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Developing a Robust Tool for Quality Health Assessment of Rivers Using Optimized Weighted Arithmetic Water Quality Index Method: A Study on River Ganges at Varanasi in India

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ABSTRACT

Lack of real time data with its accurate interpretation constraints the success of various river pollution mitigation and restoration programs. Different Water Quality Index (WQI) have been used for assessment of quality health of rivers yet there are limitations to each protocol. The present work aims at optimizing and developing a clear and user-friendly methodology for Weighted Arithmetic Water Quality Index (WAWQI) calculation taking River Ganga at Varanasi as case study. Fifteen sites along right and left banks of River Ganga were selected for the study. WQI indicate Gangetic water at Varanasi to be affected by higher coliform levels, altered pH and DO/BOD levels. Variations in WQI value for pre- and post-monsoon period indicate the significance of increased volume of water for mitigating pollution problems. The WAWQI values for water quality of River Ganga at Varanasi suggest site L14 on left bank and sites R10 and R11 on right bank as most polluted and unfit for drinking. The effect of dilution and the corresponding reduction in pollution correspond well with the optimized WAWQI values. It is thus recommended to use the optimized method of WAWQI calculation that essentially includes TC and BOD/DO in addition to all other water quality parameters for calculating WQI which may serve as a robust yet simple tool for assessing a comprehensive water quality and health of a river. Moreover, WAWQI based WQI shall be helpful in prioritizing areas for immediate management/policy actions towards restoration, rejuvenation and understanding of River Ganga ecosystem at Varanasi.

Keywords- Health, Pollution, River Ganga, WQI, WAWQI, Water quality.

I. INTRODUCTION

River Ganga is ranked among the world's top ten highly polluted water bodies. Various forms of pollutants present in River Ganga adversely effects the riverine biodiversity and human health (Nandi et al., 2016; Singh, 2016). Lack of real time data and its proper assessment have always been the major reason for failure of various government-initiated river management schemes and programs (Chaudhary et al., 2017; Dwivedi et al., 2018). Regional variations in source and pollutant characteristics, disparity in assessment parameters and lack of clear and concise representation due to data overlap are some of the constrains in data interpretation (Joshi et al., 2009; Namrata, 2010; Das, 2011; Paul, 2017; Trombadore et al., 2020). This arises need for a robust tool to ease in data interpretation amidst all the above-mentioned limitations.

River Ganga at Varanasi faces severe degradation in its water quality in recent times. Strategies for restoration programs need prioritization of areas for management actions. This prioritization is dependent on availability of real time data for water quality. Proper interpretation of large datasets of water quality is a tedious task with lack of uniformity in water quality parameters as well as no clear representation of data due to data overlap. This highlights the need for single numerical score presenting the usability of water for human consumption. WQI serves the purpose as it gives a single score representation of complex water quality datasets. Different water quality calculation indices known are constrained either by use of less parameters or involving complex calculations. Among all the indices known for calculation of WQI, Weighted Arithmetic method (WAWQI) is largely used for assessing water quality of Indian rivers. However, WAWQI often does not consider microbial load for calculating WQI neither does it give weightage to DO and BOD.

Water Quality Index (WQI) is a mathematical tool to represent large water quality dataset in a single number (Štambuk, 1999). It serves as most effective tool for easy understanding and communication of information regarding water quality (Batabyal and Chakraborty, 2015). Resource allocation, ranking of water bodies, set criteria for legislative enforcement, analysis of trend and dissemination of information regarding water quality status to the public domain are few basic uses of WQI (Ott 1978). WQI values are dependent upon the selection of water quality parameters, the transformation of raw data to a common scale, allocation of weights to each parameter and

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specification of the aggregated function (Paun et al., 2016). Therefore, several types of WQIs are known however, among these, the Weighted Arithmetic Water Quality Index (WAWQI), National Sanitation Foundation Water Quality Index (NSFWQI) and Canadian Council of Ministers of the Environment Water Quality Index (CCMEWQI) have been used commonly for developing protocols for water quality assessment of rivers in India (Table 1).

Table 1. Water Quality Index including the water parameters reported in literature and used for developing protocols for assessing water quality of rivers in India.

S. No.	River	Location	WQI type	Water Quality Parameters	Reference
1.	Narmada	Madhya Pradesh	WAWQI, NSFWQI, CCMEW QI	pH, TDS,Turbidity,NO_3-N, PO_4^{3-}, BOD and DO	Gupta et al., 2017
2.	Chitra Puzha	Kerala	NSFWQI	DO, FC, pH, BOD, PO_4^{3-}, NO_3^-, Turbidity and TDS	Deepa and Magudeshwaran, 2014
3.	Krishna	Maharashtra	WAWQI	pH, DO, BOD, Ca^{2+} Ma^{2+}, Hardness, Cl^-, NO_3^- SO_4^{2-}	Jadhav and Jadhav, 2016
4.	Ganga	Rishikesh, Uttarakhand	WAWQI	DO, BOD, COD, Free CO_2, TS, TSS and TDS	Chauhan and Singh, 2010
5.	Ganga	Rishikesh-Allahabad	NSFWQI	pH, EC, DO, TDS, Turbidity, Na^+, K^+, Mg^{2+}, Ca^{2+}, F^-, Cl^-, SO_4^{2-}, NO_3^-, Alkalinity	Meher et al., 2015
6.	Vishwamitri	Gujarat	WAWQI	pH, Conductivity, TDS, TSS, DO, BOD, Hardness, NO_3^-, F^-,SO_4^{2-}	Magadum et al., 2017
7.	Bhagirathi	Uttarakhand	WAWQI	pH, EC, TDS, TSS, DO, BOD, Alkalinity, Hardness	Pathak et al., 2015
8.	Hemavathi	Karnataka	WAWQI	Ca^{2+}, Mg^{2+}, pH, Alkalinity, TDS, EC, Hardness	Mamatha, 2017
9.	Chambal	Madhya Pradesh	NSFWQI	Temperature, Turbidity, TSS, pH, DO, NO_3^-, PO_4^{3-}, BOD	Yadav et al., 2014
10.	Kathajodi	Odisha	WAWQI	pH, TDS, Alkalinity, TSS, BOD, DO, Cl^-, NO_3^-, Hardness, Ca^{2+}, Mg^{2+}	Mallick and Baliarsingh, 2017
11.	Tapti	Gujarat	CCMEW QI	pH, Turbidity, TDS, TSS, Hardness, Alkalinity, DO, BOD,COD, Cl^-, SO_4^{2-}, NO_3^-, NO_2^-, Fe, Ca^{2+}, Mg^{2+}, Na^+, F^-, Cr, Cd, Pb, As	Desai and Tank, 2010
12.	Tapti	Madhya Pradesh	WAWQI	pH, Turbidity, Hardness, Alkalinity, TDS, SO_4^{2-}, PO_4^{3-}, NO_3^-, DO, COD	Thakre et al., 2011
13.	Mahanadi & Atharabanki	Bhubaneswar	NSFWQI	pH, DO, BOD, FC	Samantray et al., 2009
14.	Godavari	Andhra Pradesh	NSFWQI	pH, DO, EC, TDS, Alkalinity, Hardness, Ca^{2+}, Mg^{2+}	Akkaraboyina and Raju, 2012
15.	Kolong	Assam	WAWQI	pH, EC, TDS, TSS, Cl^-, Alkalinity, Hardness, DO, BOD, SO_4^{2-}	Bora and Goswani, 2017
16.	Periyar	Kerala	CCMEW QI	Ca^{2+}, SO_4^{2-}, Cl^-, NO_3-N, Hardness, F^-, EC, pH, Fe, Phenol, DO, COD	Lakshmi and Madhu, 2014
17.	Malin	Uttar Pradesh	WAWQI	Turbidity, TDS, TSS, TS, pH, Hardness, Ca^{2+}, Mg^{2+}, Alkalinity, Cl^-, Acidity, DO, BOD, COD	Bhutiani et al., 2018
18.	Subernarekha	Jharkhand	Bhargava's WQI	DO, BOD, Microbial load, Turbidity, TDS, pH	Parmar and Parmar, 2010
19.	Haora	Tripura	CCMEW QI	pH, EC, Turbidity, DO, TDS, PO_4^{3-}, NO_3^-, Cu, F^-, Fe, Ca^{2+}, Mg^{2+},Hardness	Sarkar and Mishra, 2014
20.	Godavari	Nasik	NSFWQI	DO, FC, pH, BOD, PO_4^{3-}, NO_3^-, Turbidity, TS	Nayak and Patil, 2016
21.	Mahi	Gujarat	WAWQI	DO, Microbial load, pH, BOD, COD, Turbidity, TDS	Gor and Shah, 2014
22.	Saank	Madhya Pradesh	WAWQI	pH, EC, TDS, Alkalinity, Hardness, SO_4^{3-}, NO_3^-, Cl^-, Turbidity, PO_4^{3-}, DO, BOD, COD	Kevat et al., 2016
23.	Nambul	Manipur	WAWQI	pH, Turbidity, DO, BOD, EC, Hardness,	Singh et al., 2016

