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Environmental implications of climate change on the polluted Yamuna River

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Abstract: The Yamuna River is one of the most polluted rivers in the world and is considered ecologically dead as almost all water quality parameters exceed the permissible limits. It receives 80% of total pollution load while flowing through the Delhi, the national capital of India. In recent times, the rejuvenation of Yamuna becomes a focal point and many initiatives are being taken by the Government of Delhi and India. The present review is carried out to understand the primary contributors of pollution load and its future environmental implications under the influence of climate change. The primary anthropogenic drivers are, first, the influx of large amount of partially treated or untreated wastewater into the river. Second, the excessive withdrawal of fresh water for supply leads to decline in its quantity disturbing the environmental flow and further degrade the oxygenation level. Worldwide the rivers are predicted to be impacted by climate change. It is important to predict the probability and nature of adverse impacts could be caused by a highly polluted river under the influence of climate change in future. The likelihood of pollutant dispersal and mobility of metals could be more in future, potentially leading to a disaster. The successful implementation of remediation technologies would not only rejuvenate the Yamuna in current times, nonetheless, it will prevent the adverse impacts caused by climate change in future.

Key words: Water quality; metal mobility; floods; environmental impacts; rejuvenation.

1. INTRODUCTION

The total length of Yamuna is 1,376 km originating from Yamunotri glacier and merges River Ganga at Prayagraj, India. In historical times, the water of Yamuna River was not being used for drinking purposes. It is started being in use approximately a century back and currently it is a major source of water for Delhi. It enters in National Capital of Territory of Delhi (NCT of Delhi) at Palla village, Haryana and leaves at Asgerpur, Uttar Pradesh covering the stretch of 48 km (Figure 1). The stretch is only 3.4 % of total length of river and it receives 79% of total pollution (Upadhyay et al., 2011). The drains carrying wastewater from industries, agricultural fields and Sewage Treatment Plants (STP) discharged into river (Sharma et al., 2024). A total number of 22 drains, 39 STP and 13 Common Effluent Treatment Plants (CETP) discharges wastewater collected from National Capital of Territory of Delhi into Yamuna.

The industrial setups at the banks of Yamuna are discharging partially or untreated wastewater directly into the river (Gupta et al., 2024a). The confluence of Panipat drain and discharge of wastewater from industrial and urban areas into Yamuna results in deterioration of water quality making it unsuitable for irrigation (high salinity hazard) and industrial (high corrosion potential) purposes (Kaur et al., 2021). Apart from Delhi, the water quality of river is deteriorated at culturally important cities such as Mathura and Prayagraj located in the downstream direction. However, water quality parameters such as Biological Oxygen Demand (BOD 2.9 mg/L) and Dissolved Oxygen (DO 5.7 mg/L) are observed better than Delhi (DO is negligible at most of locations) at Prayagraj (Isaac et al., 2024; Sharma et al., 2025). The studies suggest a decline in pollution level specifically Chemical Oxygen Demand (COD) and BOD during COVID lockdown is attributed to closure of industries (Yadav et al., 2023). The pattern and dynamics of microbial growth in Yamuna water is significantly impacted by level of contamination (Chaturvedi et al., 2024; Parida et al.,

2022) and abundance of *Methanosaeta* and *Taproteobacteria* are observed in sediments of Yamuna close to industries (Parida et al., 2022).

