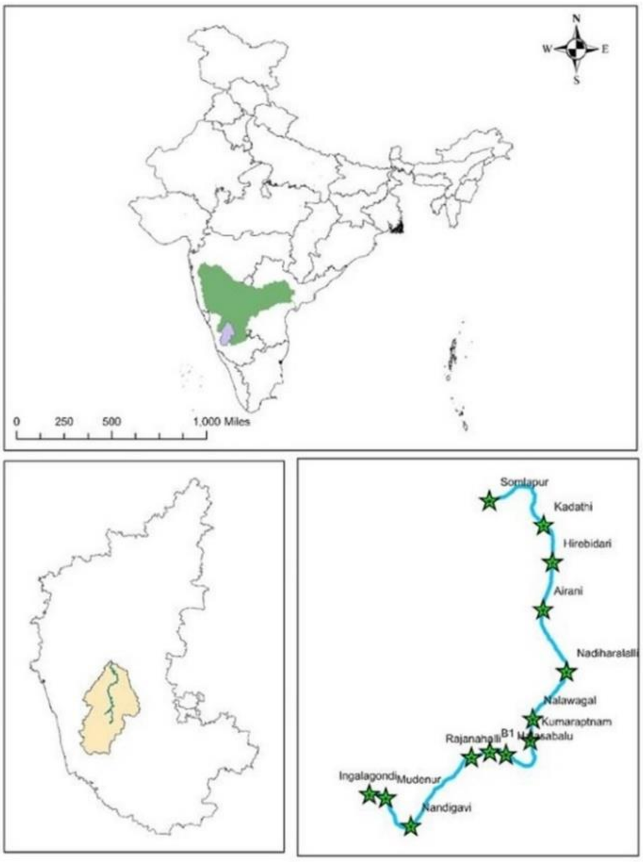

Fig. 1. Possible sample collection sites along Tungabhadra River [1].

The stream Tungabhadra is the monetary life-blood of northern Maidan and saddled both for hydropower and major irrigation purposes in the Bellary region. It waters around 480,000 hectares of land in the Raichur and Bellary districts of Karnataka and Rayalseema areas of Andhra Pradesh. It receives rain from the southwest monsoon, which is from the end of May till the end of September. The water drawing rainstorm begins mid-October and ends before the end of December. The yearly precipitation falls from 500 to 1000 millimetres. The yearly temperature ranges between 29 C and 34 C. The factors having an impact on vegetation are precipitation, soil type and temperatures in the plain zones of Karnataka.

Numerous small industries are located on the banks of the rivers, getting contaminated by the waste discharged by those industries. River Bhadra gets 15,141.65 litres/minute of untreated waste from Mysore mash and paper factories and around 56,781.177 litres daily from steel plants. The release of treated effluents carries 102 to 21 mg/L of chlorine and 91 to 14 mg/L of sulphide which have been identified even up to 18 kilometers downstream of the River Bhadra into the River Tunga. The River Tungabhadra receives effluent discharge from two significant wood based industrial units at Kumarapatnam: Harihar Polyfibre Factory (HPF) and Grasilene Fiber Factory (GRF). The enterprises in this area have no or insufficient preventive measures for contamination control. The industries' effluents are regularly released in the afternoon or in odd hours without legitimate and critical pre-treatment. The present study measures the water quality of the river water over the Tungabhadra stretch of 40.69 km, in the form of the following eight sampling stations as shown Fig. 2 and Table I.

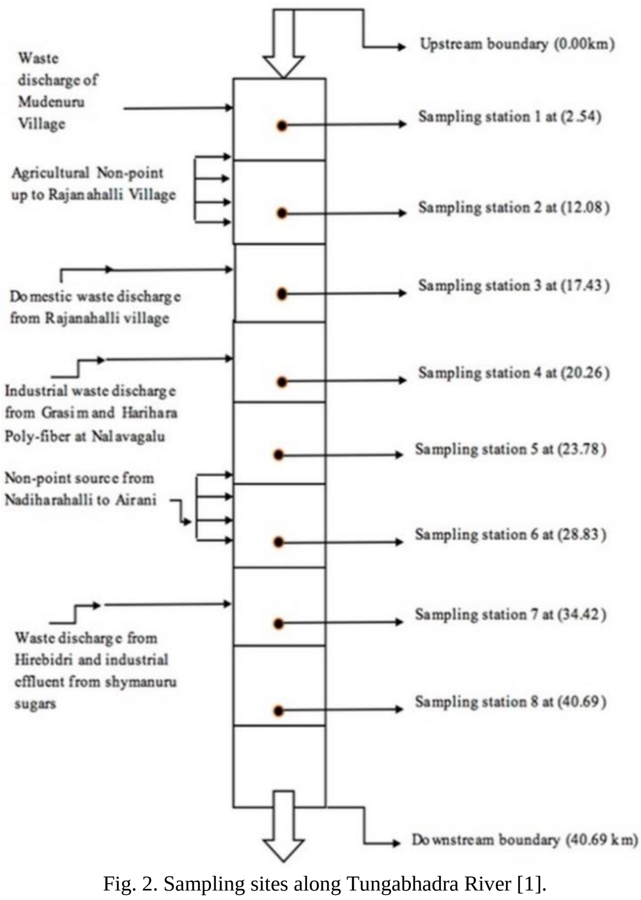

Fig. 2. Sampling sites along Tungabhadra River [1].

