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Assessment of Water Quality Characteristics Along the Course of the Yamuna River (India)

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Abstract

Yamuna river plays an important role in providing water for irrigation, life and drinking but the development of various small and large cities along its bank has deteriorated river water quality.Various physicochemical parameters of the river Yamuna were assessed over its mountainous region to confluence point near Prayagraj covering a distance of 1376km. The river water samples were studied for temperature, pH, TDS, total alkalinity, total hardness, electrical conductivity, chlorides, sulfate, phosphate, sodium, potassium, magnesium, and calcium concentration in pre monsoon and post monsoon seasons. Water samples collected from 41 different sites from its mountainous region to its confluence point to the Ganga River. The physicochemical parameters showed a significant decrease of 20-30% in nearly all parameterspost monsoon reasons.WAWQI calculated by dividing studied stretch of Yamuna River into four segments. The results unveiled that quality of river water was poor in mountainous regions, which became worse at its confluence point.The various parameters indicate that pollution from all sources-industrial, municipal and agricultural sources are responsible for the pollution of Yamuna river water. Regular analysing water samples can identify river's health, suitability for human use and to ensure that water is suitable for recreation and aquatic life. The significance of this research lies in its potential to protect aquatic ecosystem, elevate sustainable water useand contributing to the long term river's health and various communities that depends on it.

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Introduction

Rivers are important source of fresh water and these originates from melting glaciers or springs. Yamuna river is most famous river of India at which is situated National Capital City i.e., New Delhi. A number of small and largecities are situated along its entire stretch which originates at Yamunotri to convergence point to Ganga River which is at Prayagraj.

The discharge of various toxic chemicals in river water not only alters the physico-chemical parameters but also the hydro biological parameters. Yamuna River has been studied with respect to physicochemical parameters as it gives estimation of the status of river that are showed to deleterious human induced sources. On various rivers of the country many studies have been conducted regarding change inphysical and chemical parameter due to various factors such as spatial, temporal, seasonal, environmental variations and small changes due to choice of sampling sites.[1]

Except for some seasonal and spatial variation in the parameters, all the studies show the physico-chemical parameter values higher than the prescribed limit of WHO, 2006.[2] Some sites of Yamuna in Delhi, Mathura and Agra cities are highly polluted, rendering the river water unfit for any purpose.Various previous studies show that for the last many decades water of Yamuna River is being continuously contaminated beyond all the limits.[3] WQI is a beneficial technique for assessing quality of water. As it grants an idea regarding the water quality by using various parameters along with mathematical equations and helps the policy makers in making of policies for giving life to the river. In the present study various physico-chemical parameters has been estimated and calculated WAWQI which decide suitability of river water for human as well as agricultural consumption.

In recent study the pH for Yamuna water was formed with in permissible limit of WHO whereas several parameters like total hardness, specific conductance, total alkalinity calcium and magnesiumwere present in much higher concentration as compared to permissible limit of WHO, 2006 as well as BIS, 2012 standards for drinking water.[4] The concentration of Chloride, Sulphate, Phosphate, Sodium were found within permissible limit for segment-I (mountainous region) but downstream to it, all parameters increased very sharply. Literature survey reveals that there is no systematic research showing the entire stretch until now although the physicochemical parameters has been monitored but for different stretch. In the present study the main objective was to analyse various physico-chemical parameters along entire stretch in a single study and see the effect of seasonal variations as sampling has been in seasons of pre monsoon (May, 2017) and post monsoon (October, 2017). Thepresent study aim is to analyse the concentration of various physico-chemical parameters in terms of distance and seasons in river Yamuna.

Materials and Methods

Study Area

The Yamuna River is situated in northern part of India and originates from Yamnotri glacier to get confluence with Ganga River at Prayagraj. In its way, it travels through five states of the country and covers a distance of 1376 Kms.The whole river stretch studied was divided into four segments and water samples were collected at 41 sites (Figure 1a). Segment-I was of 180 km and have many industries like textile, paper, wood etc. including agricultural run-offs along the river side which may have polluted the river water. The second stretch i.e. Segment-II was of about 246 kms has all types of industries (textiles, paper, chemical, refinery and power plants) along with a large amount of waste-water released into the river as sewage and industrial effluents. The third stretch i.e. Segment-III was of about 160 km which includes two major cities, Delhi and Faridabad, on the river-side, which add a heavy load of waste both from sewage and industries (Textile, thermal power plant, drug, solid waste). Nearly 22 drains of small to large size falls in Yamuna River in this segment-III which comprises Delhi i.e. National Capital City, discharging large amount of waste water. The Segment- IV was of 120 km length downstream the Agra city, up to Ismailpur and many pharmaceutical industries are situated along it with many more industries like footwear industries, oil industry, tanneries and a huge amount of sewage waste from the city.[5]

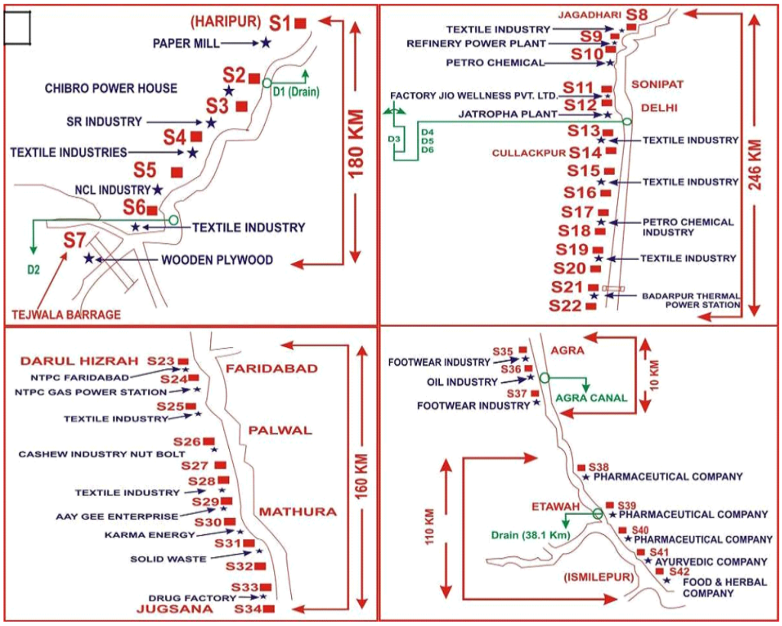


Fig. 1(a): Sampling locations along the Yamuna river.

Sample Collection

Samples collected from 41 sampling sites in May-June 2017 and October-November 2017 to examine the impacts of monsoon on Yamuna river water and were designated as pre and post monsoon. Composite samples of water were placed in clean and prewashed polythene containers of two liters capacity along river Yamuna. Composite samples were prepared after well mixing of triplicate samples collected by grab sampling following all the appropriate protocols. All the sample were stored in ice-boxes at nearly 4ºC till brought to laboratory for further analysis. Thermo-probe, EC meter and pH meter used to calculate the values of temperature, electrical conductivity and pH on the spot in the field.

