Linear Modeling-Based Assessment Of Water Quality Of River Yamuna, India (2011-2020)

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Abstract: *Since time immemorial, rivers have been the lifelines of billions worldwide. They provide fresh water for drinking, agriculture, bathing, and fulfill our various requirements. There is no life without water; hence, making sure that perennial flows remain unpolluted is one of man's prime duties. On the contrary, many industrial chemicals that pollute our water resources are common in the present times. The entire stretch of Yamuna River, from Yamunotri glacier to its confluence with the river Ganges at Allahabad, is used for various human activities. The various pollution sources, such as residential, industrial, and agricultural areas, induce many substances in the river. Domestic sources cause about 85% of the total pollution. Large clusters of industries established at Kota, Gwalior, Indore, Nagda, Khetri, Yamuna Nagar, Panipat, Sonepat, Delhi, Baghpat, Ghaziabad, Gautam Budha Nagar, Faridabad, Mathura release vast amounts of pollutants in River Yamuna. The nutrients and pesticides from agricultural fields are adsorbed by the sediment particles and reach the river, particularly during early floods. These chemicals geo-accumulate in riverbeds. The dumping of worshiping material and ashes in the water further degrades the water quality. High organic content, increased nutrients, pathogens, pollutants, and deforestation in the catchment and river usage as transport media adversely affect the river water quality. Many activities such as bathing, washing clothes, religious activities, offering of flowers, garlands, and other worship materials are also responsible for river pollution in India. This paper studies the effect of pollution on the River Yamuna and concentrates on studying water quality parameters of the entire stretch of River Yamuna flowing through five geopolitical states of India. The second part deals with the study of pollution-induced by various drains emptying their flow into River Yamuna. It also includes a study during the extraordinary condition induced by COVID-19 lockdown.*

Keywords: **water quality, assessment, case study, linear modeling, river Yamuna**

1. INTRODUCTION

Since the beginning of the human race, rivers have been the lifelines of billions, worldwide. They provide fresh water for drinking, agriculture, bathing and fulfill numerous requirements [1]. It is easy to interpret that there is no life without water. Hence, perennial flows remain unpolluted is one of the prime duties of humankind. Despite this, we see solid, liquid, and gaseous chemicals pollute our water resources [2]–[4]. These chemicals are toxic and pose a considerable threat to our water resources. Such an effect is evident in River Yamuna. The Yamuna is adored as a holy river with numerous pilgrimage centers on its banks, such as Yamunotri, Paonta Sahib, Mathura, Vrindavan, Bateshwar & Allahabad. It also supports major urban centers such as Sonepat, Delhi, Yamuna Nagar, Faridabad, Gautam Budh Nagar, Agra, Mathura, and Etawah. Also, the banks of River Yamuna are highly fertile used for extensive cultivation of food-grain, particularly at Haryana and Western Uttar Pradesh [5], [6]. Since, the river banks act as filtration beds for alleviation of pollution in river streams [7]. It plays an essential part in the country's economy. However, it

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suffers from the proceeds of industrialization, urbanization, and rapid agricultural advancements.

1.1 CHARACTERISTICS AND SEGMENTATION OF YAMUNA RIVER

Characteristics of water flow in River Yamuna vary significantly from monsoon to non-monsoon periods. From July to September, an excessive amount of water from monsoon precipitations frequently causes floods in River Yamuna [8]. Almost 80% of the total annual flow occurs during this period. For the rest of the year, a reduced river water flow exists, dries out at some locations. Seasonal variation also causes periods of drought and flood. Moreover, diversion of water to serve for irrigation and drinking purposes leaves low or no water flow in the river [9]. The river becomes segmented into four distinct, independent segments in the dry season, as shown in Figure 1.1 and Table 1[8].

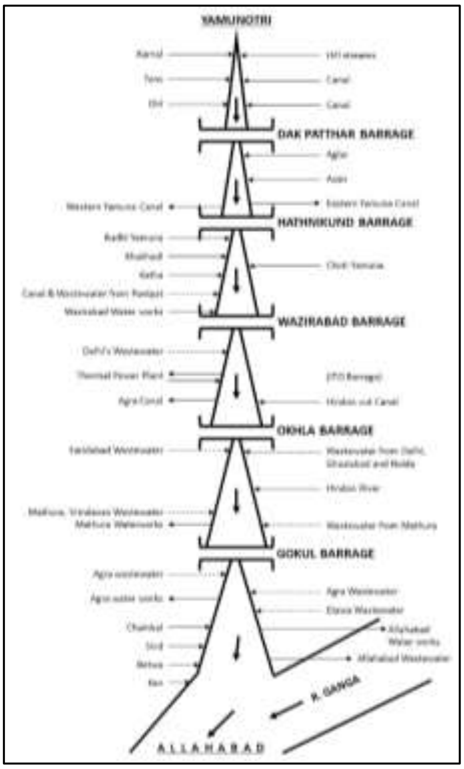


Figure 1.1 Points of Water Abstraction & Additions in Yamuna River [10]

Table 1 Segmentation of flows in River Yamuna

Segment	Length, km	Start and endpoints	Source of water
Segment I	157	Yamunotri to Hathnikund /Tajewala barrage	Melting of glaciers.
Segment II	224	Hathnikund / Tajewala barrage to Wazirabad barrage	Groundwater accrual; and small tributaries
Segment III	22	Wazirabad barrage to Okhla barrage	Seventeen sewage drains of Delhi and Upper Ganges Canal via Najafgarh drain and Hindon cut canal.
Segment IV	973	Okhla barrage to the confluence with the Ganges at Allahabad	Groundwater accrual; tributaries (Hindon, Chambal, Sindh, Ken, Betwa); and drains (from Delhi Mathura-Vrindavan, Agra, Etawah)

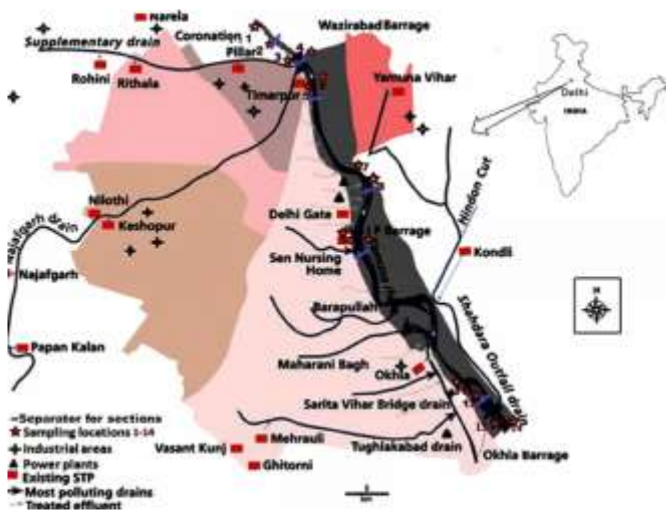
2. METHODOLOGY

This paper analyzes water quality data of the River Yamuna's entire stretch. It explicitly studies its stretch in Delhi for the BOD load contributed by 22 drains. Parameters, such as pH, electrical conductivity (EC), suspended solids (SS), dissolved oxygen (DO), biochemical oxygen demand (BOD), and chemical oxygen demand (COD) for significant drains, namely, Najafgarh Drain, Nizamuddin Bridge drain, Okhla U/s drain, Palla drain, and Shahdara Drain are analyzed. Softwares such as C/C++, MATLAB, Qual2E etc. are also effective tools [11]–[13]. Statistical analysis tool in MS Excel was used in the present paper to draw linear models for each parameter using the best-fit curve method, expresses the temporal and spatial variation of water quality parameters. Correlation matrix is also drawn to determine the relationship between multiple parameters.