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				Alkalinity, COD, TDS, Cl^-, Ca^{2+}, Mg^{2+}	
24.	Brahmani	Odisha	WAWQI	pH, Turbidity, TDS, Boron, Ca^{2+}, Cl^-, F^-, Fe, Mg^{2+}, NO_3^-, SO_4^{2-}, Alkalinity	Bhadra et al., 2014
25.	Mandakini	Madhya Pradesh	WAWQI	TDS, Turbidity, Hardness, Cl^-, BOD, DO, Alkalinity, pH, Microbial load	Dwivedi and Pathak, 2007
26.	Sabarmati	Gujarat	WAWQI	pH, DO, BOD, EC, NO_3-N, TC	Shah and Joshi, 2017
27.	Yamuna	Delhi	WAWQI	pH, TDS, DO, BOD, NO_3^-, Ammonia	Sharma et al., 2017
28.	Nambol	Manipur	WAWQI	pH, DO, Alkalinity, BOD, Hardness, Ca^{2+}, Mg^{2+}, PO_4^{3-}	Devi et al., 2015
29.	Yamuna	Uttar Pradesh	NSFWQI	pH, DO, Temperature, BOD, COD, TDS, Alkalinity, Chloride, Calcium, Magnesium, Hardness, Total Coliform	Sharma et al., 2020
30.	Ganga	Varanasi Uttar Pradesh	WAWQI	pH, TDS, Alkalinity, Total Hardness, DO, BOD, Ca^{2+}, Mg^{2+}, NO_3^-, SO_4^{3-}, Cl^-,	Present Study

Though WQI is a commonly used water quality assessment tool, yet literature does not provide any stepwise clear explanation for its calculation. There are indications of varied weight assignment to each water quality parameter in the NSFWQI and WAWQI method for WQI calculation. On the contrary, CCMEWQI gives equal weight to all the water quality parameters thus increasing the biasness of the index. Moreover, the index also becomes more susceptible to manipulation (Paun et al., 2016). Therefore, CCMEWQI does not appear to be a robust method for water quality analysis. NSFWQI method is a comparatively more acceptable method for water quality assessment, however, it faces limitations of using few parameters and requirement of rating curves for defining weights of parameters (Bharti and Katyal, 2011). In addition, NSFWQI also suffers from the limitation of eclipsing effect in which the overall index sometimes ignores the effect caused by any one or few of its calculation parameters (Bharti and Katyal, 2011). Considering the limitations of the above two methods, WAWQI stands as the most appropriate and robust option for calculating WQI. Therefore, the present study is carried out with the objective to optimize and develop a robust and region specific WAWQI protocol for River Ganga at Varanasi. The water quality of River Ganga was monitored during pre- and post-monsoon Periods for two consecutive years along the left and right banks, the water samples were collected, analyzed and the obtained data for water quality parameters have been collectively utilized to develop a clear and concise WAWQI method for quality health assessment of rivers.

II. MATERIALS AND METHODS

Study site

Varanasi is located at 25°16’59.0” N and 83°00’35.3” E at the bank of River Ganga. Being spread a distance of 6.5 km, River Ganga forms a crescent shaped structure around the banks of Varanasi (Nandi et al., 2017). Fifteen random sites along each of the left and right bank between before Asi River confluence to beyond River Varuna confluence were selected for the study as detailed in Fig. 1. The selection of the sites was based upon ghat specific anthropogenic activities with inclusion of few undisturbed sites to obtain an unbiased dataset.

Sample collection and analysis

Water samples were collected during pre- and post-monsoon season for two consecutive years (2015-2017). Sampling was carried out at a distance of 10 m from the ghats at 2-3 feet depth from the water surface and stored in Poly Tetrafluoroethylene (PTFE) plastic bottles under cold conditions. The samples were analyzed for physicochemical parameters (pH), total dissolved solids (TDS), alkalinity, total hardness, dissolved oxygen (DO) and biochemical oxygen demand (BOD), concentration of calcium (Ca^{2+}), magnesium (Mg^{2+}), nitrate (NO_3^-), sulphate (SO_4^{2-}) and chloride (Cl^-) and microbial load (total coliforms) (Table 1) following the standard water testing protocol (APHA 1999). The analysis value of each parameters represent mean of five replicates ±s.d.

The pH and TDS of water samples was measured onsite using Portable Microprocessor Based Water Soil Analysis Kit (Universal Bio, Germany). Alkalinity and total hardness of water samples were determined titrimetric ally using phenolphthalein and Eriochrome Black T (EBT) as indicator respectively. Winkler's iodometric method (APHA 1999) was used to measure dissolved oxygen in water samples. A 5-day BOD test method at 20° C following APHA (1999) protocol were carried out.

Total coliform was determined by multiple tube fermentation technique (MPN method) and calculated as MPN/100ml using standard reference chart of APHA (1999) manual.

Samples for ionic analysis were collected in prewashed borosil reagent bottle (100ml), filtered using milipore (0.02mm) filter, and analyzed by Ion Chromatography (IC) (Metrohm 930 Compact IC, Switzerland) as per standard protocol and reported in mg/l.

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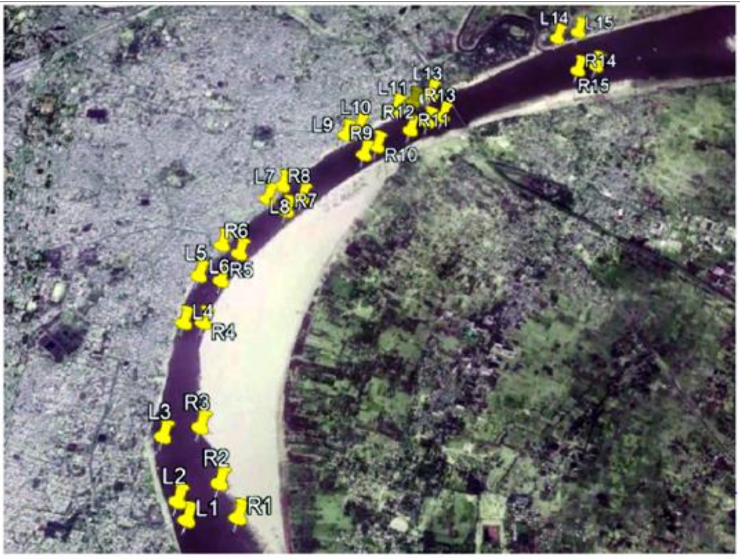