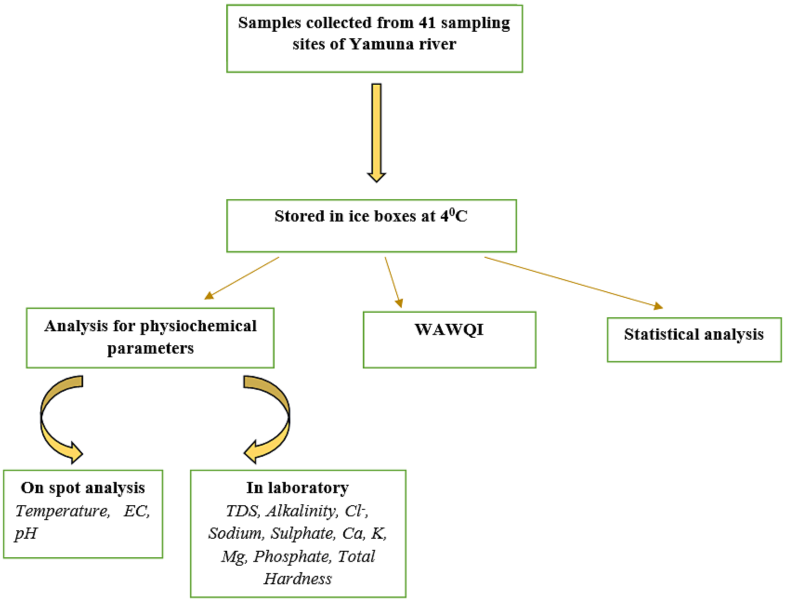


Fig. 1(b): Flow chart of methodology

Table 1: Analysed physico-chemical parameters with theiranalytical methods, units, instrument used, WHO (2006) and BIS (2012) permissible limits

Parameters	Units	Analytical method used	Instrument used	WHO International standards(2006)	BIS permissible limits (2012)
Temperature	ºC	Instrumental	Mercury thermo -meter	---	---
pH	---	Electrode method	pH meter	6.8-8.5	6.5-9.2
EC	$mScm^{-1}$	Electrode method	Conductivity meter	0.5	---
TDS	mgL^{-1}	Filtration method	---	500	300-1500
Total Hardness	mgL^{-1}	EDTA method	Titration assembly	200	300-600
Chlorides	mgL^{-1}	Argentometric method	Titration assembly	250	250-1000
Total Alkalinity	mgL^{-1}	Titrimetric method	Titration assembly	200	200-600
Magnesium	mgL^{-1}	EDTA Titrimetric method	Titration assembly	50	30-100
Calcium	mgL^{-1}	EDTA Titrimetric method	Titration assembly	75	75-200
Sodium	mgL^{-1}	Flame Photometer method	Flame photometer used	200	50
Potassium	mgL^{-1}	Flame Photometer method	Flame photometer	200	---
Sulphate	mgL^{-1}	Turbidimetric method	UV- spectrophoto -meter	200	250-400
Phosphate	mgL^{-1}	Turbidimetric method	UV- spectrophoto -meter	0.5	---

Water Quality Analysis for Physico-Chemical parameters

In this present study thirteen parameters like Temperature, pH, Total Hardness (TH), Specific Conductance, Total Alkalinity, TDS, Chlorides (Cl^-), Sulphate (SO_4^{2-}), Sodium (Na^+), Calcium (Ca^{2+}), Potassium (K^+), Magnesium (Mg^{2+}) and Phosphate (PO_4^{3}) were assessed to study the water quality using standard quality procedure as described in APHA.[6] For physico-chemical analysis, double distilled water along with analytical grade chemicals were used to made the solution. For quality assurance, all the analyses were done in triplicate. The data was statistically analysed by intercorrelation matrix to calculate pollution load in river. Correlation matrix was analysed by using Pearson's correlation.

Weighted Arithmetic Water Quality Index

Among the various available tools for expressing quality of water, WAWQI is one of the most useful and simple method. Mean or aggregate values of various important parameters are used to calculate WAWQI that affects thewater quality. WAWQI is calculated by using the following equations[7] and compared the water quality with given grading scale between 0-100. 0 to 25 (excellent) and it stands for grade A, 26 to 50 (good) which stands for B grade, 51 to 75 (poor) stands for C grade, 76 to100 (very Poor) for D grade and more than 100 (unsuitable for drinking purpose) which stands for grade E.

Calculations for WAWQI

To calculate quality rating for every parameter the given eq. is used

(i) Calculation for quality rating (Qi) is given by eq. 1

$$Q_i = (Conc._{reported} - Conc._{ideal}) / (Conc._{standard} - Conc._{ideal}) \times 100 \quad \ldots(1)$$

Where,
Q_i stands forith parameter's Quality rating fortotal of n parameters of water quality

$Conc._{reported}$= Calculatedwater quality parameters value which is obtained from labanalysis

$Conc._{ideal}$= parameter's ideal value obtained from standard table Whose pH seven and for various parameter it is liken to zero.

$Conc._{standard}$= WHO supported standard value of parameters

(ii) Calculations for Unit weight
Inversely proportional to standard values suggested for respective parameter uses equation 2

W_i(Unit weight) = K/S_i ...(2)

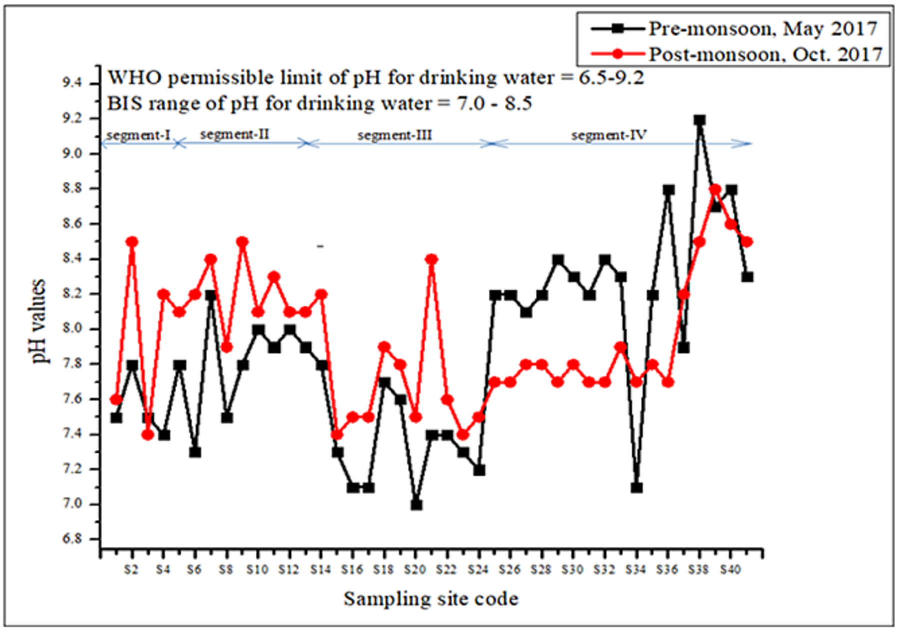
W_i stands for nth parameter's Unit weight and S_i stands for nth parameter's standard permissible value and constant is K whose value is considered as 1 for the sake of simplification.