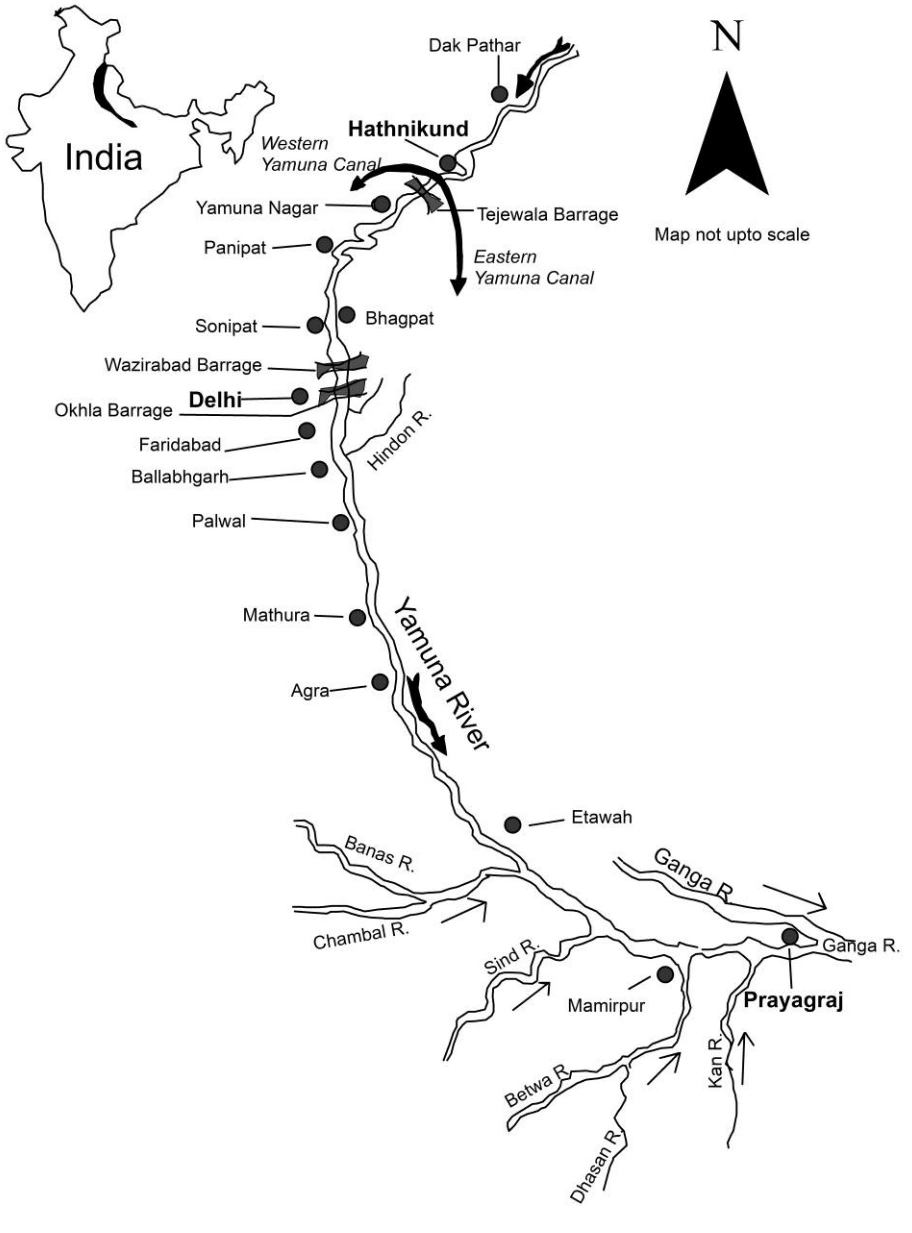

Figure 1. Yamuna River course showing important locations.

Apart from drains, Hindon river (a tributary of Yamuna) merges to Yamuna at Tilwara village, Gautam Buddha Nagar (NCT of Delhi) carrying the wastewater from nearby industries and domestic effluents (Suthar et al., 2009). Dividing the whole stream of Yamuna in three zones i.e. upper, middle and lower zone. The water quality index suggests that upper (Paonta to Palla), middle (Delhi to Etawha) and lower (Auraiya to Pratappur) zones fall in "excellent to good", "poor to marginal" and "good to excellent" categories respectively is attributed to dilution effect due to mixing of water from rivers Betwa, Chambal and Ken (Jaiswal et al., 2019). The lack of dilution with freshwater is one of major hindrance in restoration and rejuvenation of river.

The Government of India launched many initiatives to clean Yamuna however, after spending millions of rupees the condition of river is still despicable. In current scenario, Yamuna is referred as dead river and its water quality parameters exceed the permissible limits suggesting unsuitability for domestic and industrial use. The level of pollution is sufficient enough to cause carcinogenic risk (Aithani et al., 2023) and the fishes grown in Yamuna are not safe for consumption (Kumar et al., 2024). Additionally, the vegetables grown on Yamuna banks using river water are prone to metal contamination (Aithani et al., 2024). The extreme weather events are expected to increase in future due to climate change. During the events of floods, the overflow of polluted water would result in contamination of the surroundings and it is difficult to predict the intensity of future impacts. The river passes through populated cities such as Delhi, Mathura and Prayagraj the overflow during extreme events could result in disaster. As per our knowledge no study has been carried out to understand the probable impacts of Yamuna River during the extreme events of climate change. Thus, this review is designed to highlight the gap in literature discussing the future disaster of extremely polluted river. It is important to implement the remediation technologies for the removal of contaminants for today but for future also. The aim of present review is to study the source of contamination and the factors contributing to the enhancement of pollution to better understand the future impacts. Additionally, the present study is emphasis on the restoration and rejuvenation of Yamuna to avoid the future impacts due to climate change.

2. FACTORS CONTRIBUTING TO ITS ECOLOGICAL COLLAPSE

For the current study, the factors contributing to ecological collapse of Yamuna are divided into two categories, *first* degradation of water quality and *second* decline in water quantity. The major sources of pollution are discharges from industries, sewage from urban areas and chemical fertilizers from agricultural fields. The recent trends in pollution depending on the type of product consumption are also discussed. The extensive withdrawal of water for consumption reduces the self-purification capacity of river. The maintaining water level in river is important to preserve its life.

2.1 Severity of pollution

One of the major causes of pollution is abundance of organic matter and untreated sewage in Yamuna. The increase in discharge of river in Delhi region is attributed to inflow of treated or semi-treated wastewater. The dissolved oxygen (DO) is important for aquatic life and the consumption of oxygen during degradation of organic waste results in decline of dissolved oxygen in water. The influx of large amount of untreated sewage also alters the color and decline in DO also contributes to bad odour. The photographs taken from Okhla Bird Sanctuary, Delhi are depicting the extent of environmental degradation (Figure 2). The level of contaminants exceeds the national permissible limits described by Bureau of Indian Standards (BIS) and World Health Organization (WHO) for water quality as shown in Table 1.

Figure 2. Photographs captured at Okhla Bird Sanctuary and near the Okhla barrage.

The concentration of ammonium and nitrate is also very high due to dumping of nitrogenous waste into the river and the removal of nitrogen rich waste needs to be carried out (Verma et al., 2023). The major source of ammonia in Yamuna are agricultural fields and industrial waste from tanneries, food and beverages (Kumar et al., 2019). The abundance of pharmaceutical residues and critical pathogens listed by WHO are sufficient enough to pose risk to aquatic life of Yamuna (Khan et al., 2021; Lamba et al., 2020) and human beings (Mutiyar et al., 2018). The rise in pharmaceutical active compounds is observed after the Wazirabad and specifically, after confluence of the Najafgarh drain with the Yamuna (Mutiyar et al., 2018). Approximately 37 drains are discharging BOD and COD enriched waste i.e. sewage and organic matter into Yamuna and deteriorating its DO level. The Najafgarh drain is contributing the highest quantity of wastewater into Yamuna and adversely impacts its assimilation or self-purification capacity (Verma et al., 2023).