TABLE I: LIST OF SAMPLES COLLECTED STATIONS AND DISTANCE

S.No	Station Names	Station Number	Distance (km)
1	Mudenuru	1	2.54
2	Rajanahalli	2	12.08
3	Kumarapatanam	3	17.43
4	Nalavagalu	4	20.26
5	Nadiharalli	5	23.78
6	Airani	6	28.83
7	Heribedri	7	32.42
8	Somalpura	8	40.69

IV. MATERIALS AND METHODS

A. Selection of Sampling Stations

Eight points at the 40.69 km river stretch were selected for water quality evaluation relating to different biological and physico-chemical features. These points were chosen based on the impact of pollution due to waste disposal from every point and non-point source.

Water and effluents must be thoroughly examined for every water sample to properly determine physico-chemical water quality. The density of water from tributaries or effluent outfalls differs from the density of the major channel. Combining this with inadequate lateral mixing leads to the formation of long trails of unmixed water, flowing through one side of the river. Complete mixing can happen fast, however, it may not happen for several km. One of the most common mistakes in the evaluation of water quality is not developing a complete mix before sampling an effluent disposal down-stream from a point source, resulting in an under or over estimation of the effects. In the present study all sampling station are chosen based on the mixing of sewage waste with river water. When developing a water quality model for a river, it's critically essential to analyze the models' kinetic limitations. The limitations evaluated for developing the analytic BOD-DO models in the current study are the BOD loss rate, Kd, the de-oxygenation constant, Kr, and the reaeration constant, Ka. The river stretch from 19.0 to 32.1 kilometer was picked for evaluating these limitations, since the river has no further abstraction and disposal of water, except the discharge of domestic water from the up-stream reach at the Kumarapatanam village.

B. Sampling Program

The different parameters that were used for the evaluation of the water quality analysis of the River Tungabhadra are physical parameters (e.g. conductivity, temperature, and turbidity), chemical parameters (e.g. dissolved oxygen (DO), pH, chemical oxygen demand (COD), total dissolved oxygen (TDS), hardness, alkalinity, sodium, calcium, potassium, magnesium, phosphates, chloride, ammonia nitrogen (NH3-N), sulphate, nitrate, and total kjeldahl nitrogen (TKN)), and biological parameters (e.g. total coliform (TC), BOD, and faecal coliform (FC)) [3].

Samples were collected from all sampling stations during each month from March 2017 to February 2019 considering March–June, July–September, October–February as Pre-Monsoon, and Post-Monsoon Period respectively. In the pre- and post-monsoon period, samples were collected in the first seven days of each month. In the monsoon period, the samples collected for evaluation were collected during non-rainy days. Water samples were collected at approximately fifteen centimeters below water surface from three points: half, one third and two third of the river's width. Limitations like pH, temperature, DO and conductivity were measured in the field during the collection of water samples using portable measuring equipment [Multiparameter Waterproof Meter-Hanna Instruments India (HI98194)]

All parameters were determined in triplicate and the parameters of biological and physio-chemical characteristics for the pre-monsoon, monsoon and post-monsoon period were determined as an average of the two consecutive years.

The benchmark available at the Mudenuru Jack Well point is used to establish the slope of the stream of the river. Using the depth of the flow, the discharge of waste was estimated. In determining the discharging rate, the river channel's side slope and the river's width at the sampling station was considered.

The National Sanitation Foundation (NSF) created a method to assess the water quality index (WQI), existing of nine factors associated with weight, including pH, DO, BOD, temperature, total solids, turbidity, FC, nitrates and total phosphates [1]. The results of all parameters were recorded, placed on a weighing curve chart and standardized into various ranges similar to the general deceptive terms.

C. Water Quality Modelling

The mathematical modelling of the water quality levels of the river Tungabhadra was performed in different stages. The regular applied performance estimation statistics are: (1) the standard error or root mean square error (SE), (2) the normal mean error (NME), (3) the mean multiple error (MME), and (4) the correlation coefficient (r). Re-aeration is the process where oxygen is transferred into water bodies from the atmosphere. Water must be in direct contact with the atmosphere as the DO concentration drops below saturation at a certain temperature. In this way, a water body can recuperate DO.

The disposal of organic waste causes the reduction of DO concentration through the micro-organisms of the pollutant's metabolism. This biodegradable organic matter is calculated as BOD. The beneficial factor of the development of DO concentration is atmospheric reaeration, being defined as the variation between the level of actual oxygen and the saturated oxygen.

The QUAL2KW water quality model [4] is used for modelling DO, BOD and total nitrogen (TN) of current states of waste disposal. Data was collected during pre- and post-monsoon periods. The data of monsoon season is not used in this model since there was no critical difference in the water quality, due to the high flow state in the monsoon period. The QUAL2KWmodel is proposed to be used for both pre- and post-monsoon periods to help find the highest permitted polluted disposal in the river Tungabhadra and plan for strategies to reduces pollution hazards.

V. Exploratory

Water collected from the investigation site were placed in transparent carriage bags and glass bottles all of which had met the guidelines and later on preserved in the labs with no addition of chemicals. The water collected was placed under rigorous evaluation to access it components which was done within a day. To identify the water potency and nature of the water collected it was examined using the recommendedways [4]. The chemicals used in the examination process were of high standards, double purified water was also used to produce several solutions. The chemical features include the presence of the following compounds: sulphates, manganese chlorine, nitrates, power of hydrogen, potassium and calcium, where as physical attributes like emulsified content, conduction of current, condition of water, saturated oxygen, and general metals were found in the water. The sulphate element was identified through a rigorous chemical process involving absorption spectroscopy or reflectance spectroscopy in part of the ultraviolet, while as sodium together with potassium underwent process where the analysis uses the intensity of light emitted from a flame to identify the elements.