(iii)Calculation for WAWQI

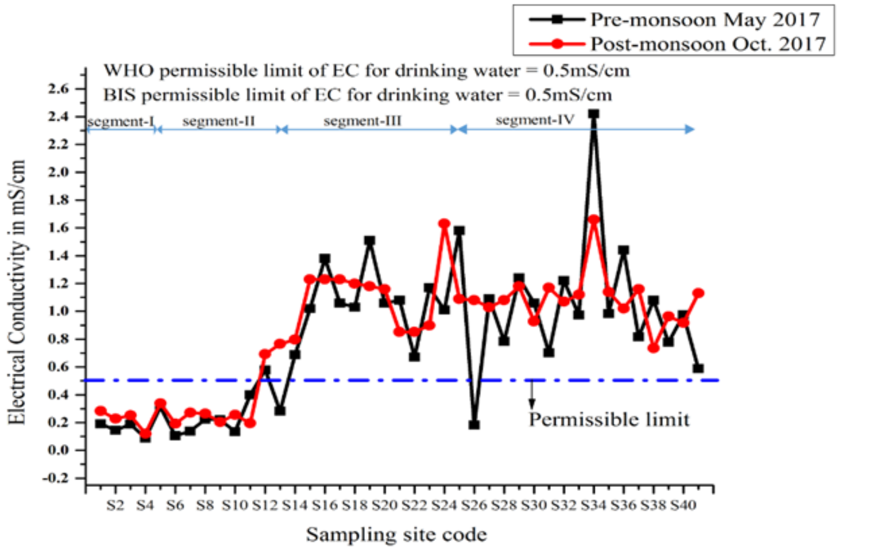
$$WQI = \sum W_i Q_i / \sum W_i \quad ...(3)$$

Wi= Unit weight
Qi=Quality rating

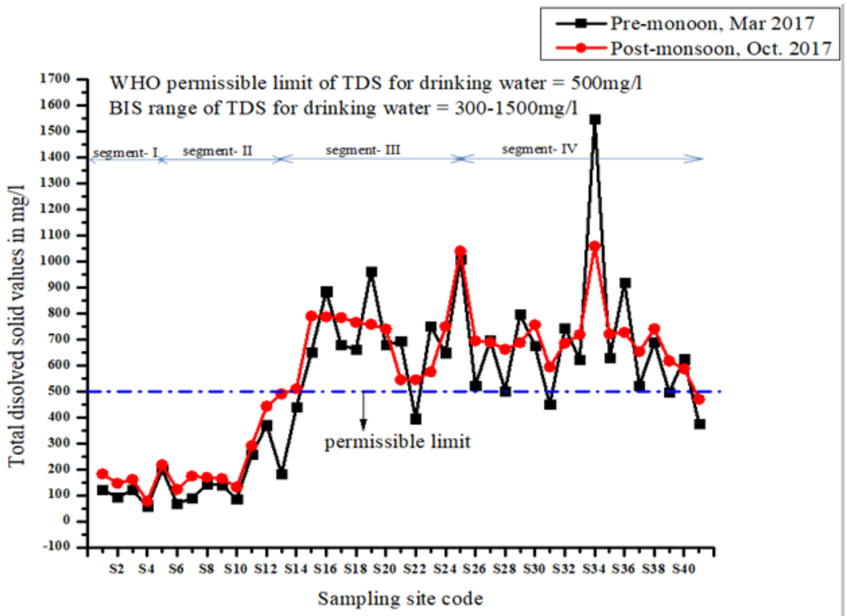
Result
Physical-chemical parameters of river Yamuna during premonsoon and postmonsoon seasons represented in figure 2(a-l)



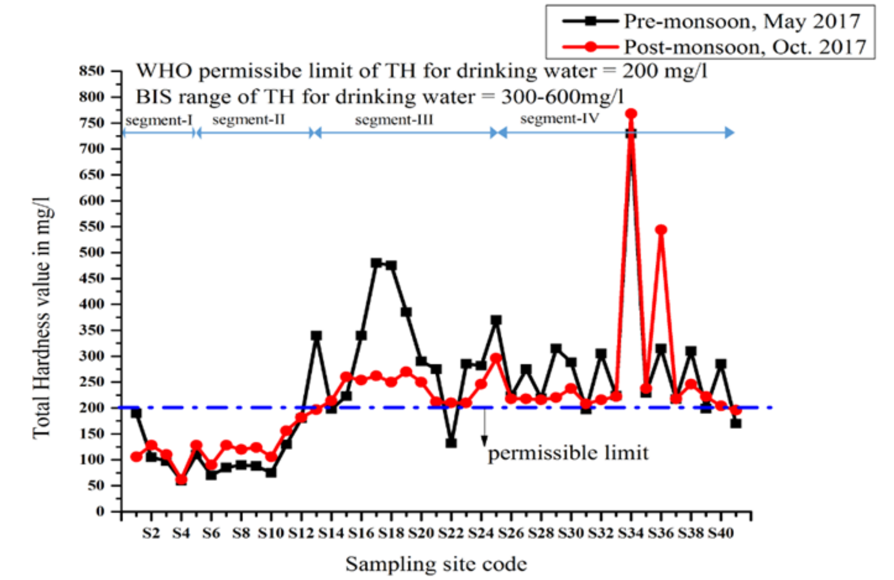
a)


Pre-monsoon May 2017
Post-monsoon Oct. 2017
WHO permissible limit of EC for drinking water = 0.5mS/cm
BIS permissible limit of EC for drinking water = 0.5mS/cm
segment-I
segment-II
segment-III
segment-IV
Electrical Conductivity in mS/cm
Permissible limit
Sampling site code

b)

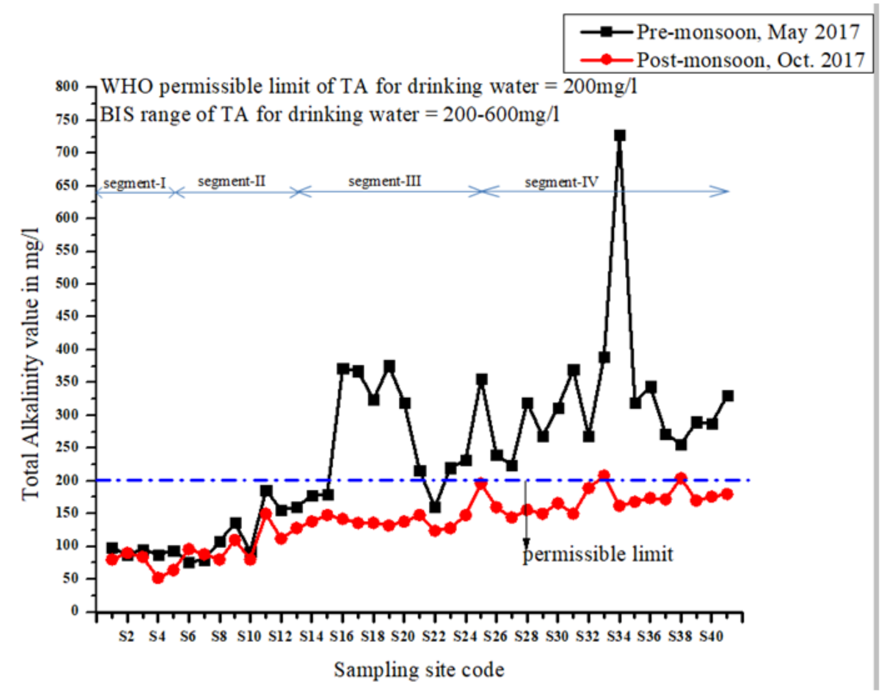

Pre-monoon, Mar 2017
Post-monsoon, Oct. 2017
WHO permissible limit of TDS for drinking water = 500mg/l
BIS range of TDS for drinking water = 300-1500mg/l
segment- I
segment- II
segment- III
segment- IV
Total disolved solid values in mg/l
permissible limit
Sampling site code

c)