Table 1. The measured parameters showing the pollution level of Yamuna River.

Locations	Parameters	Reference
Near Jagatpur	TDS (388 - 446 mg/L), Al (473-564 µg/L), Cu (83-121 µg/L), Cr (80-100 µg/L), Cd (11-37 µg/L), Fe (2.5-2.9 mg/L), Pb (202-306 µg/L), and Ni (168-254 µg/L)	Parween et al. (2017)
Near Narela industrial area	TDS (458 - 519 mg/L), Al (523-673 µg/L), Cu (93-175 µg/L), Cr (70-100 µg/L), Cd (31-53 µg/L), Fe (3.4-4.1 mg/L), Pb (316-405 µg/L), and Ni (192-203 µg/L)	
After Najafgarh drain and supplementary drain	TDS (775 - 621 mg/L), Al (831-878 µg/L), Cu (198-245 µg/L), Cr (160-280 µg/L), Cd (58-74 µg/L), Fe (6.6-8.2 mg/L), Pb (660-837 µg/L), and Ni (364-451 µg/L)	
Near Rajghat power plant	TDS (584 - 695 mg/L), Al (522-759 µg/L), Cu (112-157 µg/L), Cr (150-320 µg/L), Cd (39-64 µg/L), Fe (4.3-6.1 mg/L), Pb (522-720 µg/L), and Ni (264-547 µg/L)	
Near Indraprastha power Plant	TDS (743 mg/L), Al (465 µg/L), Cu (91 µg/L), Cr (140 µg/L), Cd (55 µg/L), Fe (6.0 mg/L), Pb (498 µg/L), and Ni (272 µg/L)	
Along Okhla Bird Sanctuary	TDS (782 - 953 mg/L), Al (716-570 µg/L), Cu (228-316 µg/L), Cr (270-480 µg/L), Cd (85-93 µg/L), Fe (4.5-6.5 mg/L), Pb (610-672 µg/L), and Ni (351-426 µg/L)	
After Shahdara outfall drain	TDS (712 mg/L), Al (424 µg/L), Cu (223 µg/L), Cr (530 µg/L), Cd (56 µg/L), Fe (6.3 mg/L), Pb (510 µg/L), and Ni (473 µg/L)	
Pala	DO (9.1 to 6.6 mg/L)	Mandal et al. (2010)
Delhi stretch (Palla to Jaitpur)	BOD in 2004 (22.8 mg/L), COD in 2004 (73.5 mg/L), BOD in 2005 (18.6 mg/L), COD in 2005 (15.6 mg/L), DO in 1999 to 2005 (1 to <1 mg/L) Total BOD Load (240.37 tons/day) Total Coliform (TC) (2.4 x 10^7 Coliforms/100 mL) Fecal Coliform (FC) (1.8 x 10^6 Coliforms/100 mL)	Upadhyay et al. (2011)
Nizamuddin bridge	BOD (10 mg/L in 1995 to 36 mg/L in year 2006) COD (31 mg/L in 1995 to 88 mg/L in year 2006) TC (3.8 x 10^5 Coliforms/100 mL in 1995 to 3.6 x 10^8 Coliforms/100 mL in 2006) FC (1.4 x 10^5 Coliforms/100 mL in 1995 to 1.7 x 10^6 Coliforms/100 mL in 2006) WQI (3 in 2006 to 11 in 1999)	
Agra canal	BOD (15 mg/L in 1995 to 30.5 mg/L in 2006) COD (49 mg/L in 1995 to 92 mg/L in 2006) TC (3.3 x 10^5 Coliforms/100 mL in 1995 to 1.1 x 10^7 Coliforms/100 mL in 2006) FC (1.8 x 10^5 Coliforms/100 mL in 1995 to 1.6 x 10^6 Coliforms/100 mL in 2006) WQI (3 in 2006 to 11 in 1995)	
Najafgarh drain	BOD Load (76.47 tons/day)	
Shahdara drain	BOD Load (44.57 tons/day)	
Drain near Bridge Sarita Vihar	BOD Load (20.45 tons/day)	
Sarita Vihar drain	BOD Load (20.18 tons/day)	
Maharani Bagh drain	BOD Load (15.76 tons/day)	
Sen Nursing Home drain	BOD Load (14.71 tons/day)	