2.1 DATA

Three datasets were used to fulfill the objectives of the paper. *Dataset 1* - CPCB's water quality data at station locations shown in Figure 2.1**Error! Reference source not found.** was used for analysis of the water quality of the entire stretch of River Yamuna. Parameters such as temperature (T), dissolved oxygen (DO), pH, electrical conductivity (EC), biochemical oxygen demand (BOD), nitrite and nitrate nitrogen (NO_2-N and NO_3-N), fecal coliform (FC), and total coliform (TC) for 2011 to 2016 were studied. *Dataset 2*, flow rates and BOD load of 22 drains were analyzed to study the pollution BOD load caused by drains joining River Yamuna in the Delhi stretch. *Dataset 3*, water quality parameters such as BOD, COD, EC, DO, pH, and SS for the five major drains, namely, Najafgarh Drain, Nizamuddin Bridge drain, Okhla U/s drain, Palla drain, and Shahdara Drain for the period of March 2018 to April 2020 was analyzed to evaluate the overall water quality of drains in the Delhi stretch.

Figure 2.1 Water quality monitoring stations along River Yamuna in the River Ganges Basin [NIH, Roorkee]



Sr. No.	*Name of Drain*
1	Najafgarh Drain
2	Shahdara Drain
3	Agra Canal
4	Barapulla Drain
5	Sarita Vihar Drain
6	Sen Nursing Home Drain
7	Maharani Bagh Drain
8	Delhi Gate (Power House) Drain
9	Tuglakabad Drain
10	Jaitpur Drain
11	Kailash Nagar Drain
12	ISBT + Mori Gate Drain
13	Molar Bandh Drain
14	Abu Fazal Drain
15	Shastri Park Drain
16	Civil Mill Drain
17	Tonga Stand Drain
18	Magazine Road Drain
19	Metcalf House Drain
20	Sweeper Colony Drain
21	Drain No.14
22	Khyber Pass Drain

Figure 2.2 Location & list of Drains in Delhi

Table 2 Descriptive Statistics of data for *Dataset I and II*

	Dataset I								*Dataset II*	
	T, °C	*DO, mg/l*	*pH*	*EC, µS/cm*	*BOD, mg/l*	*NO_2-N and NO_3-N, mg/l*	*FC, mg/l*	*TC, mg/l*	*Avg. Flow (MLD)*	*Avg. BOD Load (TPD)*
Mean	20.92	6.23	7.77	431.17	8.01	1.58	9.31×10^7	8.72×10^7		
Std. Error	0.93	0.34	0.05	53.56	1.23	0.66	5.13×10^7	4.52×10^7	144.11	12.59
Median	22.10	7.50	7.80	321.00	4.00	0.07	27020.00	70000.00	92.81	6.74
Mode	23.70	7.70	7.80	74.00	1.10	0.00	10.00	21.00	22.17	2.70
Std. Dev.	6.47	2.84	0.36	342.98	9.90	4.06	4.08×10^8	3.87×10^8	425.31	30.89

Table 3 Descriptive Statistics of data for *Dataset III*

Drain	*Description*	*pH*	*EC, µS/cm*	*DO, mg/l*	*BOD, mg/l*	*COD, mg/l*	*SS, mg/l*
Palla	*Mean*	18.61	707.00	9.67	4.42	19.50	-
	Standard Error	0.17	154.56	1.54	1.27	3.74	-
	Median	8.20	599.50	8.25	3.00	20.50	-
	Mode	7.80	-	-	3.00	28.00	-
	Standard Deviation	0.41	378.59	3.78	3.10	9.16	-
Nizamuddin Bridge	*Mean*	7.20	1355.83	1.66	30.43	83.00	-
	Standard Error	0.13	243.75	0.25	7.69	16.56	-
	Median	7.25	1254.50	1.80	30.00	85.50	-
	Mode	7.20	1140.00	-	-	-	-
	Standard Deviation	0.33	597.08	0.56	18.83	40.56	-
Okhla U/s	*Mean*	-	935.83	1.24	18.02	65.67	-
	Standard Error	0.06	105.61	0.17	2.75	10.60	-
	Median	7.25	952.00	1.20	18.50	67.00	-
	Mode	7.30	-	1.20	18.00	67.00	-
	Standard Deviation	0.14	258.68	0.39	6.75	25.97	-
Najafgarh Drain	*Mean*	7.30	1501.00	-	77.17	271.33	200.83
	Standard Error	0.03	0.00	-	11.84	26.45	27.05
	Median	7.30	1501.00	-	70.00	292.50	200.50
	Mode	7.30	-	-	-	-	-
	Standard Deviation	0.06	-	-	29.01	64.79	66.27
Shahdara Drain	*Mean*	7.20	1657.00	-	99.33	421.17	361.00
	Standard Error	0.03	0.00	-	18.18	48.15	39.13
	Median	7.15	1657.00	-	101.50	397.50	342.50
	Mode	7.10	-	-	-	-	-
	Standard Deviation	0.08	-	-	44.54	117.95	95.85

3. STATUS OF WATER QUALITY IN RIVER YAMUNA

Temperature: Naturally, water in River Yamuna is formed from the Yamunotri glaciers' thawing to develop small streams. Liquid water starts flowing from Yamunotri with average temperature of 16.5-20 °C in Segment I from Yamunotri to Hathnikund /Tajewala barrage and a minimum of 4°C. The primary source of water in this segment is the melting of glaciers. It includes the stretch of river in

Uttarakhand and Himachal Pradesh, as presented in Error! Reference source not found. In Segment II from Hathnikund / Tajewala barrage to Wazirabad barrage in Haryana stretch, the average temperature of River Yamuna waters increases to 20-22 °C due to the groundwater accrual and contribution of water from small tributaries. Finding the curve of best fit for the data for average temperature a linear model as **t = 0.5535 l + 16.131** where; t = temperature in °C, l = distance of location on the River Yamuna from the origin at Yamunotri is derived to show the trend of variation of temperature over the entire stretch of River Yamuna. The river water temperature increases to 22-24 °C in Segment III from Wazirabad barrage to Okhla barrage. Water is received from Delhi's drains, Hindon cut canal, and from various bathing ghats [14], [15]. In segment IV from Okhla barrage to Allahabad, temperature increases to 24-28 °C due to groundwater accrual and tributaries like Hindon, Chambal, Sindh, Ken, Betwa, and wastewater carrying drains of Delhi, Mathura-Vrindavan, Agra, and Etawah joining the river. During its descent from the mountainous region to planes, river water temperature is observed to be increasing gradually from freezing temp. to about 28 °C. The graph also shows that the difference between the maximum and minimum water temperatures keeps widening as water flows down into the river Ganges. It denotes the effect of terrestrial climate in the planes and the effect of local weather conditions. Heat accumulation and mixing of waters from tributaries and drains in lower latitudes cause thermal change during the flow of waters from Yamunotri to Allahabad.