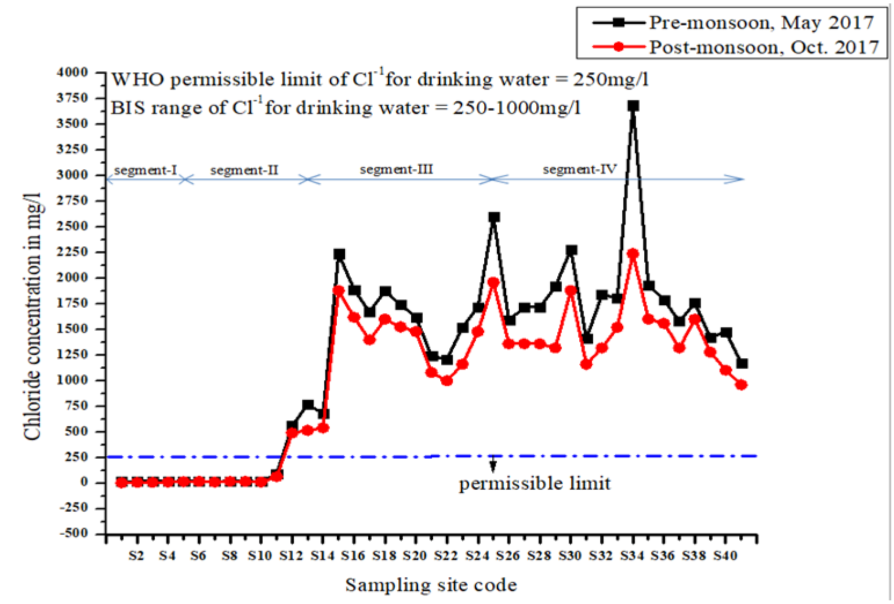
Pre-monsoon, May 2017
Post-monsoon, Oct. 2017
WHO permissibe limit of TH for drinking water = 200 mg/l
BIS range of TH for drinking water = 300-600mg/l
segment-I
segment-II
segment-III
segment-IV
permissible limit
Total Hardness value in mg/l
Sampling site code

d)

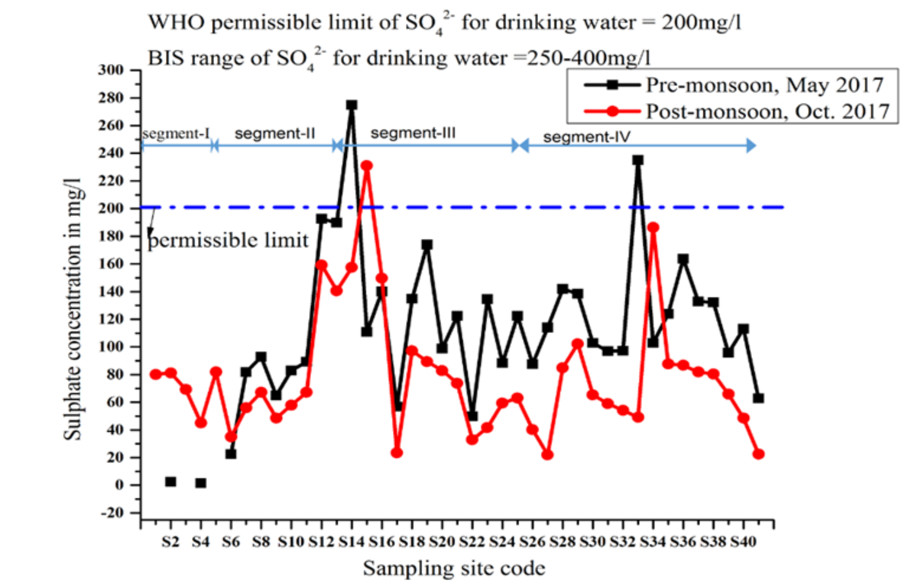


Pre-monsoon, May 2017
Post-monsoon, Oct. 2017
WHO permissible limit of TA for drinking water = 200mg/l
BIS range of TA for drinking water = 200-600mg/l
segment-I
segment-II
segment-III
segment-IV
permissible limit
Total Alkalinity value in mg/l
Sampling site code

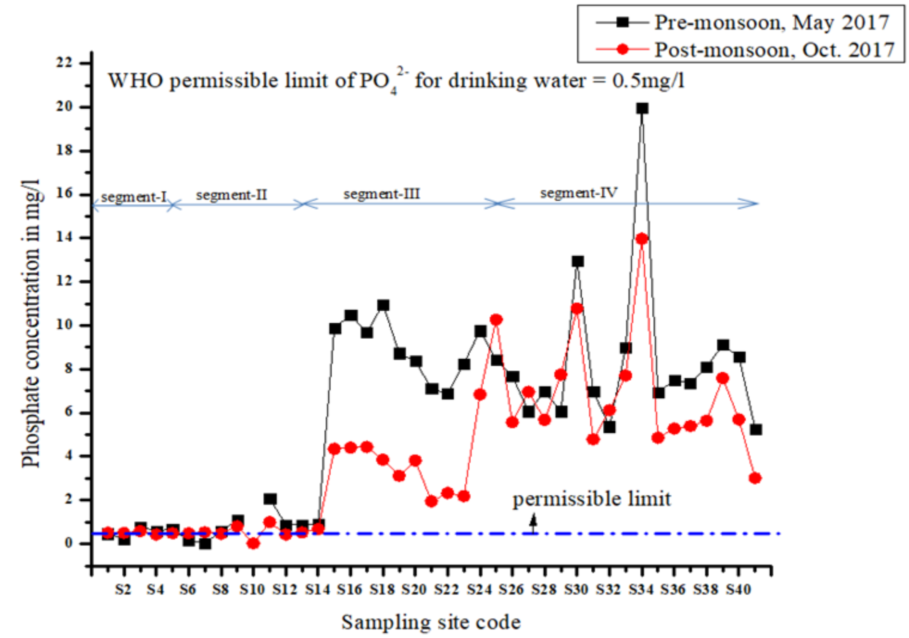
e)


Pre-monsoon, May 2017
Post-monsoon, Oct. 2017
WHO permissible limit of Cl-1 for drinking water = 250mg/l
BIS range of Cl-1 for drinking water = 250-1000mg/l
segment-I
segment-II
segment-III
segment-IV
Chloride concentration in mg/l
permissible limit
Sampling site code

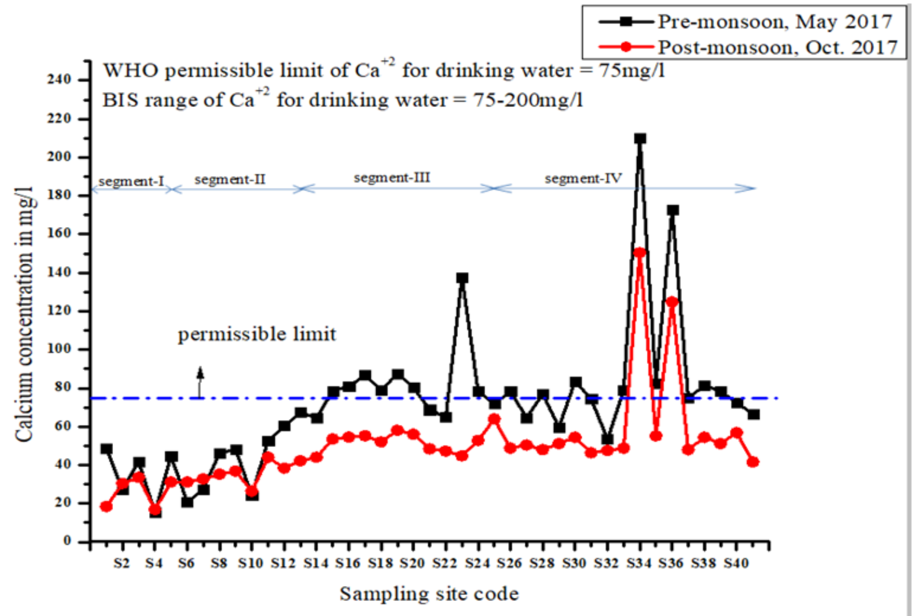
f)


WHO permissible limit of SO4 2- for drinking water = 200mg/l
BIS range of SO4 2- for drinking water =250-400mg/l
Pre-monsoon, May 2017
Post-monsoon, Oct. 2017
segment-I
segment-II
segment-III
segment-IV
Sulphate concentration in mg/l
permissible limit
Sampling site code