Before Wazirabad barrage	Cu (0.011 mg/L), Cr (1.096 mg/L), Fe (0.471 mg/L), and Pb (0.0575 mg/L)	Sehgal et al. (2012)
Near Najafgarh drain	Cu (0.0905 mg/L), Fe (3.173 mg/L), Pb (0.126 mg/L) and Ni (0.0755 mg/L)	
Near Metcalfe House bus stop	Cu (0.023 mg/L), Fe (1.0725 mg/L), Pb (0.0575 mg/L), and Ni (0.077 mg/L)	
Near Old Yamuna bridge	Cu (0.0415 mg/L), Fe (1.358 mg/L), Pb (0.767 mg/L), and Ni (0.06 mg/L)	
Near Geeta colony	Cu (0.595 mg/L), Fe (8.601 mg/L), and Ni (0.092 mg/L)	
Near Rajghat	Cu (0.034 mg/L), Fe (1.254 mg/L), Pb (0.1 mg/L), and Ni (0.143 mg/L)	
Near Yamuna barrage	Cu (0.019 mg/L), Cr (1.374 mg/L), Fe (0.896 mg/L), and Ni (0.0375 mg/L)	
Near railway track	Cu (0.0585 mg/L), Cr (0.064 mg/L), Fe (2.442 mg/L), Pb (0.1495 mg/L), and Ni (0.0405 mg/L)	
Near toll bridge, Noida	Cu (0.0165 mg/L), Fe (0.76 mg/L), and Ni (0.0475 mg/L)	
Near Dhobi Ghat, Sailing Club Road	Cu (0.017 mg/L), Fe (0.9635 mg/L), Pb (0.32 mg/L), and Ni (0.0395 mg/L)	
Near Kanal colony	Cu (0.051 mg/L), Fe (3.4885 mg/L), and Ni (0.0355 mg/L)	
Near Okhla barrage	Cu (0.064 mg/L), Fe (2.943 mg/L), Pb (0.1225 mg/L), and Ni (0.0315 mg/L)	
Away from Okhla barrage	Cu (1.371 mg/L), Cr (1.096 mg/L), Fe (19.756 mg/L), Pb (0.0965 mg/L), and Ni (0.103 mg/L)	
Pachahira	Fe (40 μg/L), Cu (50 μg/L), Co (7 μg/L), Zn (1340 μg/L), Pb (2 μg/L), and Ni (121 μg/L)	Asim & Nageswara Rao (2021)
Nizamuddin	Fe (150 μg/L), Cu (120 μg/L), Co (66 μg/L), Zn (1690 μg/L), Pb (10 μg/L), Cyanide (600 μg/L), Ni (253 μg/L), and Cr (52 μg/L)	
Okhla	Fe (160 μg/L), Cu (80 μg/L), Co (10 μg/L), Zn (1680 μg/L), Pb (7 μg/L), Cyanide (200 μg/L), Ni (147 μg/L), and Cr (40 μg/L)	
Manjhawali	Fe (190 μg/L), Cu (100 μg/L), Co (13 μg/L), Zn (840 μg/L), Pb (30 μg/L), Cyanide (300 μg/L), Ni (161 μg/L), and Cr (35 μg/L)	
Wazirabad barrage	Ni (0.0535 mg/L), Zn (0.4494 mg/L), Cu (2.2552 mg/L), Cr (0.0205 mg/L), Cd (0.0174 mg/L), Fe (11.2652 mg/L), Pb (0.0310 mg/L)	Bhardwaj et al. (2017)
Najafgarh drain	Ni (0.2244 mg/L), Zn (2.3159 mg/L), Cu (5.9397 mg/L), Cr (0.7563 mg/L), Cd (0.0165 mg/L), Fe (21.5796 mg/L), Pb (0.1177 mg/L)	
Old Yamuna Iron bridge	Ni (0.0610 mg/L), Zn (0.4891 mg/L), Cu (2.0625 mg/L), Cr (0.0172 mg/L), Cd (0.0126 mg/L), Fe (8.4319 mg/L), Pb (0.0406 mg/L)	
ITO barrage	Ni (1.0455 mg/L), Zn (0.7151 mg/L), Cu (1.7959 mg/L), Cr (0.0269 mg/L), Cd (0.1276 mg/L), Fe (5.7029 mg/L), Pb (0.0486 mg/L)	
Nizamuddin bridge	Ni (0.3195 mg/L), Zn (0.7091 mg/L), Cu (1.1801 mg/L), Cr (0.0275 mg/L), Cd (0.0155 mg/L), Fe (5.9626 mg/L), Pb (0.0820 mg/L)	
Okhla barrage	Ni (0.0635 mg/L), Zn (0.4136 mg/L), Cu (1.0833 mg/L), Cr (0.0243 mg/L), Cd (0.0156 mg/L), Fe (6.5462 mg/L), Pb (0.0978 mg/L)	
Shahdara drain	Ni (0.8612 mg/L), Zn (5.4129 mg/L), Cu (0.7463 mg/L), Cr (0.1572 mg/L), Cd (0.1279 mg/L), Fe (13.9277 mg/L), Pb (0.3969 mg/L)	
WHO guideline values	TDS (600 mg/L), Fe (0.3 mg/L), As (0.01 mg/L), Ni (0.07 mg/L), Cd (0.003 mg/L), Zn (3 mg/L), Cu (2 mg/L), Cr (0.05 mg/L), Pb (0.01 mg/L), Co (0.05 mg/L), Mg (0.08 mg/L)	WHO (2022)

The concentration of Cr, Zn, Pb and Cd in Yamuna water exceeds the WHO permissible standards and the consumption of water and fish from Yamuna are unfit (Kumar et al., 2024). In the downstream of Delhi, the groundwater from Yamuna watershed (Mathura) are contaminated with heavy metals (i.e. Cd, Pb, Cr, Ni and Fe) and 77% of samples falls in very poor-quality category of ecological risk index (Ahmed et al., 2022b). The sediments of Yamuna in Delhi are highly enriched with heavy metals (Cr, Cd, Pb, Ni and Zn) and emerging contaminants such as hormones, pharmaceuticals and personal care products. The vegetables such as spinach, beet root, radish and cauliflower grown on Yamuna sediments are highly enriched in heavy metals. The risk assessment indices suggest the significant probability of cumulative risk to the community (Parween et al., 2021). The influx of runoff carrying sediments into Yamuna during monsoon further increases the level of contamination of water (Biswas et al., 2021).