Dissolved Oxygen (DO): River Yamuna waters flowing from glaciers down through the mountainous terrain boost the water with oxygen dissolved due to the gas transfer between the water-air interfaces. Along the way, the water absorbs oxygen and thereby makes it more amenable to aquatic life. As presented in Figure 3.1, water flowing from Yamunotri bears an average DO content of about 8 mg/l in Segment I from Yamunotri to Hathnikund /Tajewala barrage Uttarakhand and Himachal Pradesh Stretch. At many locations, the dissolved oxygen content reaches the saturation DO content up to 14 mg/l. In Segment II from Hathnikund / Tajewala barrage to Wazirabad barrage in Haryana stretch, the average DO content decreases to 9 mg/l due to the groundwater accrual. The contribution of water from small tributaries balances the DO content. Finding the best fit curve for the data for average DO content, a linear model as **D = - 0.077 l + 7.001**, where D = Dissolved Oxygen in mg/l, l = distance of location on the River Yamuna from the origin at Yamunotri is derived to show the trend of variation of DO over the entire stretch of River Yamuna. It is essential to observe that the DO curve slope is negative and represents the general falling trend of dissolved oxygen level in the river waters[16]. In Segment III from Wazirabad barrage to Okhla barrage, the average DO content further reduces 6 mg/l. Water is received from sewage drains of Delhi via Najafgarh drain and various bathing ghats, which reduce the amount of DO by BOD exertion causing stress on aquatic life (Poon et al., 2016; Sharma & Kansal, 2011). The addition of DO from the Upper Ganges Canal and Hindon cut canal tries to improve the downstream condition. Segment IV from Okhla barrage to Allahabad shows dissolved oxygen content of 5 mg/l. DO content reduces due to groundwater accrual and wastewaters from various drains. Tributaries such as Hindon, Chambal, Sindh, Ken, Betwa also alleviate the DO content. DO-rich water, flowing through the high mountains, starts losing the amount of DO accumulated by various DO-consuming factors. The DO of river water is gradually decreasing from saturation DO to critical DO at many locations. The graph also widens the difference between the maximum and minimum DO content in water, which denotes the high variability due to the planes' local weather conditions and terrestrial climate. Effect of BOD, heat accumulation in plain regions, and water mixing from various drains in the lower latitudes causes dissolved oxygen to keep reducing and make it unsustainable and fatal to aquatic life during the flow from Yamunotri to Allahabad. At many locations, the presence of surface-active agents from detergents disturbs the air-water interface. It hinders gas transfer. It causes a lesser amount of oxygen to dissolve in water, and hence the DO content reduces. The presence of alluvial soils in many areas has boosted the growth of agricultural patches along the river. At many such locations, fertilizers are used widely to enhance agricultural productivity. It may also affect groundwater quality [18]. These fertilizers find their way easily in the stagnant areas of the meandering river flows in many of the lakes and causes excessive growth of algae in the water. Soon the water starts to evaporate more and finally result in the lakes' death due to eutrophication. Mass congregations during festive occasions further alleviate the dissolved oxygen [19]. Many such factors affect the dissolved oxygen content in water.

pH: Water from glaciers contains lower hydrogen ion concentration, i.e., lower pH, rendering the water more acidic. Through the mountainous terrain, pH gets exhausted to dissolve numerous minerals from rocks with which it interacts. The pH by this action increases due to the water-rock interface. Along the way, the water absorbs anions and cations and thereby makes it balanced near to neutral range where aquatic life can easily survive. As presented in Figure 3.1, water flowing from Yamunotri bears an average pH of about 7.6 in Segment I from Yamunotri to Hathnikund /Tajewala barrage in the

Uttarakhand and Himachal Pradesh Stretch. At the glacier melting zones, the pH is slightly acidic in the range of 6.5. In Segment II from Hathnikund / Tajewala barrage to Wazirabad barrage in Haryana stretch, the average pH increases to 7.7 waters River Yamuna due to ions added by the groundwater accrual water in the river flow and contribution of water from small tributaries balances the pH. From Wazirabad barrage to Okhla barrage, pH in Segment III further increases to 7.8. Water received from sewage drain models of Delhi via Najafgarh drain also from various bathing ghats, reducing pH by biochemical reactions [20]. Increased pH from and Upper Ganges Canal, and Hindon cut canal tries on the confluence points downstream.

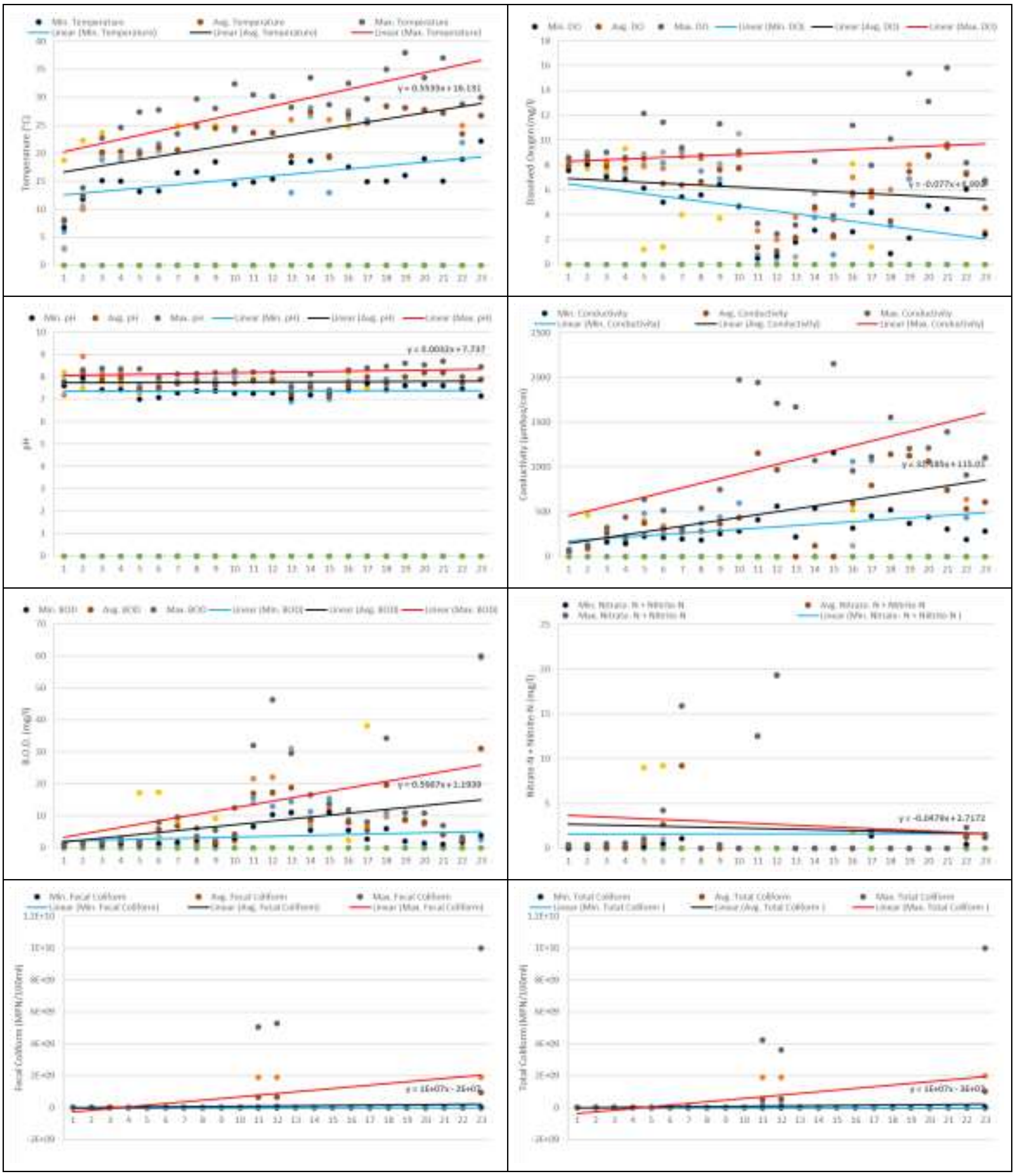


Figure 3.1 Trend of water quality parameters of River Yamuna waters from Yamunotri (origin) to Allahabad (confluence with River Ganges)

Finding the curve of best fit for the data for average pH, a linear model as **H = 0.0032 l + 7.737**, where H = pH, l = distance of location on the River Yamuna from the origin at Yamunotri is derived to show the trend of variation over the entire stretch of River Yamuna. Segment IV from Okhla barrage to