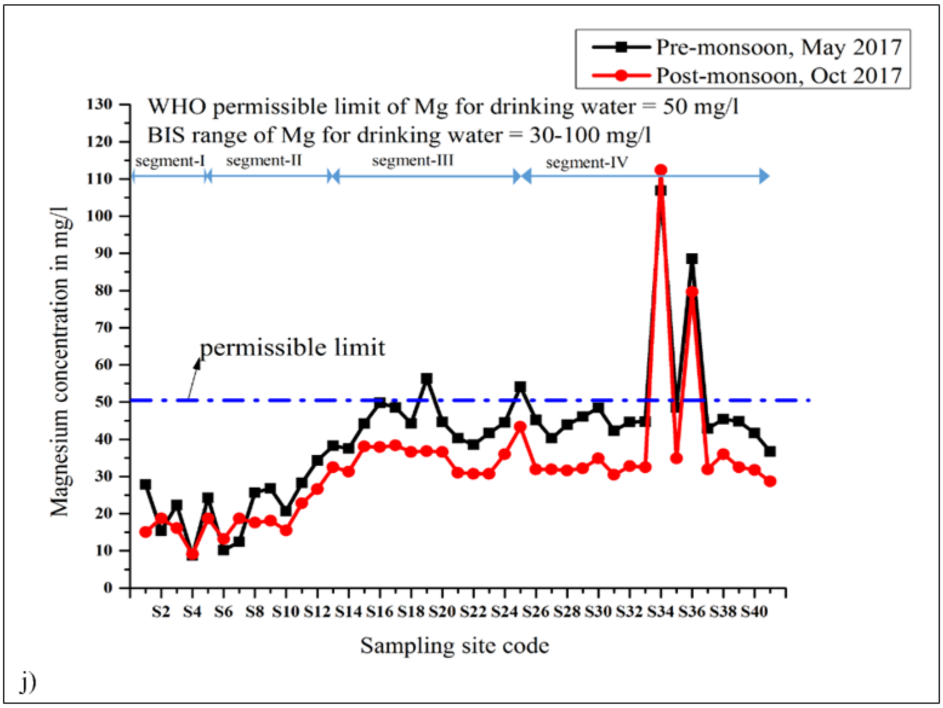
g)

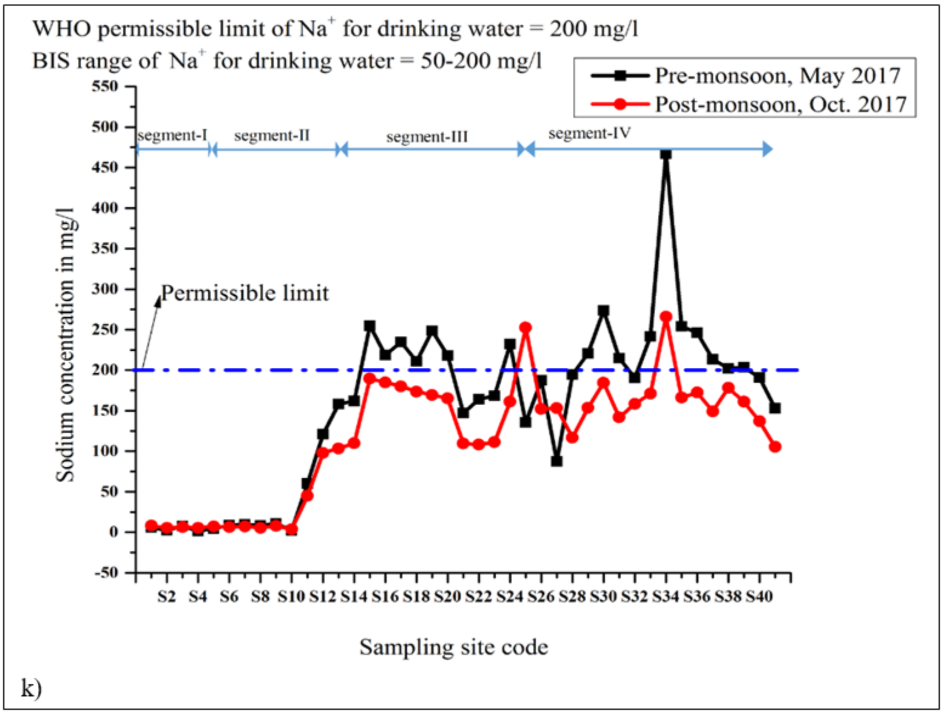

Pre-monsoon, May 2017
Post-monsoon, Oct. 2017
WHO permissible limit of PO_4^{2-} for drinking water = 0.5mg/l
segment-I
segment-II
segment-III
segment-IV
permissible limit
Phosphate concentration in mg/l
Sampling site code
S2 S4 S6 S8 S10 S12 S14 S16 S18 S20 S22 S24 S26 S28 S30 S32 S34 S36 S38 S40
0 2 4 6 8 10 12 14 16 18 20 22

h)


Pre-monsoon, May 2017
Post-monsoon, Oct. 2017
WHO permissible limit of Ca^{+2} for drinking water = 75mg/l
BIS range of Ca^{+2} for drinking water = 75-200mg/l
segment-I
segment-II
segment-III
segment-IV
permissible limit
Calcium concentration in mg/l
Sampling site code
S2 S4 S6 S8 S10 S12 S14 S16 S18 S20 S22 S24 S26 S28 S30 S32 S34 S36 S38 S40
0 20 40 60 80 100 120 140 160 180 200 220 240

i)


Pre-monsoon, May 2017
Post-monsoon, Oct 2017
WHO permissible limit of Mg for drinking water = 50 mg/l
BIS range of Mg for drinking water = 30-100 mg/l
segment-I
segment-II
segment-III
segment-IV
permissible limit
Magnesium concentration in mg/l
Sampling site code
j)


WHO permissible limit of Na+ for drinking water = 200 mg/l
BIS range of Na+ for drinking water = 50-200 mg/l
Pre-monsoon, May 2017
Post-monsoon, Oct. 2017
segment-I
segment-II
segment-III
segment-IV
Permissible limit
Sodium concentration in mg/l
Sampling site code
k)

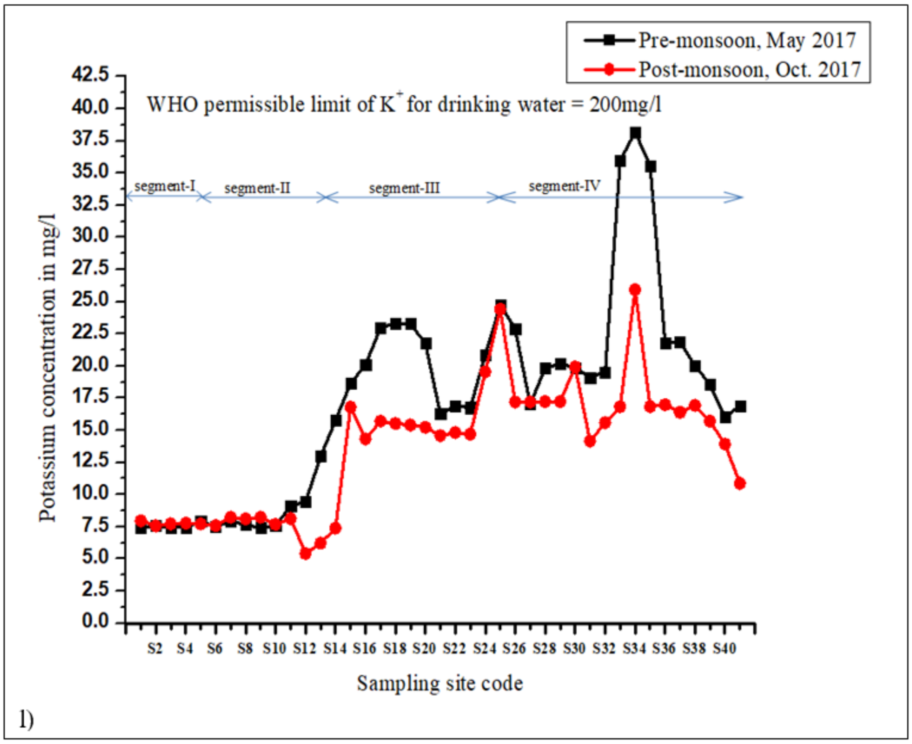


Fig. 2 (a-l): Physico-chemical parameters during pre and post monsoon for Yamuna River