VI. Results and Discussion

A. Variations in Physical Parameters

In the pre-monsoon season, the sampling stations showed an average water temperature between 28.9°C and 31.7°C, average values of turbidity between 5.6 and 17.7 NTU, and average conductivity levels ranging between 241.6 to 408.6 µmhos/cm. During the monsoon season, the physical parameters returned average values at the sampling stations of 24.2 °C to 25.1 °C for temperature, the values of turbidity at the sampling stations were between 12.7 and 22.7 NTU, and the average conductivity values ranged between 140.1 to 270.18 µmhos/cm. For the the post-monsoon season, average temperatures ranged from 26.9 °C to 29.8 °C in sampling points 1 to 8, the values of turbidity at the sampling stations were between 4.7 and 12.6 NTU, and the average conductivity values ranged between 222.6 to 410.7 µmhos/cm. Temperature is a necessary limitation in the surface-water structure, as it affects the chemical reaction rate that has natural occurrences in water systems and influences solubility of water gases.

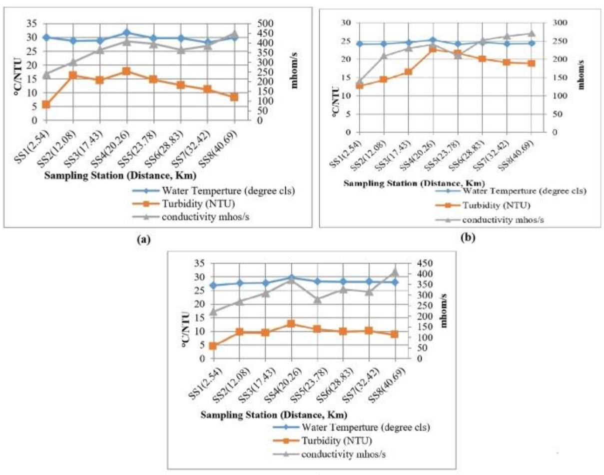

Fig. 3. Variation of temperature, conductivity and turbidity during a) pre-monsoon season; b) monsoon season; c) post-monsoon season.

Turbidity values increased during the monsoon period, due to the excessive runoffs from agricultural and urban areas.

The values reduce along the stretch, because of domestic waste water disposal from Rajanahalli village to Harihara town. Conductivity showed a slow increase in the values from sampling stations 1 to 8 in every period, because of contaminated water from domestic waste from areas located on the riverbank. Fig. 3 provides the visualization of the variation for each period.

B. Variations in Chemical Parameters

A depicted in Fig. 4, in the pre-monsoon season, the mean values of pH at the sampling stations 1 to 8 were ranged from 7.2 and 8.2, the values of alkalinity were between 84.8 and 168.7 mg/L as $CaCO_3$, the average TDS values ranged from 134.96 to 271.7 mg/L, and the total hardness showed levels from 86.2 to 160.1 mg/L as $CaCO_3$. During the monsoon season, the sampling stations showed that the mean values of pH ranged between 7.4 and 8.4, the values of alkalinity were between 69.0 and 136.6 mg/L as $CaCO_3$, the average TDS values ranged between 83.4 and 171.3 mg/L, and the total hardness ranged between 45.5 and 80.6 mg/L as $CaCO_3$. For the post-monsoon season, for all sampling stations, the average pH values were between 7.3 and 8.4, average values of alkalinity ranged from 78.7 to 148.7 mg/L as $CaCO_3$, the average TDS values ranged between 120.3 and 234.6 mg/L, and the total hardness showed levels from 71.6 to 121.6 mg/L as $CaCO_3$.

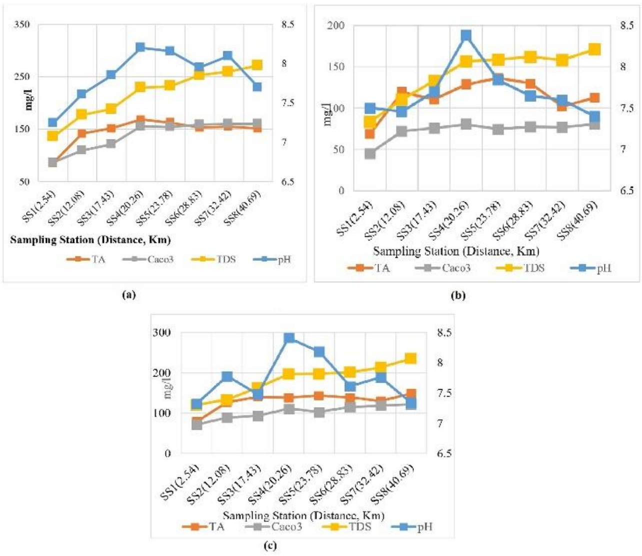

Fig. 4. Variation of pH, TDS, CaCO3 and TA during a) pre-monsoon season; b) monsoon season; c) post-monsoon season.

The increase of pH values may be due to the domestic waste disposal from Kumarapatnam town and other villages on the river bank. The pH values are considered at a standard level for drinking water for every station in every period. Due to contaminated water discharge from Harihara town as well as other villages located on the river bank, the value of alkalinity increases in the pre-monsoon period for sampling stations 2 to 5. The pH values were within the threshold limits of the IS 10500-1992 permissible limits [5]. High TDS values were due to untreated sewage disposal at the up-stream and the flow from urban and agricultural locations during the monsoon season. However, all TDS values in all seasons were within the limit of 500 mg/L, which is the standard for drinking water. As it is well established that hardness increases during the summer due to a low water level and current velocity, so it was observed that the hardness of water was at all stations in all seasons under the allowable limits of the 300 mg/L standards for drinking water.