Allahabad experiences increased pH of up to 7.9 due to groundwater accrual and addition of wastewater from drains of Delhi, Mathura-Vrindavan, Agra, and Etawah joining the river; tributaries like Hindon, Chambal, Sindh, Ken, Betwa flow with a low amount of DO help to balance the pH of the waters of River Yamuna. The pH of waters flowing through the high mountains increases due to basic salts and various alkaline minerals. Water starts accumulating more alkalinity. As a general trend, the pH of river water is observed to increase as it flows from its origin (Yamunotri) to its final confluence (Allahabad) with R. Ganges. The graph also shows an increase in the maximum and minimum pH values denoting the variability due to seasonal flows, local weather conditions, and variation in mixing waters from various tributaries and drains. Factors such as the volume of flow, interaction with alkalinity-bearing rocks, the terrestrial climate in the planes, BOD, temperature, and water mixing from various sources cause variation in water pH. Naturally, alkaline river waters rich in minerals are the most remarkable quality of water. Due to the variation of temperature and existence of stagnant zones such as lakes, reservoirs, etc., minerals tend to sediment at the river bottom at many locations. Hence, mineral content falls, reducing the premium water quality. The air-water interface further improves the taste of water and makes it more pleasant and healthy to drink [21]. The introduction of pollution load and BOD due to the various drains lowers the pH at many locations and creates acidic conditions. The river strives hard to regain its original quality and kick into actions its self-purification capacity, which governs water quality in its long run. Stagnancy causes lesser mixing of minerals, and pH starts to fluctuate in water, and hence the pH may decrease. The addition of various chemicals from agricultural patches, marshy lands, and dead animals lowers the pH. Acidic industrial wastes enter the river at many such locations through various drains from Delhi and Uttar Pradesh's industrial areas. It significantly alters the water's pH and affects the consumption patterns of the population. It affects the aquatic ecosystem and the absorption and desorption of minerals on river sediments. Also, stagnant waters tend to reduce the pH of water due to algal growth.

Electrical Conductivity (EC): Water picks up many dissolved ions in the form of minerals from water-rock interaction flowing down through the mountainous terrain. The pH by this action increases and further tries to dissolve in more minerals. Along the way, the water absorbs numerous anions and cations and thereby increases water's electrical conductivity. Conductivity or electrical conductivity (EC) measures the number of ionic species present in water. As presented in Figure 3.1., water flowing from Yamunotri bears an average conductivity of about 200 μmhos/cm in Segment I (Yamunotri to Hathnikund /Tajewala barrage). EC is very low at the glacier melting zones due to the absence of salts and ions in the glacial melt. In Segment II from Hathnikund / Tajewala barrage to Wazirabad barrage in Haryana stretch, the average EC increases to 400 μmhos/cm in River Yamuna ions added by the groundwater accrual water in the river flow and contribution of water from small tributaries and sediment dissolution [22]. From Wazirabad barrage to Okhla barrage, EC in Segment III further increases to 500 μmhos/cm. Here water is received from sewage drains of Delhi via Najafgarh drain and bathing ghats, which add ionically charged water to the river. Increased EC values from Upper Ganges Canal and Hindon cut canal tries on the downstream of the confluence points [23], [24]. Segment IV from Okhla barrage to Allahabad shows increased EC of up to 1500 μmhos/cm due to groundwater accrual and addition of wastewater from drains of Delhi, Mathura-Vrindavan, Agra, and Etawah joining the river; tributaries like Hindon, Chambal, Sindh, Ken, Betwa flow help to balance the EC of the waters of River Yamuna. Finding the curve of best fit for the data for average conductivity, a linear model as $\mathbf{C = 32.185\, l + 115.01}$, where C = Conductivity in μmhos/cm, l = distance of location on the River Yamuna from the origin at Yamunotri.as below is derived to show the trend of variation over the entire stretch of River Yamuna. The EC of waters increases due to basic salts and alkaline minerals added as it flows through the mountains. Water starts accumulating more ions as it proceeds into the lower latitudes. As a general trend, the EC of river water is observed to increase as it flows from its origin (Yamunotri) to its final confluence (Allahabad) with R. Ganges. The graph also shows an increase in the maximum and minimum pH values denoting the variability due to seasonal flows, local weather conditions, and variation in mixing waters from various tributaries and drains. Factors such as the volume of flow, interaction with alkalinity-bearing rocks, the terrestrial climate in the planes, BOD, temperature, and water mixing from various sources cause variation in EC of water. Naturally, alkaline river waters rich in minerals is the most remarkable quality of water [15]. Due to variation of temperature and the existence of stagnant zones such as lakes and reservoirs. Minerals tend to sediment at the river bottom, and hence mineral content falls, reducing the premium water quality and EC. The addition of chemicals from agricultural patches, marshy lands, and dead animals increases the EC. Stagnancy causes lesser mixing of minerals, and EC starts to fluctuate in water, and hence the EC may decrease. Industrial wastes from industrial areas of Delhi and Uttar Pradesh significantly increase the EC and affect population consumption patterns. Stagnant waters tend to reduce the EC of water.

*Biochemical Oxygen Demand (BOD):*All flowing stream of water engages their self-purification capacity to counter pollution by natural or anthropogenic sources. It does so by undertaking a sequence of actions. Firstly, the river tends to sediment the heavier particles of pollutants to the river bed; the lighter ones are separated by floatation. Activities such as redox reaction undertake inorganic degradation [4]. In contrast, biologically active organic pollutants are acted upon by bacteria to stabilize the contaminants. This process consumes a considerable amount of dissolved oxygen to support the metabolic activity of the bacterial population [25]. The amount of this oxygen required by bacteria to stabilize organic matter is called biochemical oxygen demand (BOD). BOD:COD ratio of water also act as an indicator of water pollution [26]. Water gets DO by gas transfer due to the water-air interfaces. It flows from the glaciers down through the mountainous terrain. Along the way as the DO consuming factors such as organic matter and other pollutant enters the water, the BOD increases and DO content reduces. It creates unsustainable conditions for aquatic life. DO may reach a critical level of 4 mg/l and cause mass bereavement of marine life. Water flowing from Yamunotri bears an average DO content of about 8 mg/l. At many locations, it attains saturation DO content of up to 14 mg/l. Finding the best fit curve for the data for average BOD, a linear model as $\boldsymbol{y_t = 0.5967\, l + 1.1939}$, where y_t = BOD in mg/l, l = distance of location on the River Yamuna from the origin at Yamunotri shows the trend of BOD variation over the entire stretch of River Yamuna. As presented in Figure 3.1., BOD in Segment I from Yamunotri to Hathnikund /Tajewala barrage in the Uttarakhand and Himachal Pradesh Stretch. In Segment II from Hathnikund / Tajewala barrage to Wazirabad barrage in Haryana stretch, the average BOD increases to 5 mg/l. Besides dilution of waters in River Yamuna due to the groundwater accrual, water with lower BOD content diffuses the effect of increased BOD and improves self-purification of water. Also, add to the river flow by small tributaries improves the DO content and fulfills the requirement by BOD. In Segment III from Wazirabad barrage to Okhla barrage in Delhi Stretch, the highest BOD quantity is observed [16]. The average BOD level in this area increases up to 10 mg/l. Here sewage from drains of Delhi via the Najafgarh drain and various bathing ghats contributes to BOD. BOD is supported by the addition of DO from the Upper Ganges Canal and Hindon cut canal. BOD in Segment IV further increases up to 15 mg/l from Okhla barrage to Allahabad. BOD increases here due to the wastewater from drains of Delhi, Mathura-Vrindavan, Agra, and Etawah joining the river. The BOD is diffused by the addition of water from groundwater accrual. From tributaries like Hindon, Chambal, Sindh, Ken, Betwa, flow alleviate the DO content of River Yamuna. They are flowing through the high mountains. DO-rich water starts losing DO by exertion by BOD stabilizing bacteria. Factors affecting BOD in water are observed to increase gradually from the origin of the river to the final confluence into R. Ganges. Septic conditions due to DO reduction beyond critical level may be observed at various locations. The stagnant lower limit, i.e., minimum BOD and the increasing maximum BOD graphs, show a widening difference on the rising side. Variability due to the local weather conditions and terrestrial climate in the planes, thermal changes, and water mixing from various drains in the lower latitudes causes BOD to keep increasing and make it unsuitable for aquatic life the flow of waters from Yamunotri to Allahabad. Seasonal variations such as lean periods of flow and flood conditions cause a lesser amount of oxygen to dissolve in water. Hence, the rate of BOD reduction reduces. Agricultural patches add BOD along the river banks. At many such locations, fertilizers cause excessive growth of algae in the water and disturb the air-water interface. This further causes reduced gas transfer and, as a result, causes lesser DO to enter into the water. It may create a septic condition and cause turbidity and odor nuisance in the river. Despite the rising trend of BOD along the river's length, a peculiar peak of high BOD levels is observed in the Delhi Stretch, where the BOD value may exceed 45 mg/l. It is due to the inflow of various drains into the River Yamuna. This stretch marks the filthiest patch of the river.

