DOI: https://doi.org/10.59983/s2023010109
AgroEnvironmental Sustainability, 2023, 1(1), 67-75

REVIEW

Effect of Barrages and Anthropogenic Activities on Ecological Integrity of the Ganga River: A Review on Current Issues and Restoration Efforts

Dinesh Kumar [1,*], Awadhesh Kumar [1], D. S. Malik [2], Rajesh Sharma [1] and Varsha Gupta [3]

[1] Faculty of Science, Veer Bahadur Singh Purvanchal University, Jaunpur 222003, India
[2] Department of Zoology and Environmental Science, Gurukula Kangri (Deemed to be University), Haridwar 249404, India
[3] Department of Life Sciences, Chhatrapati Shahu Ji Maharaj University, Kanpur 208024, India
[*] Author responsible for correspondence; Email: dinesh.kanaujia@yahoo.com.

ARTICLE HISTORY
Received: 19 May 2023
Revised: 11 June 2023
Accepted: 21 June 2023
Published: 26 June 2023

KEYWORDS
Anthropocene
dams and barrages
ecological integrity
environmental restoration
Ganga River

EDITOR
Pankaj Kumar

eISSN 2583-942X

Abstract

The Ganga River, a lifeline for millions of people in the Indian subcontinent, is facing significant environmental challenges due to the construction of barrages and various anthropogenic activities along its course. This review paper examines the effects of barrages and human interventions on the ecological integrity of the Ganga and explores current issues surrounding its deteriorating ecosystem. Furthermore, it discusses the restoration efforts undertaken to mitigate the ecological impacts and restore the river's health. The construction of dams and barrages can aggravate the situation in the context of the Ganga, which is already suffering from the discharge of industrial and agricultural wastes. The construction of various dams, barrages, and hydroelectric projects is affecting the water flow of the Ganga. These affect the water flow, resulting in the accumulation of solid waste on the river bed. Barrages not only affect the water flow but also restrict the migration of aquatic fauna. This affects the hydrological balance of the Ganga as well as the survival and existence of several fish species. This review provides a comprehensive analysis of the effects of barrages and anthropogenic activities on Ganga's ecological integrity, sheds light on the current issues plaguing the river, and highlights the ongoing restoration efforts. By understanding the complex interplay between human activities and ecosystem dynamics, stakeholders can work towards safeguarding Ganga's ecological health and ensuring its sustainable future.

Citation: Kumar, D., Kumar, A., Malik, D. S., Sharma, R., & Gupta, V. (2023). Effect of Barrages and Anthropogenic Activities on Ecological Integrity of the Ganga River: A Review on Current Issues and Restoration Efforts. *AgroEnvironmental Sustainability*, 1(1), 67-75. https://doi.org/10.59983/s2023010109

Statement of Sustainability: A critical examination of the challenges facing one of the most important river systems in the Indian subcontinent, the study on the impact of barrages and anthropogenic activities on the ecological integrity of the Ganga River. The findings underscore the urgent need for sustainable practices to restore and maintain the ecological health of the river. The study contributes to the broader goal of preserving the ecological integrity of the Ganga for future generations by promoting sustainable management practices, raising environmental awareness, and encouraging responsible decision-making.