C. Variations of Anions

In the pre-monsoon season, bicarbonate average values ranged from 46.2 to 101.3 mg/L as $CaCO_3$, the average content of sulphate ranged from 5.4 to 14.9 mg/L, the average values of chloride were 9.6 to 52.1 mg/L, the average values of nitrate ranged between 4.9 and 10.9 mg/L and the phosphate averages ranged from 0.5 to 2.6 mg/L, at all sampling stations. During the monsoon season, bicarbonate average values ranged from 31.4 to 74.7mg/L as $CaCO_3$ at sampling stations 1 to 8, the average content of sulphate was between 4.4 and 8.7 mg/L, the average values of chloride were between 14.1 and 38.7 mg/L, the average values of nitrate ranged between 3.7 and 8.8 mg/L and the phosphate averages ranged from 0.3 to 5.9 mg/L. For the post-monsoon season, bicarbonate values ranged between 43.1 and 91.6 mg/L as $CaCO_3$, the average content of sulfate ranged from 5.3 to 13.1 mg/L, the average values of chloride were between 25.3 and 42.1 mg/L, the average values of nitrate ranged between 4.1 and 8.5 mg/L and the phosphate averages were from 0.5 to 5.1 mg/L, at all sampling stations. The carbonate content was near insignificant in all stations and in all seasons, while there was a significant amount of bicarbonates. A gradual increase in values from station 2 to 5 in all seasons was shown (Fig. 5), due to the release of household sewage at the up-stream of all stations. The rise in sulphate content across station 2 to 5 might be due to release of household effluents at the up-stream and from agriculture in the monsoon. Chloride and sulphate values were within drinking water limits of 250 mg/L and 200 mg/L, respectively [5]. The observed nitrate values were within the limit of 45 mg/L for drinking water standards [5].

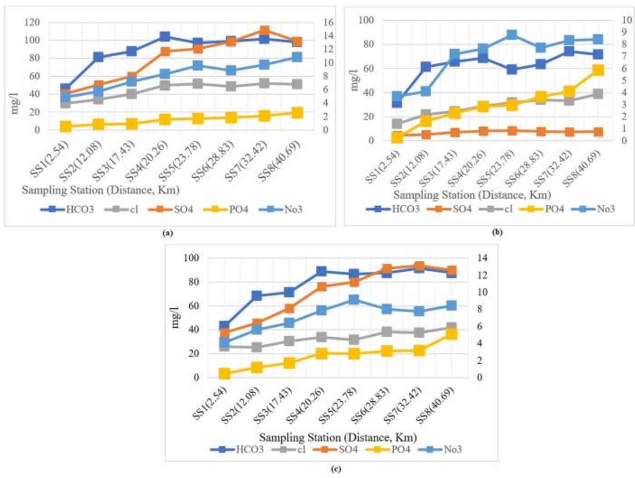

Fig. 5. Variation of Anions during a) pre-monsoon season; b) monsoon season; c) post-monsoon season.

D. Variations of Cations

In the pre-monsoon season, calcium average values across stations 1 to 8 were between 28.1 and 47.6 mg/L, the average magnesium values ranged between 4.1 and 6.7 mg/L, iron concentration varies from a minimal of 0.02 to a maximum of 0.52 mg/L in up-stream sampling stations during post and pre-monsoon, the average sodium concentration across stations was between 8.1 and 14.9 mg/L, and the potassium levels ranged from 2.15 to 9.45 mg/L. During the monsoon season, calcium average values were between 5.1 and 26.9 mg/L, average magnesium values across station 1 to 8 ranged between 2.8 and 5.1 mg/L, at down-stream sampling stations of Nadiharahalli, the iron content was reduced to 0.08 to 0.24 mg/L during monsoon and pre-monsoon, the average sodium concentration was between 4.3 and 10.1 mg/L, and the potassium levels ranged between 3.1 and 10.9 mg/L.

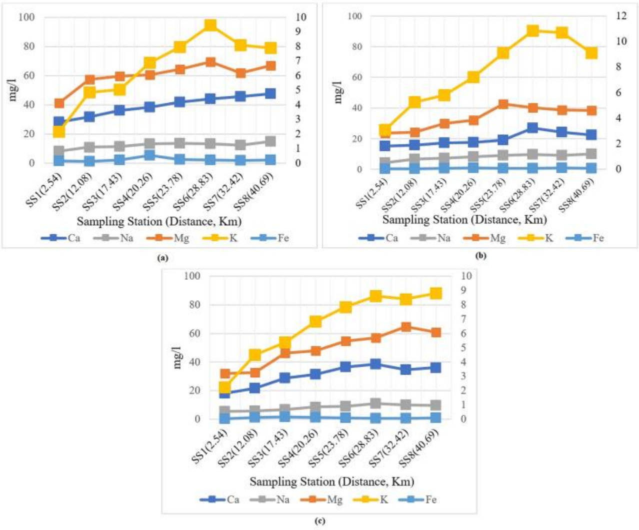

Fig. 6. Variation of Cations during a) pre-monsoon season; b) monsoon season; c) post-monsoon season.