Nitrate- Nitrogen and Nitrite-Nitrogen (NO_3-N and NO_2-N): Nitrate- Nitrogen, and Nitrite-Nitrogen are essential for all living things as a component of proteins. Nitrogen exists in the environment and transforms into many species moving through the nitrogen cycle. Nitrate-nitrogen (NO_3-N) is toxic, primarily due to its reduction to nitrate-nitrogen (NO_2-N). Excessive NO_3-N and NO^{2-}N in potable water is hazardous for pregnant women and infants. Graphical representation, as shown in Figure 3.1., may indicate a decreasing trend of NO_3-N and NO_2-N. However, it is worth observing that quantitatively the graph is relatively flat and does not signify much for the entire stretch of River Yamuna. It is worth noting that increased nitrate-nitrogen and nitrate-nitrogen values are observed only at the end of Segment I and extend up to Segment III. It indicates the pollution load induced by Segment II of the river stretch. Nitrate reactions (NO_3-) in freshwater also cause oxygen depletion.

Thus, aquatic life may suffocate due to the reduced supply of oxygen in the stream. Municipal and industrial wastewaters, septic tanks, animal wastes (including birds and fish), and emission from vehicular exhausts are the significant entry routes of nitrogen into water bodies. This segment allows entry of such ingredients from the numerous drains from the Delhi stretch that join River Yamuna. NO_3-N and NO_2-N in Segment I from Yamunotri to Hathnikund /Tajewala barrage in the Uttarakhand and Himachal Pradesh Stretch is negligible since significantly less settlement exists in the mountainous terrain. In the relatively plain landscape in Segment II from Hathnikund / Tajewala barrage to Wazirabad barrage in Haryana stretch, the value of NO_3-N and NO_2-N is 10 mg/l at the end. The addition of dilution waters in River Yamuna due to the groundwater accrual diffuses increased NO_3-N and NO_2-N. Water from small tributaries improves the DO content and negates the effect of NO_3-N and NO_2-N. The best fit curve for the data for average NO_3-N and NO_2-N used to forms a linear model as $\boldsymbol{N = -0.0479\, l + 2.7172}$, where N = NO_3-N and NO_2-N in mg/l, l = distance of location on the River Yamuna from the origin at Yamunotri. In Segment III from Wazirabad barrage to Okhla barrage in Delhi Stretch, the highest NO_3-N and NO_2-N quantities are observed. The average NO_3-N and NO_2-N level in this area increase up to 20 mg/l. Here sewage from drains of Delhi via the Najafgarh drain and various bathing ghats contributes NO_3-N and NO_2-N. NO_3-N and NO_2-N in Segment IV start reducing again from Okhla barrage to Allahabad. NO_3-N and NO_2-N decrease here is due to the dilution of wastewater from drains of Delhi, Mathura-Vrindavan, Agra, and Etawah joining the river. The self-purification capacity of River Yamuna in this segment strengthens, and hence low to negligible amounts of NO_3-N and NO_2-N are observed. Nitrogen is also diffused by water from groundwater and tributaries like Hindon, Chambal, Sindh, Ken, and Betwa. Low variability in the difference of maximum and minimum concentration of NO_3-N and NO_2-N due to the local weather conditions and terrestrial climate in the planes, thermal changes, and water mixing from various drains in the lower latitudes is observed. However, large amounts of NO_3-N and NO_2-N released in the Delhi Stretch renders the water unsuitable for aquatic life in the mid-stretch of River Yamuna from Yamunotri-Allahabad. The release of nitrogen-rich fertilizers also affects NO_3-N and NO_2-N in the agricultural patches along the river banks.

Coliform Count: Bacterial contamination in water is indicated by coliform bacteria. It causes waterborne diseases and enters into rivers mainly through untreated sewage. Coliform count by MPN (most probable number) test provides the number of bacterial colonies in water. The presence of Coliform indicates the sanitary condition of the water body. Fecal Coliform includes the bacteria released from human and animal waste. These bacteria ferment lactose and yield acid and gas. Simultaneously, total Coliform consists of the soil's bacteria, water that surface waters have influenced, and human and animal waste. Coliform indicates pathogens that may pose a threat to the population consuming water in the nearby vicinity. Water with fecal coliform count between 500 and maximum up to 2,500 MPN/100 ml can be considered fit to take a bath. Organic tissues of coliform bacteria are generally bleached during the water's redox reactions, an integral part of self-purification capacity. Hence, redox reaction and factors affecting DO consumption and replenishment are of prime importance to study Coliform in flowing water. Virgin water flowing from Yamunotri may bear a coliform count of up to 100 MPN/100ml. As shown in Figure 3.1 in segment-I, from Yamunotri to Hathnikund /Tajewala barrage in the Uttarakhand and Himachal Pradesh Stretch is flat and rises maximum to 10-100 MPN/100ml. In Segment II from Hathnikund / Tajewala barrage to Wazirabad barrage in Haryana stretch, the average fecal and total Coliform remains asymptotic to 10-100 MPN/100ml. Finding the curve of best fit for the data for average fecal Coliform and Total Coliform, a linear model as $\boldsymbol{FC = 10^7\, l - 2\times10^7}$ and $\boldsymbol{TC = 10^7\, l - 3\times10^7}$, where FC = Fecal Coliform in MPN/100ml, TC = Total Coliform in MPN/100ml, l = distance of location on the River Yamuna from the origin at Yamunotri derived to show the trend of variation over the entire stretch of River Yamuna. In Segment III from Wazirabad barrage to Okhla barrage in Delhi Stretch, the highest coliform quantity is observed. The average coliform level in this area increases up to 2500 MPN/ml. Here sewage from drains of Delhi via the Najafgarh drain and various bathing ghats contributes to Coliform. Coliform in Segment IV regains its original state after continuous flow to a level up to 10-100MPN/ml from Okhla barrage to Allahabad. Coliform increases here at instances due to the wastewater from drains of Delhi, Mathura-Vrindavan, Agra, and Etawah joining the river. Due to the bathing ghats and river banks' usage for sanitary purposes, causes at many such locations, its entry of a large amount of Fecal Coliform in water and disturb water quality. Interaction with other water quality parameters such as BOD, nitrogen, various salts, and organic matter further degrades the condition. Despite the flat trend of Coliform along the river's length, peaks of high coliform levels are observed in the Delhi Stretch, where the coliform value may exceed 5×109 MPN/ml. It is due to the inflow of various drains into the River Yamuna.