The abundance of foaming agents such as detergents and phosphates results in formation of dense layer of foams on Yamuna (Sejwal and Singh, 2023). The influx of untreated wastewater and lack of freshwater availability increase susceptibility of foam formation on surface (Neenu and Kansal, 2025). Additionally, the presence of microplastic (polyethylene terephthalate, polypropylene and polystyrene) in Yamuna are falling within the substantial contamination category of pollution load index (Pawak et al., 2024). The urban drains passing through Delhi and discharging wastewater into Yamuna are significant router of microplastic specifically Najafgarh drain (Vaid et al., 2024). The abundance of microplastic is higher during the monsoon season compared to dry season (Gupta et al., 2024b).

2.2 Water quantity

Environmental flow is the minimum quantity of water required in a river to preserve its ecosystem. A study by National Institute of Hydrology, India suggests 23 Cumecs of minimum water is needed to maintain environmental flow of Yamuna. During dry season the environmental flow of Yamuna is approximately 10 Cumecs. The construction of new STPs, proper maintenance of existing STPs, upgradation of CETPs and tapping of all major drains are recommended by Department of Environment, Govt. of NCT of Delhi (2025) to control the discharge of unauthorized sewage. Additionally, the construction of dams (such as Lakhwar-Vyasi Dam) and sand mining at upper basin from Delhi are impacting the flow regime of Yamuna and altering its morphology (Yadav et al., 2023).

The low quantity of water due to extensive withdrawal of water is one of main factors contributing to environmental degradation of Yamuna. The construction of canals or bridges and the decline in river discharge significantly decrease the erosional potential attributed to decrease in water velocity and volume of flow and a shift in meandering is also observed (Yunus et al., 2020). The construction of Hathnikund barrage results in morphological and hydrological alteration of Yamuna due to accumulation of sediments upstream the barrage and excessive withdrawal of water. The decline in river flow destructs the habitat for aquatic life and posing ecological risk to river (Mohanty and Tare, 2024). The healthy river is important for the society as it provides water and food security. The low level of water reduces flow velocity of the river leading to stagnation and limiting the oxygenation. The high-speed currents of river flush out the pollutants. The adequate inflow of freshwater dilutes the level of contaminants through dilution effect and it is minimal in water scarce conditions. Both flow velocity and dilution effect enhance the river’s self-purification capacity.

The rise and decline in monsoon seasonal rainfall significantly influence the pollution level of Yamuna River. The drains from neighboring districts of Sonipat, Karnal, Yamuna Nagar and Panipat collect the rainfall runoff and discharges into the Yamuna at the Palla. Studies reported the improvement in water quality parameters such as BOD, COD, conductivity and pH during the monsoon season due to dilution factor (Sharma et al., 2025; Joshi et al., 2022; Mandal et al., 2009). The rainfall for the two or three months improves the quality of Yamuna water. The total average precipitation of approximately varies from 500-1000 mm has the capacity to improve the quality. In contrast, it is also observed that the dilution during the monsoon has no significant influence on the coliform content of river (Lokhande and Tare, 2021).

The excessive withdrawal of water from upstream, changes in land use pattern and construction of hydraulic projects impacts river flow regime (Jain et al., 2022). Metal concentration in the rivers is observed lower during post-monsoon season compared to pre-monsoon season indicating the rainfall induced dilution effect on contaminants (Karunanidhi et al., 2024; Zhang et al., 2022). Similarly, nutrients such as total nitrogen and total phosphorus decline in surface water after floods. However, pesticides such as heptachlor epoxide, pp′-DDD, o,o,o-triethylphosphorothioate, rabon, dimethoate and fensulfothion are found enriched in the sediments after floods (Zhou et al., 2022). The pesticides accumulated in sediments can transfer into vegetation and lead to ecological disaster. The rise in environmental flow of river flushes out the contaminated sediments and prevents the siltation. Additionally, the rise in speed of river flow promotes the reaeration and self-purification capacity.

Total quantity of wastewater dumped in Ganaga and its tributaries (Kali and Ramganga) is 501 MLD industrial discharge and 6614 MLD sewage/effluent from 144 drains (Press Information Bureau, 2016). In Yamuna, 641 MLD of untreated sewage discharged into the river in Delhi.

Additionally, it is observed that out of 189 polluting industries, the treatment units of 158 industries are found operational (Ministry of Jal Shakti, 2025). Thus, it is clear that the wastewater discharge into Ganga is higher than Yamuna indicating the major hindrance in remediation of Yamuna is low environmental flow. The recent initiative taken by Government of India for cleaning Yamuna are appreciable however, major problem i.e. low quantity of water which reduces self-purification of the river is neglected.

3. ANTICIPATED CONSEQUENCES OF CLIMATE CHANGE

The major water source of river is snow/glacier melts or surface runoff. The extreme weather events due to climate change such as excessive precipitation and rise in temperature would change the river discharge rate (Minaei and Irannezhad, 2018). The intense rainfall and melting of snow/glaciers due to warmer temperature are predicted to increase the quantity of surface runoff resulting in flooding of river (Hiyama et al., 2023; McCarthy et al., 2022). Globally, the events of floods and droughts are likely to influence the quality and quantity of river water (Pourfallah et al., 2021). The appropriate measures should be taken to avoid the displacement from the river banks in near future specifically targeting the polluted rivers like Yamuna. During floods, the dispersal of pollutants in the surrounding soil and water resources from polluted river would be more disastrous (Figure 3). It would be difficult to control the adverse environmental impacts at such a larger scale. Thus, the restoration of Yamuna is not only important to prevent adverse environmental impacts in current times but to avoid the future adverse impacts during the climate change.