For the post-monsoon season, calcium average values ranged between 18.1 and 38.6 mg/L, the average magnesium ranged between 3.2 and 6.5 mg/L, the average sodium concentration was between 5.6 and 11.0 mg/L, and the average potassium levels ranged from 2.2 to 9.3 mg/L, for every sampling station. A rise in calcium content concentration was noticed across stations 2 to 5, due to the release of household sewage at the stations on the up-stream of the river. Concentrations of magnesium and calcium were 30 mg/L and 75 mg/L, which is higher in pre-monsoon season, however they were still within the limits of drinking water. The upper reaches of sampling stations near Kumarapatnam showed higher iron values to upper possible limits of the drinking water standard. The results indicate a higher concentration of sodium every season and across all stations as against potassium. The rise in values across stations 2 to 5 may, again, result from the release of household sewage from upstream stations and from agricultural flow in the monsoon season (Fig. 6).

E. Variation of BOD, DO and COD

In the pre-monsoon season, the mean BOD values at sampling stations 1 to 8 were between 2.9 and 11.0 mg/L, the mean values of DO range between 4.7 and 8.1 mg/L, and the COD values ranged from 26.7 to 79.6 mg/L. During the monsoon season, the mean BOD values were between 2.4 and 7.1 mg/L, DO values ranged between 6.2 and 9.6 mg/L, and the results showed COD values ranging from 16.1 to 49.7 mg/L at all sampling stations.

For the post-monsoon season, the mean BOD values at sampling stations 1 to 8 were between 2.7 and 9.5 mg/L, the mean values of DO ranged between 5.3 and 8.8 mg/L, and the COD values ranged from 20.6 to 70.5 mg/L. The CPCB stream order classifies rivers as stream 'D' when BOD levels are higher than 3 mg/L, for which the most beneficial uses are regulated waste water disposal, propagation of wildlife fisheries and industrial cooling and irrigation. The stream is classified as a class of stream 'C' when the BOD level lies within 2 to 3 mg/L. The BOD levels were higher in the pre-monsoon period, because of domestic waste water discharge from sampling station 2 to 5 on the up-stream. The river expanding for 2.54 kilometers from the head water is in the class of stream 'C', while the distance between 2.54 to 40.69 km is the class of stream 'D'. The entire stretch falls in category 'C', however, the value of DO reaches the lower permissible limit at 20.25 km near Nalavagalu. This alteration in DO values is due to the untreated domestic waste in the river downstream of Kumarapatanam town. COD values are on average lower during the monsoon period for all sampling stations as shown in Fig. 7.

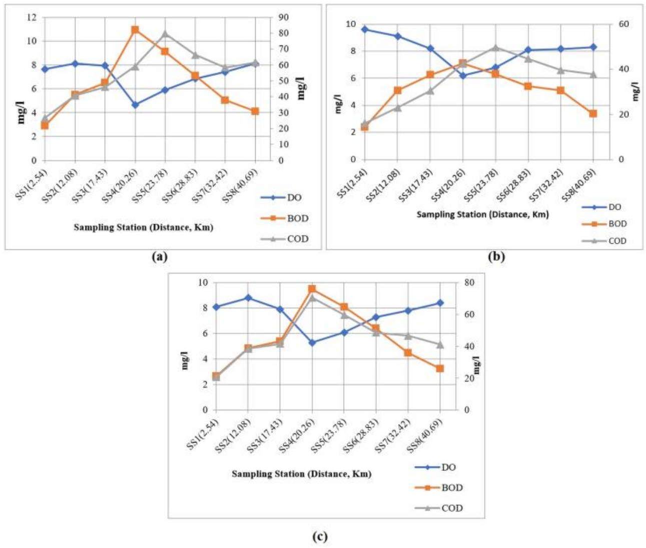

Fig. 7. Variation of BOD, DO and COD during a) pre-monsoon season; b) monsoon season; c) post-monsoon season.

F. Variations of Total Coli and Faecal Coli

Fig. 8 indicates that for the pre-monsoon season, the average total coliform values from sampling stations 1 to 8 ranged from 1050 to 4950 MPN/100 mL, while the average faecal coliform ranged from 450 to 1750 MPN/100 mL. In the monsoon season, the average total coliform values ranged from 1250 to 4950 MPN/100 mL and the average faecal coliform sampling from station 1 to 8 ranged from 550 to 1850 MPN/100 mL. During the post-monsoon season, for every sampling, the average total coliform values range from 1100 to 4900 MPN/100 mL and the average faecal coliform sampling ranged from 500 to 1800 MPN/100mL station. The growing values from sampling stations 2 to 5 can be attributed to domestic waste water disposal as compared to stations 1, 6, 7 and 8. For the CPCB stream category, the total coliform level present in river water should be under 50 MPN/100mL for domestic drinking water without conservative treatment after decontamination (class A), lower than 500 for systematized bathing outside (class B) and less than 5000 (class C) for water for drinking with conservative treatment followed by decontamination. The results showed that the standard class C level was exceeded at sampling stations 2 to 5 during the monsoon period and 3 to 4 in the post-monsoon period. The WQI was observed at every station by taking two-year average values during different phases of monsoon.