Table 3.1 Correlation matrix for statistical values of Temperature, DO, pH, Conductivity, BOD, Nitrate-N & Nitrite-N, Fecal Coliform, and Total Coliform

	tmin	tavg	tmax	domin	doavg	domax	phmin	phavg	phmax	cmin	cavg	cmax	bodmin	bodavg	bodmax	nnmin	nnavg	nnmax	fcmin	fcavg	fcmax	tcmin	tcavg	tcmax	
tmin	1.00																								tmin
tavg	0.75	1.00																							tavg
tmax	0.56	0.98	1.00																						tmax
domin	-0.20	-0.59	-0.62	1.00																					domin
doavg	-0.21	-0.28	-0.24	0.82	1.00																				doavg
domax	-0.10	0.05	0.07	0.32	0.68	1.00																			domax
phmin	-0.10	-0.21	-0.29	0.29	0.20	-0.02	1.00																		phmin
phavg	0.02	0.03	0.00	0.21	0.32	0.14	0.78	1.00																	phavg
phmax	-0.06	0.31	0.28	0.07	0.31	0.34	0.29	0.76	1.00																phmax
cmin	0.44	0.64	0.50	-0.40	-0.38	-0.21	0.06	0.17	0.08	1.00															cmin
cavg	0.30	0.63	0.66	-0.75	-0.53	-0.08	-0.10	0.13	0.33	0.88	1.00														cavg
cmax	0.34	0.66	0.65	-0.70	-0.56	-0.21	-0.15	0.10	0.02	0.57	0.96	1.00													cmax
bodmin	0.18	-0.14	0.13	-0.53	-0.74	-0.51	-0.06	-0.46	-0.34	0.62	0.10	0.38	1.00												bodmin
bodavg	0.03	0.18	0.19	-0.68	-0.71	-0.43	-0.13	-0.15	-0.14	0.44	0.64	0.67	0.60	1.00											bodavg
bodmax	0.10	0.40	0.36	-0.70	-0.65	-0.45	-0.13	-0.07	-0.08	0.44	0.73	0.55	0.56	0.97	1.00										bodmax
nnmin	0.29	0.34	0.19	-0.32	-0.56	-0.29	0.01	0.06	0.06	0.24	0.61	0.03	0.76	0.60	0.17	1.00									nnmin
nnavg	0.41	0.30	0.29	-0.60	-0.80	-0.40	-0.05	-0.05	-0.08	0.58	0.65	0.45	0.76	0.82	0.70	0.90	1.00								nnavg
nnmax	0.14	0.31	0.26	-0.46	-0.79	-0.37	-0.10	-0.11	-0.05	0.05	0.75	-0.05	0.61	0.87	0.41	0.72	0.95	1.00							nnmax
fcmin	-0.04	0.09	0.09	-0.30	-0.17	0.09	-0.05	0.00	0.04	0.14	0.40	0.25	0.05	0.20	0.17	-0.14	-0.24	-0.29	1.00						fcmin
fcavg	-0.06	0.08	0.08	-0.39	-0.40	-0.24	-0.07	0.10	0.19	0.40	0.38	0.36	0.12	0.75	0.75	-0.14	-0.22	-0.27	0.08	1.00					fcavg
fcmax	-0.08	0.07	0.07	-0.35	-0.40	-0.20	-0.08	0.10	0.15	0.10	0.33	0.17	0.11	0.75	0.62	-0.06	-0.18	-0.12	0.09	1.00	1.00				fcmax
tcmin	-0.01	0.11	0.17	-0.40	-0.39	-0.40	0.00	-0.01	-0.04	0.44	0.45	0.34	0.48	0.25	0.25	0.71	0.63	0.51	0.44	0.24	0.23	1.00			tcmin
tcavg	-0.08	0.10	0.10	-0.38	-0.33	-0.21	-0.07	0.11	0.20	0.42	0.47	0.46	0.06	0.61	0.62	0.26	0.62	0.78	0.11	1.00	1.00	0.00	1.00		tcavg
tcmax	-0.09	0.09	0.10	-0.32	-0.31	-0.17	-0.08	0.11	0.16	0.09	0.44	0.22	0.04	0.60	0.46	0.02	0.43	0.42	0.10	1.00	1.00	0.00	1.00	1.00	tcmax
	tmin	tavg	tmax	domin	doavg	domax	phmin	phavg	phmax	cmin	cavg	cmax	bodmin	bodavg	bodmax	nnmin	nnavg	nnmax	fcmin	fcavg	fcmax	tcmin	tcavg	tcmax	

The correlation matrix indicates that variation of temperature, BOD, conductivity, NO_3-N & NO_2-N, Fecal Coliform, and Total Coliform correlates with each other. It suggests that a singular source may be the reason for their variation along the length. On the contrary, Dissolved Oxygen shows an inverse correlation with conductivity, BOD, NO_3-N & NO_2-N, Fecal Coliform, and Total Coliform. A maximum positive correlation exists between BOD and NO_3-N & NO_2-N, whereas a maximum negative correlation exists between DO and BOD.

3.1 STATUS OF WATER QUALITY OF DRAINS JOINING RIVER YAMUNA - WITHIN DELHI STRETCH

16 out of 23 drains discharge their wastewater into River Yamuna between Wazirabad and Okhla. Moreover, 04 drains meet the Yamuna at the downstream of Okhla Barrage, and 03 drains discharge directly into Agra Canal and Gurgaon Canal. 5 out of 23 drains are intercepted and diverted to the nearby STPs for ensuring treatment. Najafgarh drain (including Supplementary drain), Delhi Gate drain, Sen Nursing Home drain, Barapulla, Tughlakabad, and Shahdara drain contribute about 86% of the hydraulic load and 75 % of the organic load (BOD, i.e., amount of organic matter). Leading causes of pollution in River Yamuna is the discharge of treated or untreated sewage, discharge of treated and untreated industrial effluents, bathing by the general public, washing of clothes on the banks, performing Poojas, throwing of worship materials including idols made of gypsum and decorated with toxic paints during festival season, disposal of solid waste, and flood plain farming and other activities [27]. 33 out of total 41 STPs are operational, and the remaining are non-operational. The total installed capacity of wastewater in Delhi is 3149.3 MLD, and the operational capacity of 33 STPs is 2801.27 MLD. The capacity of non-operational 08 STPs is 348.03 MLD.

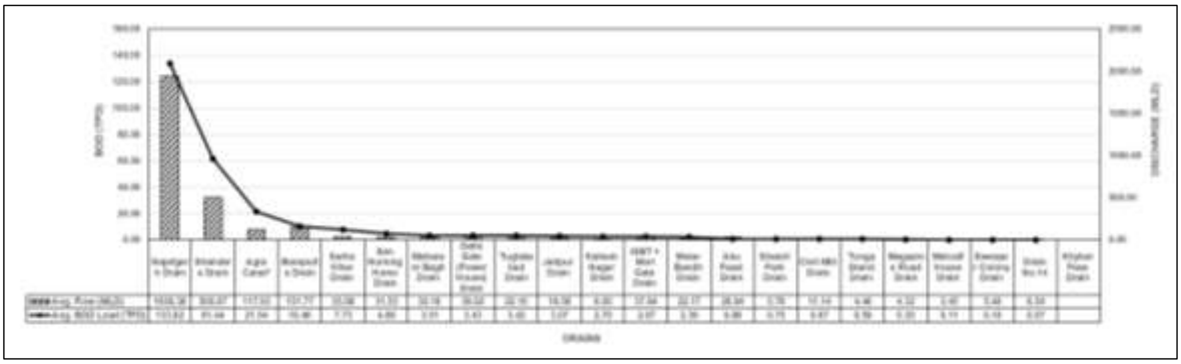


Figure 3.3.2 Variation of Biochemical Oxygen Demand (BOD) w.r.t discharge of waters of various drains joining the Yamuna