Sl. No	Sites	Coordinates (L sites)	Coordinates (R sites)
1.	BeforeAsi confluence	25°16'54.80"N ; 83° 0'39.13"E	25°16'55.48"N; 83° 0'55.51"E
2.	Asi confluence	25°17'0.10"N; 83° 0'35.36"E	25°17'5.30"N; 83° 0'48.21"E
3.	Asi ghat	25°17'19.15"N; 83° 0'27.55"E	25°17'22.00"N; 83° 0'39.56"E
4.	Harishchandra ghat	25°17'55.37"N; 83° 0'29.08"E	25°17'55.41"N; 83° 0'35.89"E
5.	Babua Pandey ghat	25°18'11.46"N; 83° 0'32.04"E	25°18'9.76"N; 83° 0'40.22"E
6.	Dashashwamedh ghat	25°18'22.36"N; 83° 0'38.96"E	25°18'19.38"N; 83° 0'45.62"E
7.	Manikarnika ghat	25°18'39.48"N; 83° 0'53.70"E	25°18'34.87"N; 83° 1'1.06"E
8.	GangaMahal II ghat	25°18'44.36"N; 83° 0'58.67"E	25°18'39.77"N; 83° 1'6.36"E
9.	Gaay ghat	25°19'4.44"N; 83° 1'20.94"E	25°18'56.55"N; 83° 1'28.45"E
10.	Trilochan ghat	25°19'6.92"N; 83° 1'25.81"E	25°18'59.75"N; 83° 1'33.27"E
11.	Teliyanala ghat	25°19'15.00"N; 83° 1'39.74"E	25°19'6.32"N; 83° 1'45.73"E
12.	Prahlad ghat	25°19'17.86"N; 83° 1'46.41"E	25°19'9.65"N; 83° 1'52.37"E
13.	Raj ghat	25°19'21.08"N; 83° 1'53.08"E	25°19'11.91"N; 83° 1'58.03"E
14.	Varuna confluence	25°19'45.04"N; 83° 2'43.67"E	25°19'31.26"N; 83° 2'51.43"E
15.	Beyond Varuna confluence	25°19'48.03"N; 83° 2'52.28"E	25°19'33.19"N; 83° 2'58.91"E

Fig. 1: Location of study sites along the stretch of River Ganga at Varanasi. L1-L15 and R1-R15 denotes left and right bank of River Ganga at Varanasi, respectively.

Optimization of WAWQI method for WQI calculation

Generally, few parameters are considered for calculating WAWQI of Indian rivers (Table 1). In general, WAWQI is calculated as the sum of the product of quality rating scale and unit weight of each parameter represented as equation below-

$$WQI = \sum_{n}^{i=1} q_i w_i$$

No uniform method for calculating quality rating scale for each parameter as well as assigning weight to each parameter have been followed by researchers (Table 1). For example, two formulas for calculation of quality rating scale for each parameter have been commonly used viz. (i) $q_i = 100 \times \left(\frac{C_i}{S_i} \right)$ (Thakre et al., 2011) and (ii) $q_i = 100 \times \left\{ \frac{(V_i - V_0)}{(S_i - V_0)} \right\}$ (Sreejani et al., 2017). Both these formulae are based on the ratio of concentration of each parameter (C_i/V_i) to its recommended standard value for that parameter (S_i) multiplied by 100 but latter formula involves the term V_o i.e. concentration at ideal condition which is based on assumption. Determining an already unknown value using assumed value further creates ambiguity, hence for calculation of quality rating scale in the study formula given by Thakre et al.,(2011) appears to be more reliable.

Unit weights are assigned based on the adverse impacts of the parameter measured on human health. However, wide variations were observed in the assignment of unit weights to each parameter in WAWQI method by researchers (Table 1). Moreover, it is natural that using large number of such parameters that adversely affect human health if included for ascertaining the indices would make the WAWQI method more comprehensive. Therefore, to obtain a reliable and robust WQI value it is important to optimize the WAWQI method for region specific rivers like River Ganga at Varanasi using large number of such parameters.

The WAWQI optimization protocol for water of River Ganga at Varanasi was based on assigning unit weights between 1 to 5 to each of the parameters under study, wherein 5 and 1 were assigned to parameter with most and least significant effect on human body, respectively. Unit weight for each parameter were then calculated as the ratio of assigned weight to each parameter by the summation of the weights assigned to all the parameters following the equation below-

$$w_i = \frac{W_i}{\sum W_i}$$

where in, w_i = Unit weight of each parameter and W_i = Weight assigned to each parameter and calculated according to Thakre et al., (2011) using maximum permissible limit for each parameter as per Bureau of Indian Standard (ISI-IS: 2296-1982)for drinking purpose were considered as standard recommended value (S_i).Among the water quality parameters measured in this study, the order of their influence on human health would likely be in the following order: TC> pH> salt concentration> Alkalinity/Hardness/TDS> BOD/DO. Weight assigned to each parameter with their unit weights and standard recommended value are given in table 2 and explained in Results and Discussion section of the article.

Table 2. Weight assigned to each parameter with their unit weights and standard recommended value for calculation of WAWQI (Standards are according to BIS-1982).

S. No.	Parameters	Weight (Wi)	Unit weight (Wi)	Standard value (Si)
1.	pH	4	0.13	8.5
2.	DO	1	0.03	4
3.	BOD	1	0.03	3
4.	TDS	2	0.06	1500
5.	Alkalinity	2	0.06	200
6.	Hardness	2	0.06	600
7.	Cl^-	3	0.09	600
8.	NO_3^-	3	0.09	50
9.	SO_4^{2-}	3	0.09	400
10.	Mg^{2+}	3	0.09	100
11.	Ca^{2+}	3	0.09	200
12.	TC	5	0.16	5000
		$\sum W_i = 32$	$\sum w_i = 1$	

The optimized WAWQI method was used to calculate the WQI for all the 30 sites (15 sites each on left (L) and right (R) banks) using data obtained for water quality parameters. Subsequently, the WQI values thus obtained were classified into the five categories namely excellent water (WQI <50); good water (WQI 50 to 100); poor water (WQI 100 to 200); very poor water (WQI 200 to 300); and water unsuitable for drinking (WQI >300).

Statistical Analysis

Descriptive statistics such as mean, minimum and maximum values were calculated. Correlation coefficient was calculated using 2 tailed test.Further, Cluster Analysis (CA) of water quality data of left bank and right bank were performed using SPSS.

III. RESULTS AND DISCUSSION

Water quality of River Ganga at Varanasi

Water quality data obtained for all the 30 sites are detailed in table 3 (left) and table 4 (right) bank of River Ganga at Varanasi for the pre- and post-monsoon period of two consecutive years. Along the left bank, the maximum to minimum values for the parameters were observed at L14 (Varuna confluence)>L2 (Asi confluence)>L15 (beyond Varuna confluence). Sites L14 and L2 were noted as the main drain discharge points for River Ganga at Varanasi (Table 3). It is also evident that at all the sites, TDS, hardness, chloride, nitrate, calcium and magnesium were within the permissible limit of drinking water standards. Whereas, pH was above the permissible limits at L5, L7, L11, L12 and L13 (Babua Pandey, Manikarnika, Teliyanala, Prahlad and Raj ghat) (Table 3). The reason for alkaline pH at site L5 can be attributed to use of phosphate-based detergent for large scale washing of clothes at this location. At site L7 the high pH could be a consequence of large amount of ashes due to cremation contributing to increased phosphorous level and thereby high pH (Tripathy and Tripathy 2014). Solid waste dumping at sites L11 to L13 is perhaps contributing towards high pH as suggested by Przydatek and Kanownik (2019). Alkalinity above permissible limit was observed at sites L2, L3, L4 and L14 (Asi confluence, Asi, Harischandra and Varuna confluence) wherein it was 1-2-fold higher than other sites (Table 3). Discharge of drains at L2 (Asi confluence) and L14 (Varuna confluence) and the lateral dispersion of pollutants at L3 (Asi ghat) and L4 (Harischandra ghat) due to their site proximity might be the cause for higher alkalinity at these sites. In addition, site specific activities like festival and tourism at L3 (Asi ghat) and cremation activities at site L4 (Harishchandra ghat) may further contribute towards higher alkalinity at sites L3 and L4. Similarly, values of DO was found within the permissible limit for all sites except the sites i.e. L2 (Asi confluence) and L14 (Varuna confluence) where discharge of main drains occur (Table 3). High BOD and TC levels are indicator of organic pollution load due to discharge of untreated sewage (Ghildyal, 2018). BOD and TC along the left bank were always 4 to 5 folds and 10 to 15 folds higher, respectively (Table 3). High levels of BOD and TC indicate discharge of

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untreated sewage directly to River Ganga highlighting limitations in treatment capacity of Sewage Treatment Plants (STPs) of Varanasi (CPCB 2013). On the contrary, along the right bank of River Ganga all the values for water quality parameters except pH, TC and BOD were within the permissible limit of standard drinking water quality (Table 4). Values for most of the parameters were highest at site L10 (Trilochan ghat) and L11 (Teliyanala ghat). Higher pH(one-fold), BOD (3-5folds) and higher TC (10-15 folds) than the permissible limit were noted for all sites at right bank (Table 4). Agricultural activities and solid waste dumping appear to contribute towards high phosphate in Gangetic water resulting thereby in elevated pH. Similarly, solid waste dumping, open human defecation and dumping of untreated sewage and its lateral movements at the sites of right bank appears as important factors contributing to higher BOD and TC levels of River Ganga at Varanasi.