Discussion

Temperature

In case of pre-monsoon season the temperature variation for over the whole of the Yamuna river stretch varied from 26 ºC to 38 ºC and in post-monsoon it varies from 16 ºC to 23 ºC. Rise in the water temperature increases rates of chemical reactions, reducessolubility of gases and solids and elevates metabolic activity of organisms.[8]

pH

It is one of the essentialparameters to explain the water quality deterioration.[9] In recent study pH values lies in between 7.0-9.2 during the season of pre-monsoon and 7.4 to 8.8 in post-monsoon as shown in figure 2(a). The average pH value of river water for whole of the stretch during pre-monsoon remains within permissible limits (6.5-8.5). The slightly alkaline nature is due to mixing of washing agents through sewage waste into the river.[10] Leaching of water from agricultural area also increases the pH.[11] Increased pH value increases the solubility of toxic chemicals in water which become harmful to the aquatic fauna.

Electrical Conductance

It measure water saltiness hazards which affect the crop productivity[12] and is a fast method to measure the total dissolved solids.[13] A water sample is considered to be fresh and unpolluted if its electrical conductivity is up to the threshold limit of 1 $mScm^{-1}$.[14] The conductivity range of samples varies between 0.0875 mS/cm at site S-4 Assan Barrage (Himachal Pradesh) and 2.42 mS/cm at site S-34 at Agra as shown in figure 2(b). The increased values of EC are at site S-34 in Agra region clearly shows the increased load of dissolved inorganic solids.

Total Dissolved Solids (TDS)

TDS is a major pollution burden on the aquatic system originating from natural and human induced sources such as sewage urban runoff, industrial effluents and agricultural runoff.[15] High concentration of total solids effects the light penetration in the river water which may result in limited growth of aquatic life. High level of total organic matters increases the biological and chemical oxygen demand (BOD and COD) depleting the dissolved oxygen (DO) which increases water toxicity thus impair the water quality.[16] The TDS value of the Yamuna River water in its entire stretch in premonsoon season varied from 56 mg/L to 1550 mg/L, while it varied from 77mg/L to 1060mg/L during postmonsoon as shown in figure 2(c). This reduction may be due to the addition of water from Chambal, Sind, Betwa and Ken like southern tributaries of river Yamuna that likely dilute the pollutants concentration. TDS is strongly correlated with TH, TA, Cl-, Mg^{2+}, Ca^{2+}, Na^{+}, K^{+} and $PO4^{3-}$.

Total Hardness (TH)

Water becomes hard due to existence of chloride, bicarbonates and sulphate of primarily magnesium & calcium. High concentration of total solids effects the light penetration in the river water which may result in limited growth of aquatic life. In current study the TH of Yamuna River water varied from 60 mg/L -730 mg/L during premonsoon where as in the season of post monsoon the range of TH from 62mg/L - 768mg/L as shown in Figure 2(d). The average value of TH falls within the permissible limit in mountainous and Haryana segments, but when it enters Delhi up to its confluence with river Ganga becomes very hard and its TH washigher than the upper permissible limit. This may be due to the heavy sewage load mixed in the river by highly populated cities such as Delhi, Mathura and Agra. Total Hardness was found to be highly correlated with Total Alkalinity, Cl^{-}, Mg^{2+}, Ca^{2+}, Na^{+}, K^{+} and PO_4^{3-} .

Total Alkalinity (TA)

Bicarbonate is the major form of alkalinity in natural water. When the number of dissolved carbonates & bicarbonates increase, TA also increases.[17] The value of alkalinity of the Yamuna river water varies from 76 mg/L to 728 mg/L during premonsoon as shown in figure 2(e). The total alkalinity in segment III and segment IV was much above the permissible limit by WHO and thus the river is unfit for irrigation and drinkingpurpose. Total alkalinity concentration showed a 43% decrease inpostmonsoon as compared to the season of pre monsoon. An increase in concentration of total alkalinity was found in last 10 years and found to be varying from 175-310 mg/L in 2013[18] to 678-723 mg/L in 2015[19] and 76-728 mg/L (present study). The overall alkalinity is within the WHO limits but is higher in the downstream areas of Delhi to Agra. Total alkalinity increases with increase in Cl^{-}, Mg^{2+}, Ca^{2+}, Na^{+}, K^{+} and PO_4^{3-} as found by the correlation matrix.

Chloride (Cl-)

Concentration of Cl-in water shows the presence of organic waste mainly of animal origin.[20] The industrial waste also adds the chloride load. The high concentration of chloride in Segment III and segment IV may be due to different domestic activities occurring along the river. The chloride concentration in pre-monsoon season of Yamuna River water from 14 mg/L to 3690 mg/L (Figure 2(f)) while during post-monsoon the range from 4mg/L to 2240mg/L with a total reduction of 19% which may be the effect of dilution due to monsoon. Different researchers observed the concentration of Cl^{-1} for Yamuna River water and concluded a continuous increase in downstream river water of Cl^{-1} concentration.

Sulphate (SO_4^{2-})

The contamination of sulphate in the river water comes through sewage chemical effluents from industries, agricultural runoff containing leachates of gypsum, effluents coming from tanneries, paper mills etc.[21] The sulphate concentration in Yamuna River water in pre-monsoon season ranges from 1.66mg/L to 274.92mg/L (Figure 2(g)). Due to the dilution, there is nearly 31.7% reduction in sulphate concentration as compare to premonsoon season. Sulphate is common parameter of water and does not have much impact on soil but a high concentration is harmful to both for human and aquatic life.[22]

Phosphate (PO_4^{3-})

The phosphate contamination in natural water is very small as it is actively taken up by plants.[23] Agricultural runoff contains phosphate fertilizers and municipal sewage containing detergents are main source of PO_4^{3-} in river water. Concentration of phosphate varied from 0.038mg/L at sight S-7 to 19.97 mg/L at site S-34 (Figure 2(h)) in pre-monsoon season which is much higher than WHO limits. The range of PO_4^{3-} during post-monsoon was found from 0.02mg/L to 13.97mg/L (figure 2(h)) with a reduction of 34.8% due to seasonal variation. The PO_4^{3-} pollution is associated with eutrophication and 0.08 ppm of PO_4^{3-} is critical value of phosphate for appearance of eutrophication.[24]

Calcium (Ca^{2+}) and Magnesium (Mg^{2+})

Calcium and Magnesium are generally found in a state of equilibrium in all kinds of water with magnesium concentration slightly lower than calcium.[13] High concentration of Magnesium effects the crop yield adversely as well as act as laxatives to human beings[25] where Calcium as such does not show any hazardous effect on human effect.[26] The concentration of Mg^{2+} and Ca^{2+} varies from 8.78-106.87mg/L and 15.43 -210.34 mg/L in pre monsoon where as they were found to be varying from 9.07-112.43 mg/L and 16.8-150.4 mg per Liter in postmonsoon season represent in figure 2(i), (j).