Industrial effluent: There are 28 Approved Industrial Estates/Areas in Delhi, and 28117 industrial units are operating in these industrial estates/areas as per the Delhi Pollution Control Committee (DPCC). Out of 28117 industrial units, 1516 industrial units are water-polluting and have installed captive

Effluent Treatment Plants (ETPs). The primary sources of water by industries in Delhi are groundwater and tankers. Total wastewater generation from these industrial estates/areas is 35.98 MLD. Also, 13 CETPs cater to the wastewater generated from 17 Approved Industrial Estates/Areas with a total treatment capacity of 212.3 MLD. Efforts for establishment of self-sustainable sewage treatment plants along the river course shall be included in planning [28]. Given the lockdown due to the COVID-19 pandemic, all the industries are not operational. Therefore, there is no discharge (domestic sewage and industrial effluent) from all the Delhi State industries. However, during the lockdown period, the release of partially treated and untreated wastewater continues to be in the business-as-usual scenario. Halted industrial activity resulted in reduction of 36 MLD of industrial effluent. Still, a BOD load of about 260 TPD is expected to be discharged through drains.

3.1.1 WATER QUALITY OF RIVER YAMUNA AND DRAINS

During the lockdown period, human activity such as bathing, washing clothes at Dhobi Ghats, religious activities, throwing of flowers, garlands, and other worship materials was absent in the sampling locations' vicinity. Water quality in River Yamuna at sites such as (i) Palla (Entry point of River Yamuna in Delhi), (ii) Nizamuddin bridge (between Wazirabad barrage and Okhla barrage – 14 drains contributing discharges, (iii) Okhla barrage Upstream (after the release of 16 drains), and (iv) two major drains (which are contributors of both hydraulic & pollution load in River Yamuna); namely Najafgarh drain and Shahdara drain improved during this period [29]–[33].

As stated earlier, sampling of River Yamuna was carried out at 3 locations, i.e., Palla, Nizamuddin Bridge, Okhla upstream, and significant two drains carrying wastewater Najafgarh drain and Shahdara drain. Water quality trend of River Yamuna as well as Najafgarh and Shahdara drain concerning pH, EC, DO, BOD and COD as observed during Pre-lockdown (04th March 2020) and Lockdown period (06th April 2020). Based on the field study and analytical results, the following findings/observations are made. About 4145 cusecs (hourly average) of freshwater is being released into River Yamuna from Wazirabad barrage, which is mainly due to (i) unavailability of satisfactory stowage size at Wazirabad Barrage (ii) increased flow of freshwater from Hathnikund Barrage and (iii) unanticipated or untimely snowfall or rainfall on U/s portion of River Yamuna, and a monthly average discharge of freshwater from Wazirabad barrage during March 2020 is 4863 cusecs. The maximum discharge of freshwater of 15,950 cusecs to River Yamuna was recorded. It was also observed that during the last week of February 2020 and the first week of March 2020, freshwater release from the Wazirabad barrage was less than 1000 cusecs. Details of freshwater discharge freshwater from Wazirabad Barrage into River Yamuna for February, March, and April 2020.

Because of the lockdown due to the COVID-19 pandemic, most of Delhi's industries were not in operation. Total wastewater discharge (both treated and untreated domestic sewage) from Delhi into River Yamuna is expected to be around 2990 MLD against the estimated total wastewater r discharge (both domestic and industrial wastewater) of 3026 MLD into River Yamuna during the pre-lockdown period. The analysis results of collected water samples during the lockdown period at Palla, Nizamuddin Bridge, Okhla Barrage U/s, as well as Najafgarh Drain and Shahdara Drain, are given in subsequent paras:- Pre-lockdown period (in March 2020) and lockdown period (06.04.2020):- At Palla, during the pre-lockdown period in March 2020, the analysis results showed pH (8.7), EC (668 µs/cm), BOD (.7.9 mg/L), DO (17.1 mg/L), and COD (28 mg/L)whereas the analysis results during the lockdown period showed pH (7.8), EC (273 µs/cm), BOD (2 mg/L), DO (8.3 mg/L), and COD (6 mg/L) and complying to the primary water quality criteria for outdoor bathing w.r.t analyzed parameters pH, DO and BOD which shows improvement in water quality of River Yamuna at Palla.

Also, comparative analysis results during the pre-lockdown and lockdown period reveal a considerable decrease in the concentration of parameters. Reduction in EC (59.18 %), DO (51.46 %), BOD (74.69 %), and COD (78.57 %) may be attributed to freshwater flow from upstream of River Yamuna and no human activity or industrial effluent discharge due to lockdown because of COVID-19 pandemic. Comparative analysis results during pre-lockdown and lockdown reveal that there is a substantial decrease in the concentration of parameters, particularly w.r.t EC (66.40 %), BOD (90.18 %), and COD (82.22 %). It is attributed mainly to the reduced activity of industrial discharge from industries and domestic sources. Also, other human activities such as bathing, throwing of worship materials, or solid waste were absent. At U/s of Okhla Barrage, during the pre-lockdown period in March 2020, the analysis results showed pH (7.20), EC (861 µs/cm), BOD (.27 mg/L), DO (not detected), and COD (95 mg/L). In contrast, the analysis results during the lockdown period showed pH (7.1), EC (488 µs/cm), BOD (6.1 mg/L), DO (1.2 mg/L) and COD (18 mg/L) and not complying with the primary water quality criteria for outdoor bathing w.r.t analyzed parameters such as DO and BOD.