Assigning weights for optimization of WAWQI and its explanation

Optimization of WAWQI method mainly focused on modifying the unit weight according to the quality characteristics of water for River Ganga at Varanasi. Accordingly, weights from 1 to 5 were assigned based on their adverse effect on human health. Total coliform was assigned a weight of 5 as it indicates fecal contamination and presence of other enteric pathogens causing various form of water borne diseases (Mosher,2011). Moreover, all the sites along the left and right bank of River Ganga at Varanasi have 10-15 folds higher TC levels compared to drinking water standard (Tables 3 and 4). pH was assigned a weight of 4 next to TC as high pH results into bitter taste and reduces the effectiveness of the disinfectants while low pH water leads to corrosion or dissolution of metals and other substances. Change in pH severely affects the composition of gut microbes leading to various forms of health ailments (Sofi et al.,. 2014). Nearly 2-fold higher pH found at different sites along the stretch of River Ganga at Varanasi (Table 2) would imply unsafe water for human consumption.

The various ions in water samples were assigned a weight of 3 as they contribute significantly to human health. Ca^{2+} forms an important structural component of bones and teeth and its inadequate intake leads to incurable diseases including osteoporosis, nephrolithiasis (kidney stones), colorectal cancer, hypertension, stroke, coronary artery disease, insulin resistance and obesity (Atkinson et al., 2009). Mg^{2+} is an important constituent of energy metabolism as it forms cofactor for nearly 350 cellular enzymes and plays significant role in protein and nucleic acid synthesis, for normal vascular tone and insulin sensitivity (Atkinson et al., 2009). Excess NO_3^- in water is known to form methemoglobin (oxidation of haemoglobin) and carcinogenic N-nitroso compounds leading to various forms of cancer (Benjamin, 2000). Cl^- plays significant role in maintaining the osmotic and acid base balance of body (Lewis et al., 2006). It is also required for the production of gastric hydrochloric acid secreted from the stomach parietal cells, in the activation of pepsinogen by forming hydrochloric acid, for Vitamin B12 absorption and mucous production, to prevent bacterial overgrowth in stomach and function as exchange ion in the red blood cells during chloride shift (Lewis et al., 2006). Excess of chloride is found to be associated with hypertension, increased polymorphonuclear leukocyte and disturbed blood cell counts (Bashir et al., 2012). SO_4^{--} plays a significant role in our body as they form sulphur containing proteins (Nimni et al., 2007). Sulphate also forms an important element of B Vitamins, biotin, thiamine, insulin and glutathione (GSH) (Nimni et al., 2007). Excess of sulphate in body leads to laxative effect and causes diarrhoea (WHO, 2004). However, most of these ions were within permissible limits at all sites of River Ganga at Varanasi (Table2).

Alkalinity, TDS and Hardness were assigned a weight of 2 as these do not directly affect human body yet indirectly represent the adequacy of water for human consumption. Alkalinity is known for its buffering capacity i.e. the ability to neutralize change in concentration of acids and bases in the water body (USGS, 2018). High Hardness and TDS in water indirectly plays role in causing various forms of heart ailments, myocardial infections and kidney stones in humans (Abeywickarama et al., 2016). TDS and Hardness were found to be well within the drinking water standard for the sites along the stretch of River Ganga at Varanasi with higher alkalinity at certain sites (Table3).

DO and BOD were assigned least weight of 1 as these do not have any direct impact on human, however they form an indicator of organic pollution load (CENR, 2000). Values of DO and BOD were above the permissible limit of drinking water standards at sites along the stretch of River Ganga at Varanasi (Table 3 and 4).

Table 3. Details of water quality data obtained for all parameters at the study sites along the left bank of River Ganga at Varanasi.

Sites	pH	DO (mg/l)	BOD (mg/l)	TDS (mg/l)	Alkalinity (mg/l)	Hardness (mg/l)	Cl^- (mg/l)	NO_3^- (mg/l)	SO_4^{2-} (mg/l)	Mg^{2+} (mg/l)	Ca^{2+} (mg/l)	TC (MPN/100ml)
L1 (Pre)	8.17± 0.04	6.90± 0.05	21± 0.04	304± 0.05	132± 0.05	133± 0.05	47.71± 0.05	2.42± 0.05	30.03± 0.05	21.13± 0.05	59.03± 0.05	$8.00x10^4$
L1 (post)	8.35± 0.04	6.85± 0.05	16± 0.04	224± 0.05	135± 0.05	85± 0.05	40.71± 0.05	2.19± 0.05	25.03± 0.05	16.13± 0.05	44.03± 0.05	$6.75 x10^4$