During the pre-monsoon season, the WQI stayed at a 50 to 70 range, showing that water can be used for any purpose except for drinking it directly. It needs to be professionally treated before drinking; else it could be harmful. The samples at station 4 and 5 showed WQI levels between 25 and 50. The river water can only be used for irrigation or industrial cooling and should not be drunken under any circumstances even if it is treated, as there is still a high chance of pollution in it which can be fatal. The wastage from nearest rivers and industries decreased DO, causing the water quality to drop significantly. The WQI from station 6 to 8 were better. The WQI ranged from 51 to 67 during monsoon which is of medium value. The WQI throughout the study area was stable, meaning it was not too polluted and not 100% safe either. Post-monsoon, water quality values stayed between the ranges of 50.1 to 64.5 at stations. This indicates that water quality was on safe level at station 4 having only a value of 50. BOD and DO along with coliform and turbidity were the major factors behind the decrease of WQIs.

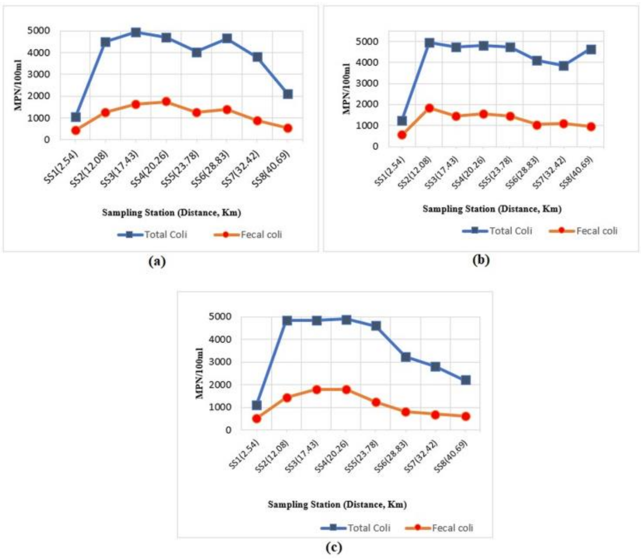

Fig. 8. Variation of total coli and fecal coli during a) pre-monsoon season; b) monsoon season; c) post-monsoon season.

G. BOD-DO Modelling

The level of DO on the up-stream of the waste discharge will be close to saturation for the originally unpolluted stream. The addition of untreated sewage would decrease the level of the DO, implying that the suspended solids raise water turbidity and thus light is unable to penetrate deep into the water resulting in plant growth being superseded and the nutrition for heterotopic organisms is provided by organic matter. The vast population of the decomposer organism breaks up the organic matter in water and depletes the DO in the process. Therefore, organic matter decomposition happens in the sludge bed and sediment oxygen demand (SOD) contributes to DO depletion. As the level of oxygen goes down, there is an influx of atmospheric oxygen to make up for the loss of oxygen. It is at this point that oxygen will attain its lowest level. After this point, reaeration will have the upper hand and the level of oxygen will begin to increase. The water in this zone gets clearer because a considerable quantity of the solid matter from the waste will have precipitated. This process is best explained by the systematic BOD and DO mathematical model that can be expressed as the classic Streeter Phelps model

$$L = L_0 e^{-K_r(x/u)}$$

$$D = D_0 e^{-K_a(x/u)} + [K_d L_0/(K_a - K_\gamma)][e^{-K_r(x/u)} - e^{-K_a(x/u)}]$$

When other sources and removers of oxygen are considered, the equation transforms into

$$D = \underbrace{D_0 e^{-K_a(x/u)}}_{point\ deficit} + \underbrace{[K_d L_0/(K_a - K_\gamma)][e^{-K_r(x/u)} - e^{-K_a(x/u)}]}_{point\ CBOD}$$

$$+ \underbrace{[K_N N_0/(K_a - K_n)][e^{-K_n(x/u)} - e^{-K_a(x/u)}]}_{point\ NBOD}$$

$$+ \underbrace{[[-P + R + (SB/H)/K_a][1 - e^{-K_a(x/u)}]}_{distributed\ deficit}$$

where D is the DO deficit in mg/L, L_0 is initial BOD mg/L, u is up-stream velocity in km/d, x is distance travelled in km, L is BOD concentration, K_r, K_d, K_s, and K_a are BOD loss rate, de-oxygenation constant, settling velocity and reaeration constant (per day), respectively, P and R are volumetric rate of plant photosynthesis and respiration, SB is sediment oxygen demand, and H is depth of water in metres.

1) *Evaluation of the BOD loss rate and the de-oxygenation constant*

The BOD loss rate represents the removal of BOD and can be expressed as

$$K_r = K_d - K_s$$

$$K_s = V_s/H$$

where V_s is the BOD settling velocity (m/d). To achieve the structure which assesses the rate of removal in the system with plug flow, the natural logarithm can be taken from the first equation

$$\ln L = \ln L_0 - K_r(x/u)$$

giving the linear slope of K_r. The measurement of the BOD values were obtained using the river length between 19 to 32.1 kilometer, this part was void of extra waste addition into the river and removal of water has been discharged at the up-stream end of the river. Both before and after the monsoon season, measurements were taken. The results shows that the values K_r and K_d were 1.45 and 0.76, respectively, before the monsoon season. A different set of data confirmed the results before the monsoon season. Hence, the measured and confirmed parameters were reasonable. From the results, for the post-monsoon period, the values of K_r and K_d measured were 1.85 and 1.45 per day, respectively. For a different set of data taken for validation, K_r and K_d values were 1.78 and 0.99 per day, respectively. The values show that the parameters for assessment and confirmation agree with each other. For depth of the river between 0.2 and 1.0 meter, the rate of decomposition inside the stream (K_d) differs from 0.4 per day to 3.0 per day. The values obtained through measurement also fall in this range.