Sodium (Na^+) and Potassium (K^+)

Sodium ion does not produce hardness to water but it is an essential parameter as it determines the feasibility of water for irrigation and drinking purpose. A very high concentration of sodium ion was found in segment II, segment III and segment IVshowing that water in these segments is unfit for irrigation and drinking. If this water is used for agricultural purposes then it is hazardous for crops. Potassium is considered as an essential nutrient and its concentration varied from 7.39 mg/L to 38.2 mg/L in pre monsoon whereas its values in the season of post monsoonwas 5.41 mg/L to 25.93 mg/L as shown in figure 2(k), (l) which is very less than the set limit of WHO.

Weighted Arithmetic Water Quality Index

WQI of river Yamuna was calculated fordifferent segments for all analysed parameters are shown in Table 3 and Figure 3.

Table 2: Range, Mean, Standard Deviation of different parameters in whole Yamuna stretch

(a) Premonsoon Season

Param-eters	SegmentI		SegmentII		SegmentIII		SegmentIV	
	Range	Mean±SD	Range	Mean±SD	Range	Mean±SD	Range	Mean±SD
pH	7.4-7.8	7.6±0.16	7.3-8.2	7.8±0. 27	7.0-8.2	7.4±0. 33	7.1-9.2	8.3±0.44
EC	0.08-0.31	0.18±0.07	0.10-0.57	0.26±0.14	0.67-1.58	1.10±0.26	0.18-2.42	1.02±0.45
TDS	56-199	118±47.01	68-370	166.62±95.64	395-1010	704.41±175.58	376-1550	676.06±262.27
TA	88-98	92.8±4.11	76-186	124.25±38.45	160-376	275.16±81.27	224-728	326.25±112.72
TH	60-190	112.6±42.50	70-340	132.25±85.56	132-480	311.25±100.44	170-730	281.31±124.69
Ca^{2+}	15.43-48.71	35.52±12.38	20.8-67.43	43.40±16.26	64.45-137.6	81.58±18.38	53.45-210.34	88.05±40.50
Mg^{2+}	8.78-27.81	19.71±6.80	10.21-38.23	24.57±9.15	37.54-56.36	45.38±5.61	36.72-106.87	50.69±18.28
Na^+	1.54-7.67	4.47±2.23	2.18-158.32	47.38±56.70	135.55-2 54.84	199.62±39.86	87.4-467.4	221.36±76.04
K^+	7.39-7.89	7.54±0.18	7.39-12.97	8.69±1.77	15.78-24.74	20.11±3.03	16.03-38.2	22.70±6.91
$SO4^{2-}$	1.64-2.51	2.07±0.43	22.52-192.67	102.10±55.49	49.87-274.92	125.67±56.13	62.81-234.98	121.33±37.81
$PO4^{3-}$	0.22-0.78	0.54±0.19	0-2.07	0.70±0.64	0.92-10.97	8.28±2.52	5.27-19.97	8.36±3.48
Cl^-	14-22	18±2.84	16-770	188.75±280.89	680-2600	1667.5±473.57	1170-3690	1819.25±543.86

(b) Postmonsoon season

Parameters	SegmentI		SegmentII		SegmentIII		SegmentIV	
	Range	Mean±SD	Range	Mean±SD	Range	Mean±SD	Range	Mean±SD
pH	7.4-8.5	7.9±0.40	7.9-8.5	8.2±0.18	7.4-8.4	7.7±0.30	7.7-8.8	7.9±0.37
EC	0.12-0.33	0.24±0.07	0.19-0.76	0.35±0.21	0.797-1.63	1.11±0.22	0.73-1.66	1.08±0.18
TDS	77-217	156.6±46.39	123-490	248.12±135.33	510-1040	715.75±143.41	470-1060	691.5±117.99
TA	52-90	74±13.97	80-150	105.5±23.03	124-196	142.83±17.65	144-208	170.56±17.62
TH	62-128	106±24.15	90-197	137.87±34.80	210-296	244±26.40	196-768	274.5±150.02
Ca^{2+}	16.8-33.6	26.08±7.02	26.4-44	35.87±5.41	44-64	52.55±5.51	41.6-150.4	61.12±29.48
Mg^{2+}	9.07-18.73	15.54±3.54	13.17-32.5	20.63±5.94	30.74-43.33	35.62±3.74	28.69-112.43	40.37±21.88
Na^{+}	5.31-8.06	6.50±1.03	3.8-103.41	34.59±40.19	108.33-252.6	159.60±41.72	105.43-265.85	160.44±33.93
K^{+}	7.56-7.95	7.73±0.12	5.41-8.23	7.44±0.99	7.39-24.4	15.69±3.71	10.89-25.93	16.80±3.03
$SO4^{2-}$	45.09-81.84	71.48±13.98	35-159.22	78.96±42.34	23.42-230.97	91.82±57.73	22.06-186.37	71.07±37.39
$PO4^{3-}$	0.43-0.59	0.50±0.05	0.02-0.99	0.53±0.26	0.68-10.27	4.02±2.41	3.01-13.97	6.67±2.52
Cl^{-}	4-14	8±3.57	10-515	141.87±208.89	540-1960	1393.75±378.58	960-2240	1433.93±297.47

Table 3: Calculations of WAWQI for different segments of study area, Segment-I (Mountainous region), Segment-II(Haryana region), Segment-III(Delhi region), Segment-IV (Uttar Pradesh region)

WAWQI for Segment-I(Mountainous region)

Parameters	Observe Values	Standard Values	Unit Weight (W_i)	Quality Rating (Qi)	Weighted Values (WiQi)
pH	7.6	8.5	0.1176	40	4.704
EC	0.1845	0.5	2	36.9	73.8
TDS	118	500	0.002	23.6	0.047
Total Hardness	112.6	200	0.005	56.3	0.281
Chloride	18	250	0.004	7.2	0.028
Alkalinity	92.8	200	0.005	46.4	0.232
Magnesium	19.714	50	0.02	39.42	0.788
Calcium	35.52	75	0.013	47.36	0.629
Sodium	4.472	200	0.005	2.23	0.011

Potassium	7.54	200	0.005	3.77	0.018
Sulphate	2.0775	200	0.005	1.03	0.005
Phosphate	0.54	0.5	2	109.74	219.48
			$\sum W_i$ = 4.181		$\sum W_iQ_i$= 300.02

WQI= $\sum W_iQ_i / \sum W_i$ = 71.74

WAWQI for Segment-II(Haryana region)

Parameters	Observe Values	Standard Values	Unit Weight (W_i)	Quality Rating (Qi)	Weighted Values (WiQi)
pH	7.8	8.5	0.1176	53.33	6.27
EC	0.26	0.5	2	40	80
TDS	166.62	500	0.002	33.32	0.066
Total Hardness	132.25	200	0.005	66.12	0.33
Chloride	188.75	250	0.004	75.5	0.302
Alkalinity	124.25	200	0.005	62.12	0.310
Magnesium	24.57	50	0.02	49.14	0.98
Calcium	43.40	75	0.013	57.88	0.76
Sodium	47.38	200	0.005	23.69	0.11
Potassium	8.69	200	0.005	4.34	0.021
Sulphate	102.10	200	0.005	51.05	0.255
Phosphate	0.707	0.5	2	141.56	283.12
			$\sum W_i$ = 4.181		$\sum W_iQ_i$= 372.54

WQI= $\sum W_iQ_i / \sum W_i$ = 89.12

WAWQI for Segment-III(Delhi region)