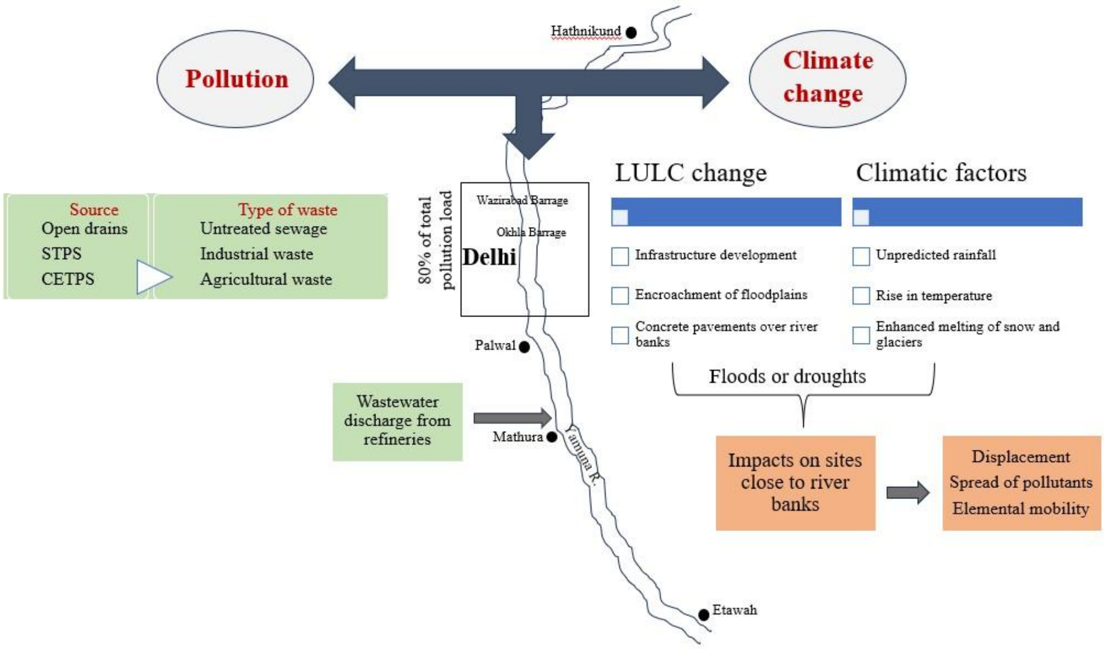

Figure 3. Flowchart illustrating the anticipated consequence of a polluted river combined with climate change.

Heavy rainfall in the Himalayas and Delhi results in the flooding of Yamuna River. The events of floods during 1978, 1988, 1995, 2010, 2023 and 2025 result in displacement of families living in the villages and unauthorised colonies close to Yamuna River banks (Government of National Capital Territory of Delhi, 2025). Apart from social impacts, floods have adverse environmental consequences such as spread of contaminants and rise in toxic elemental mobility (Ponting et al., 2021). The dispersal of contaminants during floods is bidirectional i.e. from urban areas into rivers and vice-versa. It is observed that heavy and intense rainfall results in inflow of contaminants from urban areas into rivers exceeding the pollution level to its self-purification capacity (Lin et al., 2024). The coverage area of Delhi exceeds 1000 km^2 suggesting the discharge of huge quantity of treated and untreated sewage into Yamuna. Major contributor to Yamuna pollution is the discharge of treated and untreated sewage from urban areas (Samui et al., 2025) indicating a huge content of sewage in the river. Backflow from the river to urban areas could result in filling of lakes and water bodies with sewage polluted water.

It is complicated to understand the influence of climate change on water quality due to unpredicted processes and events occurring in future (Li et al., 2024). The interaction of land and river are important for assessing the water quality as the surface runoff from landscape carries dissolved solutes from flow path into the river. The urbanization and concrete structures adversely impact the hydrodynamics of river and the extent of urban land cover is difficult to predict. The secondary channels are disappearing from Yamuna River due to concrete structures and human encroachment resulting in variations in flow dynamics and loss of water bodies originated from rivers such as oxbow lakes (Asim and Rao, 2024). The urbanization results in sudden inflow of runoff contributing to flush floods followed by long dry spell. The high-speed runoff flowing over the land surface have low recharge potential and declines in soil moisture. The uncertainty in level of expansion of urban patterns hinders the accurate forecast of river flow rate in near future.

Future climate-change scenarios are important to predict the consequences of elevated pollutants concentration in river. The hazards induced due to climate change can impact water quality and enhance the contamination (Asresu et al., 2025). The future scenario predicted by Coupled Model Intercomparison Project Phase 5 suggests a decline in surface water yield and groundwater recharge in Yom river basin of Northern Thailand (Petpongpan et al., 2020). The application of SWAT model suggests that the variation in annual runoff of Yangtze River, China is majorly attributed by the climate change as compared to change in land use and land cover (Ahmed et al., 2022a). In tropical regions where rainfall is major factor influencing the catchment characteristics of river are more prone to climate change in future. The flooding during the extreme precipitation results in erosion of river banks and displace human settlements (Das and Samanta, 2023). The silts or contaminated sediments deposited in the downstream agricultural fields resulting in accumulation of heavy metals in the vegetables. During the events of high precipitation, the contaminants from urban areas would mix into the river and the intensity of pollution potential would increase in future. The magnitude and frequency of floods are increasing under the influence of rapid urbanisation in Yamuna basin (Kumar et al., 2020).