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L2 (Pre)	7.26± 0.04	1.90± 0.05	51± 0.04	478± 0.05	300± 0.05	230± 0.05	61.12± 0.05	44.68± 0.05	29.25± 0.05	27.15± 0.05	81.15± 0.05	11.75 x10^4
L2 (post)	7.44± 0.04	3.75± 0.05	31± 0.04	398± 0.05	303± 0.05	182± 0.05	54.12± 0.05	35.10± 0.05	26.56± 0.05	22.15± 0.05	66.15± 0.05	9.25 x10^4
L3 (Pre)	8.10± 0.04	5.70± 0.05	34± 0.04	332± 0.05	272± 0.05	152± 0.05	50.57± 0.05	9.30± 0.05	31.42± 0.05	22.36± 0.05	67.35± 0.05	10.50 x10^4
L3 (post)	8.28± 0.04	6.65± 0.05	28± 0.04	252± 0.05	275± 0.05	104± 0.05	43.57± 0.05	8.10± 0.05	30.36± 0.05	17.36± 0.05	52.35± 0.05	8.00 x10^4
L4 (Pre)	8.05± 0.04	6.10± 0.05	29± 0.04	328± 0.05	200± 0.05	144± 0.05	50.38± 0.05	3.33± 0.05	31.58± 0.05	21.59± 0.05	60.99± 0.05	9.75 x10^4
L4 (post)	8.23± 0.04	7.05± 0.05	25± 0.04	248± 0.05	203± 0.05	96± 0.05	43.38± 0.05	2.75± 0.05	30.56± 0.05	16.59± 0.05	45.99± 0.05	7.25 x10^4
L5 (Pre)	8.34± 0.04	6.10± 0.05	27± 0.04	324± 0.05	150± 0.05	140± 0.05	50.79± 0.05	1.91± 0.05	31.87± 0.05	22.71± 0.05	60.37± 0.05	8.75 x10^4
L5 (post)	8.52±0.04	7.05± 0.05	21± 0.04	244± 0.05	153± 0.05	92± 0.05	43.79± 0.05	1.75± 0.05	30.66± 0.05	17.71± 0.05	45.37± 0.05	6.25 x10^4
L6 (Pre)	8.41± 0.04	6.70± 0.05	25± 0.04	318± 0.05	144± 0.05	137± 0.05	51.00± 0.05	1.59± 0.05	31.98± 0.05	22.05± 0.05	59.72± 0.05	7.75 x10^4
L6 (post)	8.59±0.04	7.65± 0.05	19± 0.04	238± 0.05	147± 0.05	89± 0.05	44.00± 0.05	1.44± 0.05	30.81± 0.05	17.05± 0.05	44.72± 0.05	5.25 x10^4
L7 (Pre)	8.33±0.04	5.90± 0.05	28± 0.04	321± 0.05	150± 0.05	142± 0.05	51.17± 0.05	1.44± 0.05	31.99± 0.05	22.16± 0.05	61.28± 0.05	8.50 x10^4
L7 (post)	8.51± 0.04	6.85± 0.05	22± 0.04	241± 0.05	153± 0.05	94± 0.05	44.17± 0.05	1.15± 0.05	30.82± 0.05	17.16± 0.05	46.28± 0.05	6.00 x10^4
L8 (Pre)	8.33±0.04	5.70± 0.05	26± 0.04	318± 0.05	148± 0.05	137± 0.05	50.39± 0.05	0.47± 0.05	31.77± 0.05	22.48± 0.05	60.93± 0.05	9.00 x10^4
L8 (post)	8.51± 0.04	6.65± 0.05	20± 0.04	238± 0.05	151± 0.05	89± 0.05	43.39± 0.05	0.28± 0.05	30.57± 0.05	17.48± 0.05	45.93± 0.05	6.50 x10^4
L9 (Pre)	8.29± 0.04	6.20± 0.05	24± 0.04	314± 0.05	148± 0.05	139± 0.05	50.41± 0.05	0.86± 0.05	33.04± 0.05	22.64± 0.05	60.33± 0.05	7.50 x10^4
L9 (post)	8.47± 0.04	7.85± 0.05	18± 0.04	234± 0.05	151± 0.05	91± 0.05	43.41± 0.05	0.62± 0.05	32.14± 0.05	17.64± 0.05	45.33± 0.05	5.00 x10^4
L10 (Pre)	8.36± 0.04	5.90± 0.05	30± 0.04	324± 0.05	152± 0.05	140± 0.05	53.53± 0.05	0.80± 0.05	32.68± 0.05	22.51± 0.05	60.95± 0.05	7.00 x10^4
L10 (post)	8.54± 0.04	7.85± 0.05	25± 0.04	244± 0.05	155± 0.05	92± 0.05	46.53± 0.05	0.54± 0.05	30.56± 0.05	17.51± 0.05	45.95± 0.05	4.50 x10^4
L11 (Pre)	8.38± 0.04	5.70± 0.05	36± 0.04	329± 0.05	160± 0.05	145± 0.05	54.97± 0.05	1.31± 0.05	33.22± 0.05	23.87± 0.05	61.62± 0.05	9.75 x10^4
L11 (post)	8.56± 0.04	6.65± 0.05	30± 0.04	249± 0.05	163± 0.05	97± 0.05	47.97± 0.05	0.99± 0.05	32.34± 0.05	18.87± 0.05	46.62± 0.05	7.25 x10^4
L12 (Pre)	8.60± 0.04	6.10± 0.05	31± 0.04	320± 0.05	148± 0.05	140± 0.05	54.94± 0.05	1.28± 0.05	33.22± 0.05	23.64± 0.05	60.57± 0.05	8.75 x10^4
L12 (post)	8.78± 0.04	7.65± 0.05	26± 0.04	240± 0.05	151± 0.05	92± 0.05	47.94± 0.05	0.99± 0.05	32.34± 0.05	18.64± 0.05	45.57± 0.05	6.25 x10^4
L13 (Pre)	8.50± 0.04	6.00± 0.05	29± 0.04	318± 0.05	146± 0.05	139± 0.05	54.64± 0.05	0.96± 0.05	33.49± 0.05	22.64± 0.05	60.24± 0.05	9.25 x10^4
L13 (post)	8.68± 0.04	7.45± 0.05	24± 0.04	238± 0.05	149± 0.05	91± 0.05	47.64± 0.05	0.74± 0.05	32.19± 0.05	17.64± 0.05	45.24± 0.05	6.75 x10^4
L14 (Pre)	7.49± 0.04	0.00± 0.05	71± 0.04	670± 0.05	458± 0.05	274± 0.05	86.37± 0.05	4.27± 0.05	30.59± 0.05	48.90± 0.05	106.15± 0.05	15.50 x10^4
L14 (post)	7.67± 0.04	2.75± 0.05	61± 0.04	490± 0.05	461± 0.05	226± 0.05	79.37± 0.05	1.97± 0.05	29.34± 0.05	43.90± 0.05	91.15± 0.05	13.00 x10^4
L15 (Pre)	8.17± 0.04	5.70± 0.05	41± 0.04	422± 0.05	270± 0.05	192± 0.05	64.77± 0.05	3.60± 0.05	33.54± 0.05	26.36± 0.05	80.55± 0.05	12.00 x10^4
L15 (post)	8.35± 0.04	6.65± 0.05	36± 0.04	342± 0.05	273± 0.05	144± 0.05	57.77± 0.05	1.11± 0.05	32.33± 0.05	21.36± 0.05	65.55± 0.05	10.00 x10^4

WQI calculation and classification of sites at banks of River Ganga

WQI values calculated for the left and right bank of River Ganga at Varanasi using the optimized WAWQI method and their classification are listed as table 5. Lowered WQI values on both the left and right bank suggest relatively improved water quality during the post-monsoon period, which is likely due to pollution reduction from dilution effect.

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Along the left bank minimum and maximum WQI obtained at sites L10 (Trilochan ghat) and L14 (Varuna confluence) with values of 281.18 and 601.73 respectively, for pre-monsoon and 197.52 and 512.71 for post-monsoon period. At the right bank however, the minimum and maximum values for WQI were 255.67 at R1 (above Asi confluence) and 362.25 at R10 (Trilochan ghat), during pre-monsoon. During post-monsoon the values were 169.39 (R1) and 275.71 (R10), respectively. Unlike right bank, the trends of WQI values during pre- and post-monsoon periods varied along the left bank. The WQI values during pre-monsoon period were in the order L10〈L9〈L6〈L1〈L7〈L5〈 L12〈L8〈L13〈L4〈L11〈L3〈L15〈L2〈L14 whereas the order altered as L10〈L9〈L6〈L7〈L5〈L12〈L8〈L1〈L13〈L4〈L11〈L3〈L2〈L15〈L14 during post-monsoon period. It is noticeable that in both pre- and post-monsoon periods the L10 had least and L14 had highest WQI values. Right bank exhibited ascending WQI values in the order R1〈R15〈R2〈R3〈R14〈R4〈R6〈R5〈R13〈R7〈R8〈 R9〈 R12〈 R11〈 R10 during both pre- and post-monsoon period.

Upon comparing WQI values with the classification of water quality, the quality of water at the sites along the left bank during pre-monsoon period except for L6, L9 and L10 (Dashashwamedh, Gaay and Trilochan ghat) are found unfit for drinking (Table 5), however, during post-monsoon period the water quality at most of the sites relatively improved as suggested by the change in class from unfit for drinking to very poor water quality (Table 5). The sites along right bank R1, R2, R3, R14 and R15 (above Asi confluence, Asi confluence, Asi, Varuna confluence and beyond Varuna confluence) fell under very poor water quality whereas the rest of the sites (R4 to R13) were unfit for drinking during pre-monsoon period. During post-monsoon period the quality of water at these sites however, changed from category very poor to poor and from unsuitable to drinking to very poor category (Table 5). Standard values while calculating WQI were considered from Class C (Drinking water source with conventional treatment followed by disinfection) of water use as per Indian standard (ISI-IS: 2296-1982).

Low WQI implies better water quality. Least WQI is noted at L10 (Trilochan ghat) along the left bank followed by L9 (Gaay ghat) as these sites experience least human interactions and associated pollution. At the right bank sites R10 (Trilochan ghat) and R11 (Teliyanala ghat) had the highest WQI value suggesting them to be most polluted (Table 5). This may be attributed to flow reversal along R10 creating a zone of flow retardation at R10 and R11 (Fig. 1). Flow retardation leads to accumulation of contaminants and therefore high WQI values (Choudhary, 2008). Though L1 (above Asi confluence) site has less anthropogenic activities yet its WQI ranks at fourth place during pre-monsoon period owing to transverse movement of contaminants from drain discharge at L2 (Asi confluence). Likewise, L3 (Asi ghat) and L4 (Harishchandra ghat) also faces dual pollution sources viz. lateral dispersion of discharge of drain at Asi confluence as well as aggressive site-specific anthropogenic activities, hence had comparatively higher WQI. Similarly, site L15 (beyond Varuna confluence) has high WQI perhaps due to mixing of water from drain discharge at Varuna confluence, a highly polluted site (Table 3 and 5). Sites like L7 (Manikarnika ghat), L5 (Babua pandey ghat), L12 (Prahlad ghat), L8 (Ganga Mahal II ghat), L11 (Teliyanala ghat), L13 (Rajghat) also exhibit relatively higher WQI. This could be due to site-specific anthropogenic activities such as cremation, laundry, boating, large number of visitors, solid waste dumping, discharge of drains, etc. Surprisingly, during post-monsoon season WQI of L1 (above Asi confluence) were much higher as compared to sites L7 (Manikarnika ghat), L5 (Babua pandey ghat), L12 (Prahlad ghat) and L8 (Ganga Mahal II ghat). This may be perhaps due to higher flow rate of water that reduces the site-specific anthropogenic activities. However, no much change was observed at the drain discharge sites.