2) Evaluation of the re-aeration constant

The Dissolved Oxygen Balance Technique (DOBT) was used to evaluate the reaeration constant, K_a. The estimated values of K_r and K_d were incorporated in the equation given below

$$D = D_0 e^{-K_a(x/u)} + [K_d L_0/(K_a - K_\gamma)][e^{-K_r\left(\frac{x}{u}\right)} - e^{-K_a\left(\frac{x}{u}\right)}]$$

A reach from 19.0 to 32.1 kilometer was picked for evaluating K_r, K_a and K_d. A total of six sampling points were chosen for BOD and DO assessment for calculating the kinetic limitations. The evaluation of the reaeration constant is done based on the observations from pre-monsoon and post-monsoon period. The results showed that the estimated value of K_a at 20°C is 5.8 per day and another set of values obtained during the pre-monsoon period showed at 20°C to be 5.7 per day, validating the result of the first period. Similar K_a values were obtained for two different periods in post-monsoon season. The value of K_a obtained in the first period was 5.2 per day and was 6.3 per day in the second period. A change in these values during the seasons may be due to a change in the sewage and effluent flow conditions. The reaeration constant at 20°C as the observation temperature, can be calculated using the following relation

$$K_a(T) = K_{a(20)}\theta^{T-20}$$

where $\theta = 1.024$ for pure water.

H. Predictive Reaeration Equations

Numerous researchers devised equations predicting the reaeration constant for rivers and streams. In this subsection, the values of K_a obtained by different reaeration equations are compared with the values of K_a estimated in this study and their performance is considered. The result showed that the predicative equations developed by Thackston & Krenkel [6], Churchill *et al*. [7], Tsivoglou & Wallace [8], Krenkel & Orlob [9], Owens *et al*. [10] and Smoot [11] were not suitable for this study, since the predicted reaeration constant did not show an agreement with the measured values. The value obtained from the equation proposed by Jha *et al*. [12] showed the best agreement with the measured values. It should be stated that all predictive equations, except for the one proposed by Jha *et al*. [12], were developed for the rivers outside of India. Since the current study involves a typical Indian river, it was expected that the values of this study are in closest agreement with the predictive equation proposed by Jha *et al*. [12].

A redefined predictive equation for the reaeration constant was developed and recommended for the river Tungabhadra, utilizing flow, depth, and velocity variables. The equation was obtained utilizing least squares and Newton-Raphson techniques. The equation is given by

$$K_a = 5.17U^{-0.36}H^{-0.79}$$

where U is velocity in m/s and H is depth of water in metres.

TABLE II: VALUES MEASURED BY DOBT AND PREDICTED REFINED EQUATIONS

sl.no	Ka measured by DOBR	Predicted by refined equation
1	6.27	6.510911
2	6.11	6.072828
3	6.54	6.343871
4	6.67	6.548126
5	5.929	5.984236
6	6.76	6.621008
7	6.57	6.46519
8	6.01	6.323062
9	4.57	4.979471
10	5.96	6.26913

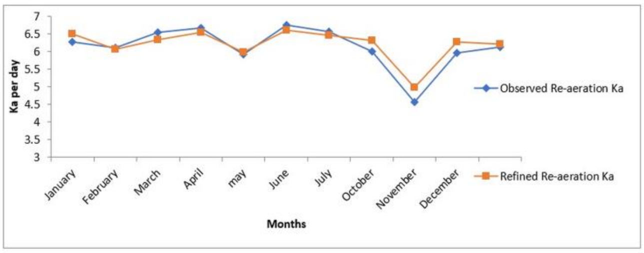

Fig. 8. Compression of predictive and measured Ka values.

The values of Ka calculated by DOBT and predicted by the advanced reaeration Lotion (5, 10) are provided in Table II. The graphical comparison of calculated and predicted values of ka is displayed in Fig. 8. In the current work, the error estimates compared with the measured values were enhanced relative to the literature illations provided in Table II. The values are SE-0.36, MME-1.04, NME-0.16, and correlation coefficient 1=0.986. The results gotten are promising and emphasize the improved performance of the advanced predictive equation.

I. Application of QUAL2KW Model

Chapra and Pelletier [13] used the QUAL2KW model for developing a framework simulating water quality for streams and rivers. In this study, the QUAL2KW model is used to assess the River Tungabhadra's water quality using the pre- and post-monsoon observations. For the pre-monsoon data, the water quality parameters were measured on the 4th and the 5th of April 2018 and the observations on the 8th and the 9th of May 2018 were used for validating the model. For the post-monsoon data, the water quality parameters were measured on the 20th and the 21th of November 2018. The observations on the 20th and the 21th of December 2018 were used for validating the model. For the pre-monsoon season data calibration, the BOD water quality levels did not meet the standards of class 'C' standards. These findings were mainly attributed to the high discharge of untreated waste from the municipal and other villages. Based on the DO values, the river is classified as a class 'C' type (>4 mg/L) for drinking purposes with conventional treatment followed by disinfection at all locations. The values of the TN were within the required standards of drinking water across all locations. For the validation of the pre-monsoon season data, the BOD water quality levels after a distance of 2.5 kilometer towards the downstream of Harihara Town did not meet the standard quality that is required to be within the range of class 'C'. This may be due to the discharge of untreated waste that is discharged into the water bodies from Harihara Town. The DO valued ranged from 5 to 8.5 mg/L, with the lowest being recorded at 3.93 mg/L at 20.26 kilometer. The water quality did not meet the standard criteria of class ‘C’ (>4 mg/L) at 20.26 to 23.5 kilometer; however, the TN values were within the required range of 45 mg/L at all locations. Calibrating the data of the post-monsoon season, the BOD results stood between 2 and 7.5 mg/L; at 20.26 kilometer, the highest value was 6.3 mg/L. The water did not meet the water quality standards of class ‘C’ up to 38.5 kilometer from the up-stream boundary. The DO values ranged from 6 to 8.7 mg/L with the lowest values at 6 mg/L recorded at 20.26 kilometer. The DO values were at the required range of class ‘C’. The values of the TN were within the required standards of drinking water across all locations. For the validation of the data in the post-monsoon season, the BOD values ranged between 2.5 to 8.5 mg/L and the highest value recorded at 8.24 mg/L at station 2. These values did not meet the standard quality within class ‘C’. The DO values ranged from 5.5 to 8.75 mg/L, the lowest recorded at 5.86 mg/L at 23.78 kilometer. The TN values were within the required range of 45 mg/L for drinking water purposes.