The rainfall pattern and temperature impact hydro-morphological dynamics of river (Kayitesi et al., 2022). The rise in temperature and decrease in rainfall will decrease river discharge and increase concentration of nutrients in the freshwater (Vagheei et al., 2023). The change in water flow rate due to climate change are enhancing the incision of channels across the globe (Arbós et al., 2023). The rainfall patterns of Yamuna River basin will alter under the influence of climate change and it is expected to decrease (Chaudhary et al., 2019). Considering the temperature, it is expected to rise at upper basin of Yamuna resulting in increase in surface and groundwater flow and decline in evapotranspiration (Rathee and Mishra, 2024). The application of QUAL2K model to assess the impact of climate change using hypothetical scenario on Yamuna water quality suggests DO is more prone to climate change than BOD (Walling et al., 2014). Similar trends are observed at global level i.e. the rise in water temperature, algae and nutrient levels along with the decline in DO (van Vliet et al., 2023).

The variation in climatic factors influence the mobility of metals at higher altitude environments (Zaharescu et al., 2016) and the transported sediments are deposited in lower altitudes during floods (Lin et al., 2018). The inland water bodies of Asia and Africa are under threat of metal (Cu, Cr, Zn and Cd) contamination and climate change may worsen the release of metals (Jin et al., 2025). The level of organic micropollutants such as food additives and fatty acids are observed higher during the monsoon season (Mishra et al., 2023) suggesting the impact of precipitation on contaminants mobility and dispersion. The analysis of water with variation in climate suggest that with rise in temperature and fall in humidity the concentration of Pb and Ni increases in Yamuna (Sankhla et al., 2022). With rise in temperature, the level of DO concentration is decreasing in the catchments of Indian river basin (Rajesh and Rehana, 2022). Additionally, with rise in temperature the evaporation of water would increase resulting in decline of water level. The fluctuations in water level and variation in seasons (dry and wet) effects the mobility of metals from sediments (Du et al., 2025). Considering the impact of climate change, the future environmental condition of the Yamuna River in New Delhi and its surroundings could reach critical levels. It underscores the need of immediate actions to control the metal pollution.

The water crisis in Delhi reaches to peak in summers (Hothi, 2025) and the situation may degrade further in future with rise in population. In addition to Delhi, Yamuna water is also diverted to different states such as Haryana and Rajasthan falling in semi-arid and arid region for water supply. The rise in frequent events of drought and heatwaves is predicted for India (Kishore et al., 2022) resulting in more demand of freshwater and further decline in environmental flow. The major problem in achieving the sustainable remediation of Yamuna pollution is availability of low quantity of water. The water quality of river Yamuna improves during monsoon season (Joshi et al., 2026). The events of droughts and heatwaves deteriorate the river water quality worldwide (Graham et al., 2024). The extreme events of drought and floods are predicted to increase in Yamuna River basin in future (Chauhan et al., 2025) suggesting the further deterioration of water quality.

4. SUGGESTIONS FOR THE IMPROVEMENT OF WATER QUALITY

4.1 Environmental flow

The Sutlej River flows through the Roopnagar of Punjab and the Yamuna River through the Yamuna Nagar in Haryana. The distance between Roopnagar and Yamuna Nagar is 134 km only. The connection of Sutlej and Yamuna could increase the water quantity in the Yamuna resulting in dilution of contaminants. The river flows slowly due to the low volume of water and replenishing water could restore its environmental flow promoting the self-purification. The faster speed leads to turbulence supporting the oxidation of water. DO is an important parameter to support the aquatic life in the water bodies. The minimum water flow i.e. 10 m^3/sec is absent in Delhi from Wazirabad to Okhla barrage resulting in negligible self-purification capacity (Upadhyay et al., 2011). A study Lokhande and Tare (2021) by suggested that major focus for the restoration and rejuvenation of Yamuna should be on BOD, COD, nutrient and coliform. The mechanical generation of dissolved oxygen in the course of river flow would rejuvenate the dead river. The placement of boulders in the river channel would create turbulence resulting in oxidation. The presence of boulders and macroroughness in the streambed induces deeper oxic zones compared to plane-bed streams (Adler et al., 2025).

The distance between two rivers i.e. Yamuna and Sutlej at Yamuna Nagar and Roopnagar respectively is only 134 km and both falls in the same climatic conditions (subtropical) suggesting minimal ecological consequences of the project. Both are Himalayan originated rivers and the influence of anthropogenic activities is less in the region of Shivalik foothills where Yamuna Nagar and Roopnagar lies. The hydrological feasibility of the interlinking of Yamuna and Sutlej needs to be studied for its better implementation. One of the main institutional constraints in the implementation of project is the requirement of huge financial investment. However, the proper planning and implementation may result in financial gains in terms of agricultural output and other development activities. The interlinking of two rivers is socio-politically challenging task as the diversion of its water could be opposed by the community.