Table 4. Details of water quality data obtained for all parameters at the study sites along the right bank of River Ganga at Varanasi.

Sites	pH	DO (mg/l)	BOD (mg/l)	TDS (mg/l)	Alkalinity (mg/l)	Hardness (mg/l)	Cl^- (mg/l)	NO_3^- (mg/l)	SO_4^{2-} (mg/l)	Mg^{2+} (mg/l)	Ca^{2+} (mg/l)	TC (MPN/100ml)
R1(Pre)	9.24± 0.04	6.80± 0.05	17.00± 0.04	307± 0.05	147± 0.05	305± 0.05	48.65± 0.05	3.65± 0.05	31.53± 0.05	21.64± 0.05	56.93 ± 0.05	6.50 $\times 10^4$
R1(post)	8.73± 0.04	7.85± 0.05	12.00± 0.04	222± 0.05	152± 0.05	245± 0.05	39.85± 0.05	2.45± 0.05	26.53± 0.05	15.74± 0.05	32.33 ± 0.05	4.00 $\times 10^4$
R2(Pre)	9.25± 0.04	6.70± 0.05	19.00± 0.04	309± 0.05	152± 0.05	322± 0.05	49.79± 0.05	4.01± 0.05	31.69± 0.05	21.98± 0.05	58.62 ± 0.05	7.25 $\times 10^4$
R2(post)	8.74± 0.04	7.65± 0.05	14.00± 0.04	224± 0.05	157± 0.05	262± 0.05	40.99± 0.05	2.81± 0.05	26.69± 0.05	16.08± 0.05	34.02 ± 0.05	4.75 $\times 10^4$
R3(Pre)	9.25± 0.04	6.70± 0.05	19.00± 0.04	309± 0.05	152± 0.05	322± 0.05	50.56± 0.05	4.35± 0.05	31.86± 0.05	22.20± 0.05	58.63 ± 0.05	7.25 $\times 10^4$
R3(post)	8.74± 0.04	7.65± 0.05	14.00± 0.04	224± 0.05	157± 0.05	262± 0.05	41.76± 0.05	3.15± 0.05	26.86± 0.05	16.30± 0.05	34.03 ± 0.05	4.75 $\times 10^4$

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R4(Pre)	9.26± 0.04	6.50± 0.05	22.00± 0.04	310± 0.05	153± 0.05	324± 0.05	52.01± 0.05	2.91± 0.05	31.87± 0.05	22.32± 0.05	58.65 ± 0.05	7.75 x10^4
R4(post)	8.75± 0.04	7.45± 0.05	18.00± 0.04	225± 0.05	158± 0.05	264± 0.05	43.21± 0.05	1.71± 0.05	26.87± 0.05	16.42± 0.05	34.05 ± 0.05	5.25 x10^4
R5(Pre)	9.26± 0.04	6.50± 0.05	23.00± 0.04	311± 0.05	153± 0.05	325± 0.05	52.11± 0.05	3.91± 0.05	31.96± 0.05	22.53± 0.05	58.69 ± 0.05	7.75 x10^4
R5(post)	8.75± 0.04	7.45± 0.05	19.00± 0.04	226± 0.05	158± 0.05	265± 0.05	43.31± 0.05	2.71± 0.05	26.96± 0.05	16.63± 0.05	34.09 ± 0.05	5.25 x10^4
R6(Pre)	9.26± 0.04	6.50± 0.05	23.00± 0.04	311± 0.05	156± 0.05	327± 0.05	53.19± 0.05	2.54± 0.05	32.40± 0.05	22.73± 0.05	58.77 ± 0.05	7.75 x10^4
R6(post)	8.75± 0.04	7.45± 0.05	19.00± 0.04	226± 0.05	161± 0.05	267± 0.05	44.39± 0.05	1.34± 0.05	27.40± 0.05	16.83± 0.05	34.17 ± 0.05	5.25 x10^4
R7(Pre)	9.27± 0.04	6.10± 0.05	25.00± 0.04	314± 0.05	156± 0.05	327± 0.05	53.32± 0.05	2.46± 0.05	32.62± 0.05	22.77± 0.05	60.41 ± 0.05	8.00 x10^4
R7(post)	8.76± 0.04	7.05± 0.05	21.00± 0.04	229± 0.05	161± 0.05	267± 0.05	44.52± 0.05	1.26± 0.05	27.62± 0.05	16.87± 0.05	35.81 ± 0.05	5.50 x10^4
R8(Pre)	9.27± 0.04	6.10± 0.05	27.00± 0.04	314± 0.05	157± 0.05	330± 0.05	54.00± 0.05	2.41± 0.05	32.73± 0.05	22.95± 0.05	60.65 ± 0.05	8.00 x10^4
R8(post)	8.76± 0.04	7.05± 0.05	22.00± 0.04	229± 0.05	162± 0.05	270± 0.05	45.20± 0.05	1.21± 0.05	27.73± 0.05	17.05± 0.05	36.05 ± 0.05	5.50 x10^4
R9(Pre)	9.27± 0.04	6.10± 0.05	28.00± 0.04	316± 0.05	157± 0.05	335± 0.05	54.05± 0.05	1.96± 0.05	32.82± 0.05	22.96± 0.05	61.25 ± 0.05	8.00 x10^4
R9(post)	8.76± 0.04	6.85± 0.05	23.00± 0.04	231± 0.05	162± 0.05	275± 0.05	45.25± 0.05	0.76± 0.05	27.82± 0.05	17.06± 0.05	36.65 ± 0.05	5.50 x10^4
R10(Pre)	9.35± 0.04	5.70± 0.05	36.00± 0.04	320± 0.05	162± 0.05	362± 0.05	54.65± 0.05	1.96± 0.05	34.26± 0.05	24.35± 0.05	64.30 ± 0.05	9.25 x10^4
R10(post)	8.84± 0.04	6.40± 0.05	31.00± 0.04	235± 0.05	167± 0.05	302± 0.05	45.85± 0.05	0.76± 0.05	29.26± 0.05	18.45± 0.05	39.699 ± 0.05	6.75 x10^4
R11(Pre)	9.32± 0.04	5.80± 0.05	34.00± 0.04	323± 0.05	167± 0.05	352± 0.05	58.08± 0.05	1.90± 0.05	34.21± 0.05	23.98± 0.05	62.89 ± 0.05	8.75 x10^4
R11(post)	8.81± 0.04	6.55± 0.05	29.00± 0.04	238± 0.05	172± 0.05	292± 0.05	49.28± 0.05	0.70± 0.05	29.21± 0.05	18.08± 0.05	38.29 ± 0.05	6.25 x10^4
R12(Pre)	9.30± 0.04	6.00± 0.05	31.00± 0.04	320± 0.05	165± 0.05	342± 0.05	56.86± 0.05	1.91± 0.05	34.04± 0.05	23.40± 0.05	62.26 ± 0.05	8.00 x10^4
R12(post)	8.79± 0.04	6.70± 0.05	26.00± 0.04	235± 0.05	170± 0.05	282± 0.05	48.06± 0.05	0.71± 0.05	29.04± 0.05	17.50± 0.05	37.66 ± 0.05	5.50 x10^4
R13(Pre)	9.27± 0.04	5.70± 0.05	27.00± 0.04	310± 0.05	161± 0.05	337± 0.05	54.79± 0.05	2.08± 0.05	33.66± 0.05	23.79± 0.05	62.08 ± 0.05	7.75 x10^4
R13(post)	8.76± 0.04	6.45± 0.05	22.00± 0.04	225± 0.05	166± 0.05	277± 0.05	45.99± 0.05	0.88± 0.05	28.66± 0.05	17.89± 0.05	37.48 ± 0.05	5.25 x10^4
R14(Pre)	9.27± 0.04	6.10± 0.05	23.00± 0.04	309± 0.05	159± 0.05	322± 0.05	52.77± 0.05	2.04± 0.05	33.40± 0.05	23.70± 0.05	61.30 ± 0.05	7.25 x10^4
R14(post)	8.76± 0.04	7.05± 0.05	18.00± 0.04	224± 0.05	164± 0.05	262± 0.05	43.97± 0.05	0.85± 0.05	28.40± 0.05	17.80± 0.05	36.70 ± 0.05	4.75 x10^4
R15(Pre)	9.25± 0.04	6.50± 0.05	21.00± 0.04	308± 0.05	153± 0.05	317± 0.05	50.87± 0.05	1.62± 0.05	32.32± 0.05	22.99± 0.05	61.28 ± 0.05	7.00 x10^4
R15(post)	8.74± 0.04	7.45± 0.05	16.00± 0.04	223± 0.05	158± 0.05	257± 0.05	42.07± 0.05	0.58± 0.05	27.32± 0.05	17.09± 0.05	36.68 ± 0.05	4.50 x10^4