The performance of the model was evaluated using the standard error (SE) and the mean multiplicative error (MME) for calibration and validation during pre-monsoon and post monsoon season. The results for the pre-monsoon indicate that there was no significant variation in the error estimates during the calibration and validation period. The post-monsoon season results indicate some variation in the error estimates from calibration to validation. The SE values for BOD, DO and TN during calibration were 0.61, 0.51 and 1.69, respectively, and during validation, these values were 0.76, 0.37 and 1.46. Similarly, the MME values during calibration for BOD, DO and TN were 0.976, 0.99 and 0.841, respectively, and during validation the values were 0.96, 0.96 and 0.86.

VII. Conclusion

The river Tungabhadra takes up a lot of domestic and industrial waste while it flows from Harihara town, harming people and wildlife. The people of Harihara and Ranebennur Taluk use this river as their primary source of drinking water without realizing the harmful impact it will have on their health. This emphasizes the importance of water quality assessments and modelling. The water quality assessment of this study took physico-chemical and biological parameters into account. The water quality indices (WQIs) were determined by using the National Sanitation Foundation (NSF) guidelines regarding parameters such as dissolved oxygen (DO), faecal coliform, pH, biochemical oxygen demand (BOD), temperature, phosphate, nitrates, turbidity and total solids.

The first conclusion that could be drawn from the results is that the physico-chemical parameters should abide the IS:10500, 1992 standard, being suitable for drinking water. The BOD values in the headwaters to a distance of 2.54 kilometers are classified as class ‘C’ and the rest up to 40.69 was classified as class ‘D’, making it unsuitable for drinking purposes. In terms of DO values, from 17.43 to 23.48 kilometers, values of 4.6 mg/L were found, falling under class ‘C’ category. This is due to a lot of domestic waste ending up in the river. The highest total coliform count was measured throughout different periods of the monsoon. The values were higher than 50 MPN/100 ml due to the untreated waste mixing in the stream. The results of this study show the river is classified as class ‘C’, because of the contamination and waste from industries mixing in.

During the pre-monsoon season, the WQI stayed between a 50 to 70 range, showing that water can be used for any purpose except for drinking. The WQI levels at stations 4 and 5 ranged from 25 to 50, making it only useful for irrigation or industrial cooling use. Drinking the polluted water can be fatal. The wastage from nearest rivers and industries decreased DO, causing the water quality to drop. During the monsoon season, the WQI ranged from 51 to 67, showing a similar situation. The WQI throughout this period was stable, meaning it was not too polluted and not 100% safe either. Similar results were found for the post-monsoon season. A BOD-DO model was built using the classic Streeter & Phelps equation. Reaeration values observed were compared to the obtained values using the dissolved oxygen balance technique (DOBT). It was found that the predictive reaeration equation stated by Jha *et al*. [12] to be the best match with the measured value. An improved predictive equation created, made use of the flow rate, depth and velocity. The results obtained from the QUAL2KW model showed that the predicted values and measured values were similar. The standard of class ‘C’ was not met for the BOD values measured in the pre-monsoon season after a distance of 2.54 kilometer down-stream of Mudenur Village, because of the discharge of domestic waste from Kumarapatanam and Harihara town and the industrial effluent discharge near Nalvagalu village. The DO values met the standards of class ‘C’ at all locations and the value of total nitrogen (TN), which was within the drinking standards at all locations. During post-monsoon season, the water quality of the river Tungabhadra met the standard of class ‘C’ with respect to BOD, DO, and the TN values.

From the results it may be concluded that, to maintain the standard of class of stream ‘C’ of water quality of the river Tungabhadra, the flow of the river has to be more than $6m^3/s$ and municipal waste and industrial effluent from Kumarapatanam and other villages located on the bank of the river, need to be treated to reduce the BOD load to less than 30 mg/L. This can be achieved by releasing water from the Tunga and Bhadra reservoirs which are all up-stream of Harihara town. By releasing water from the reservoirs, both the volume and velocity of the river would increase. These scenarios may help planners evaluate their intended actions’ effectiveness to prevent pollution before they are actually implemented.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

M. Mohan Babu: Conceptualization, Methodology, Project Administration. **B. Damodhara Reddy**: Software, Validation, Writing—original draft. **Anand V. Shivapur**: Resources, Data Collection. **S. Ranjith**: Investigation and Data Collection, **P. Narasimha Reddy**: Investigation and Data Collection. **Bode Venkata Kavyateja:** Investigation and Data Collection. **Kaushik Kumar**: Writing—Final and revised version, corresponding. All authors had approved the final version.

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