The interlinking of rivers is not only the solution for water scarcity. The practices such as water conservation, reuse and rainwater harvesting are equally important to solve the water scarcity problem (Jain et al., 2007). The linking of rivers via constructing ponds and check dam instead of channels will restrict the movement of micronutrients and macronutrients from one system to another (Ramkumar et al., 2019). However, Yamuna faces rise in water level and sometimes events of floods during monsoon season resulting in loss of life health (Singh et al., 2024). The feasibility of interlinking of rivers should be considered only after thoroughly understanding the parameters related to the monsoon season.

4.2 Nature based solutions

Many parks namely Yamuna Biodiversity, Asita East and West, Bansera, Mayur Nature etc. are developed at the banks of Yamuna. The grasses are planted to enhance the beauty of landscape. The grasses are short lived and overflow of debris or decaying matter during rainfall in Yamuna River contribute significantly the organic matter. BOD of Yamuna exceeds the BIS permissible limits (< 3 mg/L) due to excessive presence of organic waste from urban and industrial source. Yamuna River would fall in hypoxic condition in coming future and needs urgent attention (Kumar et al., 2019). Further rise in organic matter due to grasses waste from parks would depletes dissolved oxygen from the river water. However, the plantation of trees along the bank of Yamuna would enables the infiltration capacity and improve the hydrologic conditions.

4.3 Floodplain protection

The development of Mega-projects and urban settlements on the floodplain of Yamuna should be avoided to protect its ambiance and to mitigate the impacts of extreme events of climate (Follmann, 2015; Anand et al., 2024). The settlements constructed on the Yamuna floodplain are prone to flood risks (Sachdeva and Kumar, 2025). The unplanned urbanization reduces land's infiltration capacity leading to more runoff and a heightened likelihood of flooding. The surface water bodies and tributaries such as Sahibi and Hindon are on the verge of extinction due to rapid urbanization in the Yamuna basin of Delhi. The urban settlements are disturbing the hydrological cycle of Yamuna basin and adversely impacting the quantity and quality of water (Kumar et al., 2020).

4.4 Monitoring and wastewater treatment technologies

The implementation of technologies targeting organic waste pollution (BOD, COD, DO, nutrient level and fecal coliform) would facilitate the rejuvenation of Yamuna (Lokhande and Tare, 2021). Cyanobacterial species namely *Nostoc* and *Oscillatoria* are more effective in removing BOD and COD from wastewater than treatment plants (Kumar et al., 2024a). Similarly, algal species like *Monoraphidium* sp. and *Chlorococcum* sp. are also efficient in removing COD and ammonia respectively from water (Kumar and Sahoo, 2024). Algal species such as *Scenedesmus sp.*, *Klebsormidium sp.* and *Oocystis sp.* are found efficient in removing the pollutants such as phosphate, nitrate, sulfate, silicon and chloride from Yamuna water (Kumar et al., 2024b; Kumar et al., 2023). Phytoremediation using *Canna indica* has efficiency to TDS and EC from the contaminated water (Sharma et al., 2025). The native plants such as *Hygroryza aristata*, *M. quadrifolia*, *E. alba* and *S. platensis* are good options for treatment of metals (Cd, Cu, Hg, Pb and Cr). It is observed that *H. verticillata* is found suitable for phytostabilization of Pb and Cr from contaminated sites (Ahmad et al., 2011).

The ecological diversity, areal coverage and water quantity of a river is much higher than drain and controlled system. Thus, the implementation of sustainable remediation technology for the river is a challenging task. The impacts of polluted rivers on community (e.g. displacement, health risk, livelihood etc.) and environment (e.g. contamination, degradation of natural resources etc.) are diverse in nature depending on the climatic and geological conditions. The adverse impacts of a polluted river are of broader scale compared to localized drain or controlled system. Thus, the proper planning considering current and future impacts before the implementation of treatment technology improves its feasibility and efficiency. The ecological diversity and contribution of different environmental factors influencing the water quality in case of drains and controlled systems are less complex and easy to identify.

4.5 Public awareness

Despite the water quality parameters exceeding the permissible limits in Yamuna, the community awareness of chemical pollution remains low. The study carried out to assess community perception about the water quality management of river suggest that 94% of people's perception is only based on taste, color and odor for water quality due to lack of scientific knowledge (Tarannum et al., 2018). The awareness among the community about the cleanliness of river is important to prevent the contamination from local community.

5. CONCLUSIONS

The physio-chemical water quality parameters of Yamuna exceed the permissible limits set by BIS and WHO suggesting the excessive pollution level. The river is considered as ecological dead river due to loss of aquatic life and its natural ambiance. The extent of the impacted zone is currently limited; however, the affected coverage may rise significantly under the influence of climate change. The successful implementation of remediation technologies would not only rejuvenate the river, but it will evade the negative impacts caused by climate change.

Following recommendations for the revival of the Yamuna are proposed based on an understanding of pollution sources and anthropogenic drivers. The proposed interlinking of the Sutlej and Yamuna rivers will not only rejuvenate the environmental flow of the river but also help dilute the pollutants. The implementation of bioremediation-based technologies could be cost effective as many microbial species present within the Yamuna and the abundance of solid substrate supports the growth of microbes. The installation of mechanical systems to induce turbulence in Yamuna is recommended to improve dissolved oxygen levels. Recently, many parks are being developed on the banks of river and influx of decayed litter or grasses are contributing to organic matter. The encroachment of floodplain for development of mega projects should be avoided to control the erosion. Raising awareness within the community about the severity of pollution and its adverse effects should be promoted to encourage pollution control at the individual level.

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