Table 5. WQI calculated for pre- and post-monsoon period along the left and right bank of River Ganga at Varanasi.

Sites	pH	DO (mg/l)	BOD (mg/l)	TDS (mg/l)	Alkalinity (mg/l)	Hardness (mg/l)	Cl^- (mg/l)	NO_3^- (mg/l)	SO_4^{2-} (mg/l)	Mg^{2+} (mg/l)	Ca^{2+} (mg/l)	TC (MPN/100ml)
R1(Pre)	9.24± 0.04	6.80± 0.05	17.00± 0.04	307± 0.05	147± 0.05	305± 0.05	48.65± 0.05	3.65± 0.05	31.53± 0.05	21.64± 0.05	56.93 ± 0.05	6.50 x10^4
R1(post)	8.73± 0.04	7.85± 0.05	12.00± 0.04	222± 0.05	152± 0.05	245± 0.05	39.85± 0.05	2.45± 0.05	26.53± 0.05	15.74± 0.05	32.33 ± 0.05	4.00 x10^4
R2(Pre)	9.25± 0.04	6.70± 0.05	19.00± 0.04	309± 0.05	152± 0.05	322± 0.05	49.79± 0.05	4.01± 0.05	31.69± 0.05	21.98± 0.05	58.62 ± 0.05	7.25 x10^4

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R2(post)	8.74± 0.04	7.65± 0.05	14.00± 0.04	224± 0.05	157± 0.05	262± 0.05	40.99± 0.05	2.81± 0.05	26.69± 0.05	16.08± 0.05	34.02 ± 0.05	4.75 x10^4
R3(Pre)	9.25± 0.04	6.70± 0.05	19.00± 0.04	309± 0.05	152± 0.05	322± 0.05	50.56± 0.05	4.35± 0.05	31.86± 0.05	22.20± 0.05	58.63 ± 0.05	7.25 x10^4
R3(post)	8.74± 0.04	7.65± 0.05	14.00± 0.04	224± 0.05	157± 0.05	262± 0.05	41.76± 0.05	3.15± 0.05	26.86± 0.05	16.30± 0.05	34.03 ± 0.05	4.75 x10^4
R4(Pre)	9.26± 0.04	6.50± 0.05	22.00± 0.04	310± 0.05	153± 0.05	324± 0.05	52.01± 0.05	2.91± 0.05	31.87± 0.05	22.32± 0.05	58.65 ± 0.05	7.75 x10^4
R4(post)	8.75± 0.04	7.45± 0.05	18.00± 0.04	225± 0.05	158± 0.05	264± 0.05	43.21± 0.05	1.71± 0.05	26.87± 0.05	16.42± 0.05	34.05 ± 0.05	5.25 x10^4
R5(Pre)	9.26± 0.04	6.50± 0.05	23.00± 0.04	311± 0.05	153± 0.05	325± 0.05	52.11± 0.05	3.91± 0.05	31.96± 0.05	22.53± 0.05	58.69 ± 0.05	7.75 x10^4
R5(post)	8.75± 0.04	7.45± 0.05	19.00± 0.04	226± 0.05	158± 0.05	265± 0.05	43.31± 0.05	2.71± 0.05	26.96± 0.05	16.63± 0.05	34.09 ± 0.05	5.25 x10^4
R6(Pre)	9.26± 0.04	6.50± 0.05	23.00± 0.04	311± 0.05	156± 0.05	327± 0.05	53.19± 0.05	2.54± 0.05	32.40± 0.05	22.73± 0.05	58.77 ± 0.05	7.75 x10^4
R6(post)	8.75± 0.04	7.45± 0.05	19.00± 0.04	226± 0.05	161± 0.05	267± 0.05	44.39± 0.05	1.34± 0.05	27.40± 0.05	16.83± 0.05	34.17 ± 0.05	5.25 x10^4
R7(Pre)	9.27± 0.04	6.10± 0.05	25.00± 0.04	314± 0.05	156± 0.05	327± 0.05	53.32± 0.05	2.46± 0.05	32.62± 0.05	22.77± 0.05	60.41 ± 0.05	8.00 x10^4
R7(post)	8.76± 0.04	7.05± 0.05	21.00± 0.04	229± 0.05	161± 0.05	267± 0.05	44.52± 0.05	1.26± 0.05	27.62± 0.05	16.87± 0.05	35.81 ± 0.05	5.50 x10^4
R8(Pre)	9.27± 0.04	6.10± 0.05	27.00± 0.04	314± 0.05	157± 0.05	330± 0.05	54.00± 0.05	2.41± 0.05	32.73± 0.05	22.95± 0.05	60.65 ± 0.05	8.00 x10^4
R8(post)	8.76± 0.04	7.05± 0.05	22.00± 0.04	229± 0.05	162± 0.05	270± 0.05	45.20± 0.05	1.21± 0.05	27.73± 0.05	17.05± 0.05	36.05 ± 0.05	5.50 x10^4
R9(Pre)	9.27± 0.04	6.10± 0.05	28.00± 0.04	316± 0.05	157± 0.05	335± 0.05	54.05± 0.05	1.96± 0.05	32.82± 0.05	22.96± 0.05	61.25 ± 0.05	8.00 x10^4
R9(post)	8.76± 0.04	6.85± 0.05	23.00± 0.04	231± 0.05	162± 0.05	275± 0.05	45.25± 0.05	0.76± 0.05	27.82± 0.05	17.06± 0.05	36.65 ± 0.05	5.50 x10^4
R10(Pre)	9.35± 0.04	5.70± 0.05	36.00± 0.04	320± 0.05	162± 0.05	362± 0.05	54.65± 0.05	1.96± 0.05	34.26± 0.05	24.35± 0.05	64.30 ± 0.05	9.25 x10^4
R10(post)	8.84± 0.04	6.40± 0.05	31.00± 0.04	235± 0.05	167± 0.05	302± 0.05	45.85± 0.05	0.76± 0.05	29.26± 0.05	18.45± 0.05	39.699 ± 0.05	6.75 x10^4
R11(Pre)	9.32± 0.04	5.80± 0.05	34.00± 0.04	323± 0.05	167± 0.05	352± 0.05	58.08± 0.05	1.90± 0.05	34.21± 0.05	23.98± 0.05	62.89 ± 0.05	8.75 x10^4
R11(post)	8.81± 0.04	6.55± 0.05	29.00± 0.04	238± 0.05	172± 0.05	292± 0.05	49.28± 0.05	0.70± 0.05	29.21± 0.05	18.08± 0.05	38.29 ± 0.05	6.25 x10^4
R12(Pre)	9.30± 0.04	6.00± 0.05	31.00± 0.04	320± 0.05	165± 0.05	342± 0.05	56.86± 0.05	1.91± 0.05	34.04± 0.05	23.40± 0.05	62.26 ± 0.05	8.00 x10^4
R12(post)	8.79± 0.04	6.70± 0.05	26.00± 0.04	235± 0.05	170± 0.05	282± 0.05	48.06± 0.05	0.71± 0.05	29.04± 0.05	17.50± 0.05	37.66 ± 0.05	5.50 x10^4
R13(Pre)	9.27± 0.04	5.70± 0.05	27.00± 0.04	310± 0.05	161± 0.05	337± 0.05	54.79± 0.05	2.08± 0.05	33.66± 0.05	23.79± 0.05	62.08 ± 0.05	7.75 x10^4
R13(post)	8.76± 0.04	6.45± 0.05	22.00± 0.04	225± 0.05	166± 0.05	277± 0.05	45.99± 0.05	0.88± 0.05	28.66± 0.05	17.89± 0.05	37.48 ± 0.05	5.25 x10^4
R14(Pre)	9.27± 0.04	6.10± 0.05	23.00± 0.04	309± 0.05	159± 0.05	322± 0.05	52.77± 0.05	2.04± 0.05	33.40± 0.05	23.70± 0.05	61.30 ± 0.05	7.25 x10^4
R14(post)	8.76± 0.04	7.05± 0.05	18.00± 0.04	224± 0.05	164± 0.05	262± 0.05	43.97± 0.05	0.85± 0.05	28.40± 0.05	17.80± 0.05	36.70 ± 0.05	4.75 x10^4
R15(Pre)	9.25± 0.04	6.50± 0.05	21.00± 0.04	308± 0.05	153± 0.05	317± 0.05	50.87± 0.05	1.62± 0.05	32.32± 0.05	22.99± 0.05	61.28 ± 0.05	7.00 x10^4
R15(post)	8.74± 0.04	7.45± 0.05	16.00± 0.04	223± 0.05	158± 0.05	257± 0.05	42.07± 0.05	0.58± 0.05	27.32± 0.05	17.09± 0.05	36.68 ± 0.05	4.50 x10^4