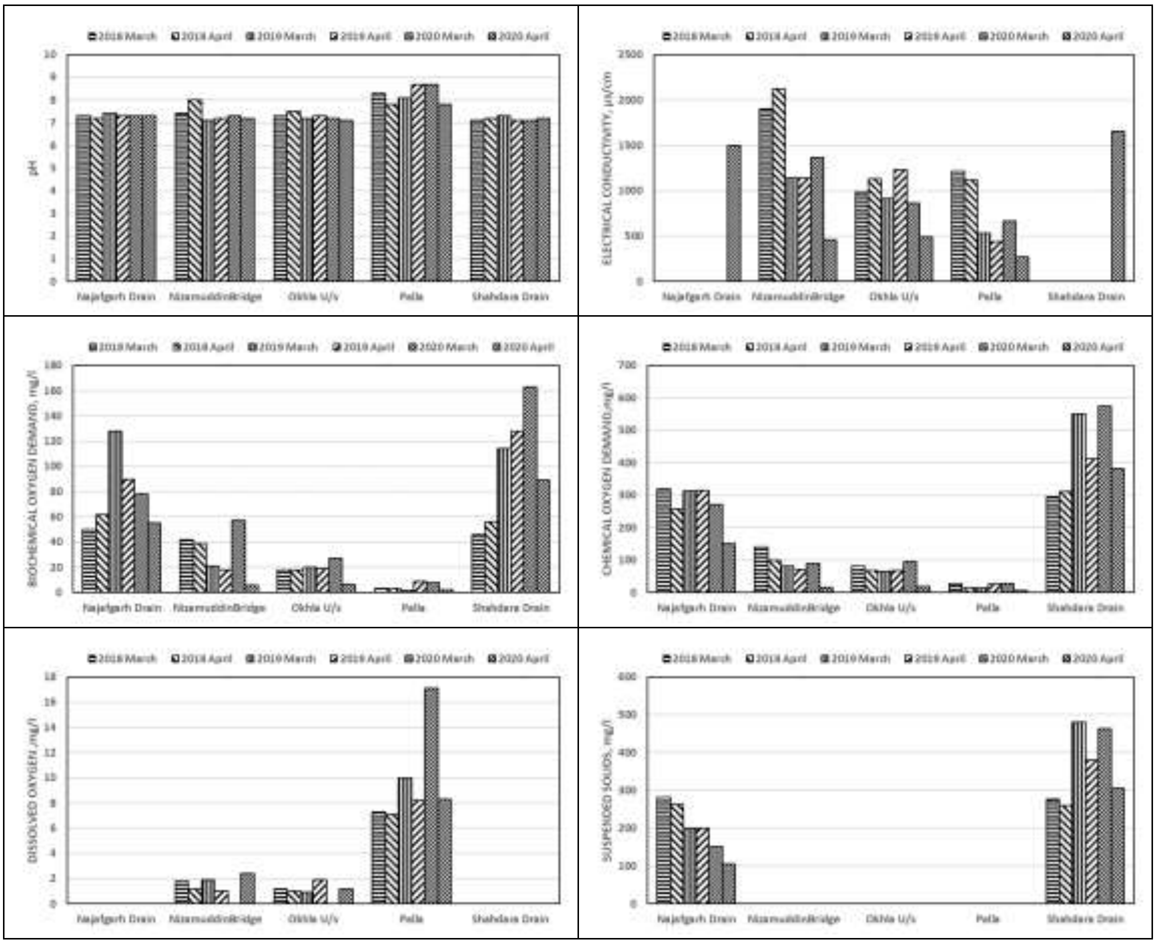


Figure 3. Trend of water quality parameters of drains joining River Yamuna

Comparative analysis results (pre-lockdown and lockdown period) reveal that there is a considerable decrease in the concentration of parameters w.r.t. analyzed parameters viz., EC (43.32 %), BOD (77.41 %), and COD (81.05 %). It is attributed to contribution only from Najafgarh Drain (which discharges 1938 MLD of wastewater into River Yamuna), during the pre-lockdown period in March 2020, the analysis results showed pH (7.3), SS (152 mg/L), BOD (78 mg/L), COD (271 mg/L). In contrast, the analysis results during the lockdown period (on 06.04.2020) showed pH (7.3), SS (106 mg/L), EC (1501 µs/cm), BOD (55 mg/L), and COD (150 mg/L). Also, the comparative analysis results (pre-lockdown and lockdown period) reveal that there is a decrease in the concentration of analyzed parameters, i.e., SS (30.26 %), BOD (29.49 %), and COD (44.65 %), which can be attributed to carrying of untreated and treated sewage. At Shahdara Drain, during the pre-lockdown period in March 2020, the analysis results showed pH (7.1), SS (464 mg/L), BOD (163 mg/L), COD (574 mg/L). In contrast, the analysis results during the lockdown period (on Page 14 of 21 06.04.2020) showed pH (7.2), SS (305 mg/L), EC (1657 µs/cm), BOD (89 mg/L) and COD (303 mg/L). Also, comparative analysis results (pre-lockdown and lockdown period) reveal that there is a decrease in the concentration of analyzed parameters, i.e., a slight increase in alkalinity, SS (34.27 %), BOD (45.4 %), and COD (33.28 %).

4. CONCLUSIONS

The analysis of the water quality of the entire stretch of River Yamuna reveals that the pristine waters of River Yamuna flowing from the Yamunotri glacier in the Uttarakhand stretch get polluted as its flows along the way. Due to the settlement pressure and discharge of domestic wastewaters and industrial effluent, river water quality worsens rapidly in the Haryana and most severely in the Delhi Stretch. River Yamuna nearly appears like a drain in the Delhi Stretch. Numerous pollutants affect the waters here; hence peaking of the majority of contaminants can be observed. Parameters such as temperature is observed to be increasing from Yamunotri to Allahabad. A general trend of falling dissolved oxygen is observed along the length of the river. Due to the dissolution of minerals in the water, the pH increasing from slightly acidic to alkaline. A general increasing trend of pH is observed. Similar to pH, conductivity also follows a rising trend from Yamunotri to Allahabad. BOD increases significantly in the settlement areas along the river. BOD value is observed to peak in Segment III, i.e., in the Delhi stretch. Nitrate-nitrogen (NO_3-N) and nitrite-nitrogen (NO_2-N) indicate peaks of organic pollution at the start of the Delhi stretch and continues to just after the Delhi stretch. Total Coliform and fecal Coliform follow similar trends to that of BOD. It increases along the length with peaks at segment III. The correlation matrix indicates that the existence of temperature, BOD, conductivity, NO_3-N and NO_2-N, Fecal Coliform, and Total Coliform correlates with each other and suggests that a singular source is a reason for their variation along the length. On the contrary, Dissolved Oxygen shows an inverse correlation with conductivity, BOD, NO_3-N & NO_2-N, Fecal Coliform, and Total Coliform. A maximum positive correlation exists between BOD and NO_3-N & NO_2-N, whereas a maximum negative correlation exists between DO and BOD. Most of the dilution and alleviation of pollution is undertaken by groundwater accrual, and water from small tributaries also attenuates the pollutant concentration. In general, pollutants in Segment III from Wazirabad barrage to Okhla barrage are in high concentration due to the water received from sewage drains of Delhi via Najafgarh drain also from various bathing ghats. Waters from Upper Ganges Canal and Hindon cut canal tries to improve the condition the downstream. However, segment IV from Okhla barrage to Allahabad experiences a reduction in water quality due to the wastewater from drains of Mathura-Vrindavan, Agra, and Etawah joining the river. Tributaries like Hindon, Chambal, Sindh, Ken, and Betwa flow to alleviate the pollution load on River Yamuna. At many locations, detergents and other frothing agents from bathing ghats and washing areas disturbs the air-water interface causing a hindered gas transfer. Hence lesser aeration is possible, which leads to unfavorable conditions for aquatic life. At many locations, agricultural patches contribute fertilizers, which cause excessive growth of algae in the water, and eventually lead to eutrophication. Study on flow rates and BOD load in 23 drains joining River Yamuna in the Delhi stretch shows that out of all the drains that flow into the River Yamuna, Najafgarh drain (including Supplementary drain), Delhi Gate drain, Sen Nursing Home drain, Barapulla, Tughlakabad, and Shahdara drain contributes significant hydraulic load (volume of waste water) and organic load (amount of organic matter). Leading causes of pollution in River Yamuna are discharge of treated or untreated sewage, discharge of treated and untreated industrial effluents, bathing by the general public, washing of clothes on the banks, performing Poojas, throwing of worship materials including idols made of Plaster of Paris (PoP) and decorated with toxic paints during festival season, disposal of solid waste, and Flood-plain farming and other activities. Overall status of water quality in the Delhi stretches of River Yamuna, water quality parameters for five significant drains show positive results. Analysis showed an improvement in the water quality of the River Yamuna from March 2018 to April 2020. The concentration of DO, BOD, and COD compared with the pre-lockdown and lockdown period at all the observed River Yamuna locations shows a declining trend. However, River Yamuna's water quality at Nizamuddin and Okhla U/s does not meet the primary water quality criteria for bathing standards concerning DO and BOD. Post –lockdown, improvement in water quality is due to release of freshwater from Wazirabad Barrage and availability of dilution in River Yamuna, absence of industrial effluent discharge (about 35.9 MLD) at present due to lockdown because of COVID-19 pandemic; good penetration of solar radiation in a water body can be expected due to washing out of bottom sediments as well as the settleable and colloidal form of pollutants in River Yamuna, and human activity such as the throwing of worshiping materials, solid waste disposal, bathing, washing of clothes minimized due to the ongoing lockdown due to the COVID-19 pandemic. It is high time that citizens shall realize that there is no life without water. Moreover, making sure that such river water flows shall remain unpolluted is the prime duty of humans.

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