Parameters	Observe Values	Standard Values	Unit Weight (W_i)	Quality Rating (Qi)	Weighted Values (WiQi)
pH	7.5	8.5	0.1176	33.33	3.91
EC	1.03	0.5	2	207.6	415.2
TDS	690.92	500	0.002	138.18	0.276
Total Hardness	302.35	200	0.005	151.17	0.755
Chloride	1665.71	250	0.004	666.28	2.66
Alkalinity	269	200	0.005	134.5	0.672
Magnesium	45	50	0.02	90.00	1.80
Calcium	80.13	75	0.013	106.84	1.42
Sodium	190.73	200	0.005	95.36	0.476
Potassium	20.08	200	0.005	10.04	0.050
Sulphate	122.13	200	0.005	61.06	0.305
Phosphate	8.08	0.5	2	1617.2	3234.4
			$\sum W_i$ = 4.181		$\sum W_iQ_i$= 3661.94

WQI= $\sum W_iQi / \sum W_i$ = 875.66

WAWQI for Segment-IV(Uttar Pradesh region)

Parameters	Observe Values	Standard Values	Unit Weight (W_i)	Quality Rating (Qi)	Weighted Values (WiQi)
pH	8.3	8.5	0.1176	86.66	10.19
EC	1.07	0.5	2	214	428
TDS	685.5	500	0.002	137.1	0.274
Total Hardness	285.92	200	0.005	142.96	0.714
Chloride	1842.71	250	0.004	737.08	2.94
Alkalinity	339.71	200	0.005	169.85	0.849
Magnesium	51.83	50	0.02	103.66	2.07
Calcium	90.42	75	0.013	120.56	1.60
Sodium	233.36	200	0.005	116.68	0.583
Potassium	23.10	200	0.005	11.55	0.057
Sulphate	124.26	200	0.005	62.13	0.310
Phosphate	8.58	0.5	2	1716	3432
			$\sum W_i = 4.181$	$\sum W_iQ_i = 372.54$	

WQI= $\sum W_iQ_i / \sum W_i = 927.71$

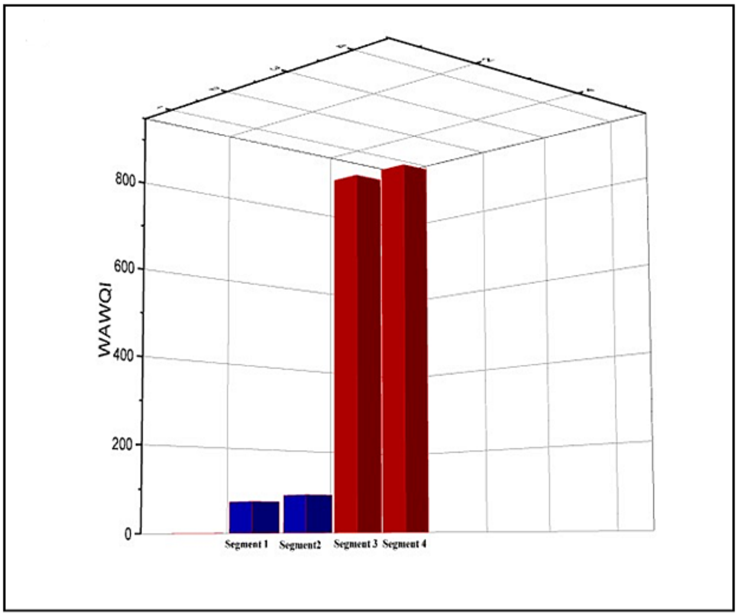


Fig. 3: WAWQI for different segments of Yamuna River

The water quality values were in the range of poor to unfit for drinking purpose using the method of WAWQI at all sampling sites. For segment-I the water quality was found poor with 71.74 values which fall in category of poor in the scale of WAWQI. The qualities of river water degrade as we move down from segment-II of Haryana to Segment-III and segment-IV which fall in the category of very poor to unsuitable for drinking.

Table 4: The correlation matrix for various physico-chemical water quality parameters

	pH	EC	TDS	Temp	Total Hardness	Chloride	Alkalinity	Mg	Ca	Na	K	Sulphate	Phos -phate
pH	1												
EC	0.00656	1											
TDS	0.02432	0.980789**	1										
Temp	0.256987	0.503112**	0.542232**	1									
Total Hardness	-0.09418	0.856171**	0.870447**	0.469311*	1								
Chlori de	0.102411	0.904435**	0.932929**	0.585894**	0.82330**3	1							
Alkalinity	0.062267	0.855764**	0.873308**	0.483129*	0.83471**	0.867297**	1						
Mg	0.099874	0.877921**	0.903317**	0.501614*	0.833399**	0.852672**	0.876465**	1					
Ca	-0.00157	0.791663**	0.81544**	0.367664*	0.763985**	0.746528**	0.79374**	0.931148**	1				
Sodium	0.061517	0.836357**	0.861573**	0.619193**	0.803736**	0.91869**	0.879579**	0.871563**	0.800469**	1			
Potassi um	0.103221	0.781092**	0.817907**	0.532835**	0.723333**	0.884595**	0.867647**	0.78877**	0.694746**	0.881027**	1		
Sulphate	0.230008	0.355931*	0.353124*	0.472677*	0.303615*	0.298874*	0.275639*	0.38383*	0.336628*	0.399972*	0.380422*	1	
Phosphate	-0.02184	0.846359**	0.876884**	0.496707*	0.799572**	0.928573**	0.868781**	0.810806**	0.760378**	0.898683**	0.822059**	0.12866*	1

Statistical Analysis of different Parameters

Correlation matrix among the different physical &chemical parameters of water samples shows interdependence of different parameters, and also suggests about the sources of pollutants as shown in Table 4.

Positive correlation was observed between all studied parameters excluded pH and total hardness, pH and calcium and between pH and phosphate. In correlation matrix of various physico-chemical parameters, the linear correlations found were not positive every time. There is too strong (0.99-0.9) correlation, others mean (0.66-0.61) correlation and some quite weak (0.27-0.01) correlations. A significant positive correlation with too strong category was observed in EC and TDS, EC and Cl^-, TDS and Cl^-, TDS and Mg^{2+}, Cl- and Na^+, Cl^- and PO_4^{3-}, Ca^{2+} and Mg^{2+} whereas a significant -ve correlation was observed between pH and hardness.

Conclusion

The values of all the physico-chemical parameters from Delhi to Agra are beyond permissible limits of WHO. So, Yamuna river water is not currently fit for drinking, bathing, washing purpose over this stretch. The WQI calculated for this stretch put the water in E categories in all three segments except Segment-I rendering it unfit for any purpose. The government river action plans appear to be bringing no significant results. There are only two options which can make the river pollution free: either stop all types of wastes mixing with river water or develop a technique to redress the wastes of all type so that river water can be cleaned quickly and efficiently in large volumes. The various parameters indicate that pollution from all sources-industrial, municipal and agricultural sources are responsible for the pollution of Yamuna river water. An approach to tackle all the three sources will have to be devised in order to make Yamuna river water fit for human use again. Further studies in different season by taking into consideration including heavy metals and trace organic compounds are recommended.

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Data Availability Statement

The manuscript incorporates all datasets produced or examined throughout this research study.

Ethics Statement

This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Informed Consent Statement

This study did not involve human participants, and therefore, informed consent was not required.

Author Contributions

All study completed by the authors at Deenbandhu Chhotu Ram University Of Science And Technology, Murthal in Centre of Excellence for Energy and Environmental Studies with assistance from the authors.

- **Anita Singh:** Conceptualisation; Methodological Analysis; Investigation; Writing – original draft; Writing – review & editing.
- **Naresh Kumar and Ekta Antil:** Field Sampling, Writing – review & editing
- **Sudesh Chaudhary and Brijnandan S. Dehiya:** Supervision; Project administration; Writing – review & editing

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