Cluster analysis of the water quality data for the sites on the two banks of river Ganga (Fig. 2) revealed formation of three clusters each on left and right banks wherein sites L2, L3, L4, L11, L15 formed Cluster 2, L1, L5 to L10, L12, L13 grouped as Cluster 1 and L14 stood alone as Cluster 3 on left bank. On the right bank Cluster 2 had sites R2 to R9, R12 to R14, Cluster 1 comprised of R1 and R15 whereas Cluster 3 figured sites R10 and R11. This further confirmed site L14 on left bank and R10- R11 on the right bank to be the outliers representing the most polluted sites along the river Ganga.

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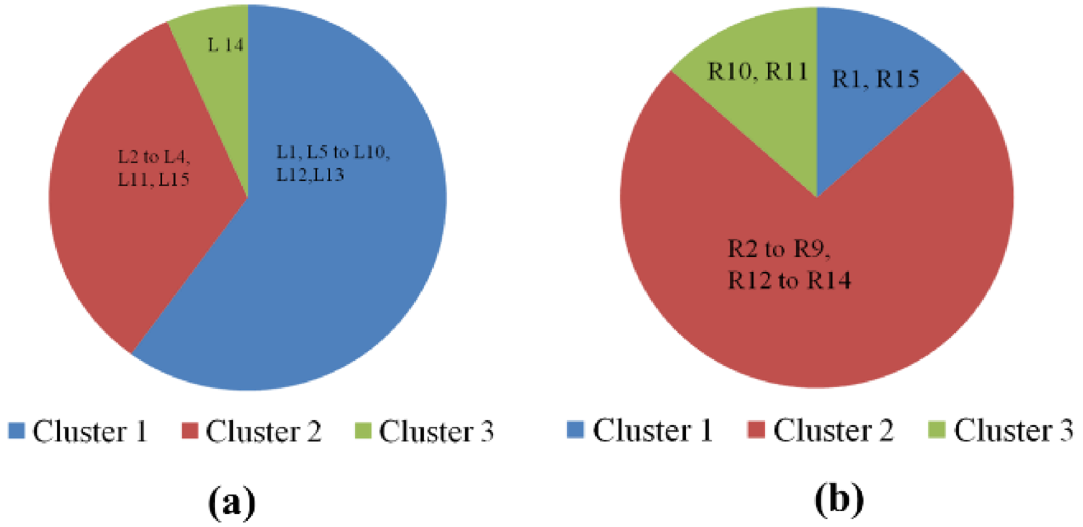

Fig. 2: Cluster analysis of the sites on a) left bank and (b) right bank using water quality data

To understand the contribution of each water quality parameter and their importance in WQI the correlation between the two were analyzed. The correlation of WQI with different water quality parameters studied herein has been listed as Table 6. From the Table a good correlation between, TC, alkalinity, BOD, TDS and calcium is noted at both the banks of river Ganga at Varanasi whereas, NO_3^- and SO_4^{2-} were least correlated to WQI.

Table 6. Correlation Table of WQI values with different water quality parameters under study.

Parameters	WQI Pre				WQI Post			
	Left bank		Right bank		Left bank		Right bank	
	Pearson correlation	Sig. (2-tailed)	Pearson correlation	Sig. (2-tailed)	Pearson correlation	Sig. (2-tailed)	Pearson correlation	Sig. (2-tailed)
pH	-.759**	.001	.922**	.000	-.739**	.002	.918**	.000
DO	-.878**	.000	-.808**	.000	-.873**	.000	-.824**	.000
BOD	.953**	.000	.952**	.000	.922**	.000	.962**	.000
TDS	.932**	.000	.896**	.000	.919**	.000	.893**	.000
Alkalinity	.958**	.000	.801**	.000	.945**	.000	.796**	.000
Hardness	.937**	.000	.964**	.000	.919**	.000	.960**	.000
Cl^-	.905**	.000	.829**	.000	.897**	.000	.827**	.000
NO_3^-	0.398	.142	-.514	.050	.299	.280	-.531*	.042
SO_4^{2-}	-0.347	.204	.780**	.001	-.202	.470	.773**	.001
Mg^{++}	.866**	.000	.763**	.001	.859**	.000	.757**	.001
Ca^{2+}	.953**	.000	.780**	.001	.947**	.000	.772**	.001
TC	.997**	.000	.997**	.000	.997**	.000	.997**	.000

Therefore, there is a need to focus upon reducing the solid -waste dumping, excess use of wood for cremation, laundry activities, drains thereby increasing the natural flow of River Ganga at Varanasi not only to improve its water quality but also to restore river ecosystem.

IV. CONCLUSIONS

The water quality parameters analyzed for river Ganga water at two banks at Varanasi suggested river Ganga to be affected by higher coliform levels, altered pH and DO/BOD levels. The WAWQI method was optimized herein accommodating all the water quality parameters which otherwise remained unconsidered. Unit weights 1 to 5, an important component of WAWQI calculation were assigned to water quality parameters based upon its effects on human health. Subsequently, observed WQI values suggested severe degradation of water quality of River Ganga falling under the category unfit for drinking purpose. WQI values further highlighted untreated sewage discharge points as major pollution sources thereby serving as tool for pollution source identification for River Ganga at Varanasi. Variations in WQI value for pre- and post-monsoon period indicate the significance of increased volume of water for mitigating pollution problems. From the results it can be concluded that site L14 on left bank and sites R10 and R11 on right bank are most polluted. The discharge of drains and reduced flow of water contribute largely to this pollution and poor health of River Ganga at Varanasi. Water quality of most of the ghats on the left bank are unfit for human consumption unlike right bank where the water quality is comparatively better and may be used for human activities other than drinking purpose. It is thus recommended to use the optimized method of WAWQI calculation that essentially includes TC and BOD/DO in addition to all other water quality parameters for calculating WQI which may serve as a robust yet simple tool for assessing a comprehensive water quality and health of a river. The WQI thus calculated will help prioritize areas/sites for immediate management/policy actions towards restoration, rejuvenation and understanding of River Ganga ecosystem at Varanasi.

Competing interest

The authors declare no competing interest.

Author contributions

Data collection and analysis were carried out by IN, CP, VC and KS. CP and KS contributed towards writing and editing of the MS.

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