1. Introduction

Ganga has a well-developed ecosystem with rich aquatic biodiversity. The Ganga River covers a large catchment area of a fertile basin of about 1,000,000 km^2 with a long distance of 2,525 km from Gangotri to the Bay of Bengal. With an average population density of about 1,000 per km^2, it supports the highest human population density in the world. The river water is used for irrigation, aquaculture, and domestic purposes and its basin is used for agricultural activities. These activities are essential for meeting the nutritional requirements and improving the economic status of millions of households. The entire course of the Ganga River from Gangotri to the Bay of Bengal is divided into three major sections, i.e., the upper section from Gangotri to Haridwar, the middle section from Haridwar to Varanasi and the lower section from Varanasi to the Bay of Bengal (Tare et al., 2003; Vass et al., 2010). The Ganga flows for about 250 km through the narrow Himalayan mountainous region up to Rishikesh and enters the Gangetic plain at Haridwar district, Uttarakhand. Here, the Bhimgoda Barrage diverts the river water into the Upper Ganga Canal for hydroelectric power generation and irrigation. The river covers about 60 km to reach Balawali from where it turns southeast to enter Bijnor district of Uttar Pradesh. At Bijnor, the Madhya Ganga barrage has been constructed which diverts river water into the Madhya Ganga canal for irrigation. River passes through Garhmukteshwar to reach Narora, district Bulandshahar, where river water is diverted into Lower Ganga Canal by Narora barrage and water is supplied to Narora Atomic Power Station, industries, and urban areas. The river covers a long distance and passes through Farrukhabad and Kannauj districts to reach Kanpur. In Kanpur, the Luvkush barrage has been constructed at Nawab Ganj, Kanpur. All these barrages affect the flow of water in the river, depositing solid waste and sandy clay on the river bed. The Ganga is joined by its major tributaries like Ramganga and Kali in the Kannauj district and also minor tributaries like Ishan, Noon, and Pandu in the Kanpur district. Though such tributary rivers provide a slight improvement in water flow, their pollution levels remain high and add toxic wastes to Ganga (Gurjar and Tare, 2019; Gurjar et al., 2022). Several cities like Haridwar, Bijnor, Garhmukteswar, Anupshar (Narora), Farrukhabad, Kannauj, and Kanpur discharge industrial and municipal wastes directly into the Ganga. More than 3,811.2 MLD (million liters per day) of industrial and municipal wastes are discharged from these cities and about 853.3 MLD of toxic wastes are discharged from Ramganga and Kali River (CPCB, 2016; Pathak et al., 2018). According to literature reports, only 50% of the effluents from the main sewer of the cities are treated by sewage treatment plants (STP), and the rest of the effluents coming from non-point sources (drains) are discharged directly into the river basin (CPCB, 2021; CPCB, 2022). This is the main reason for the continuous failure of tremendous efforts to clean Ganga and its tributaries by various government schemes. Climate change also affects a riverine ecosystem in terms of changes in the overall hydrology and dynamics of the river, such as water quality, eutrophication, acidification, and water resource management (Stagl and Hattermann, 2016; Jain and Singh, 2020).

Untreated industrial wastewater, agricultural spills, and anthropogenic materials contain various health-hazardous heavy metals such as Cr, Cu, Cd, Pb, Hg, As, salts, and pesticides (Gupta et al., 2017; Maurya and Malik, 2019). These heavy metals accumulate in the water column, sediments, and tissues of aquatic organisms, and their high concentration is gradually transferred into the ecosystem through the food chain causing metal toxicity in organisms (Malik and Maurya, 2014; Kumar et al., 2017, Kumar et al., 2018, Kumar et al., 2020, Gupta et al., 2022). Therefore, the entry of these metals into the river ecosystem causes continuous loss of natural habitat and aquatic biodiversity.

2. Barrages and their Impacts on Ganga River Flow

The middle stretch of the Ganga River is facing challenges in maintaining its ecological integrity due to the heavy deposition of solid wastes and sandy clays due to the reduction in water flow by four Ganga barrages located on the main stem of the Ganga River from Haridwar to Kanpur. The barrages not only affect the water flow, it also degrades the water quality and restricts the migration of aquatic life thus adversely affecting the ecosystem of the Ganga River. The water velocity of the Ganga gradually decreases from Haridwar to Kanpur. A study has reported that the water velocity of the Ganga River is about 1.00–1.90 m/s in the Haridwar region after the Bhimgoda barrage and 0.21–0.51 m/s at Sarsaiya Ghat and Siddha Nath Ghat after Luv- Kush barrage, Kanpur (Kumar et al., 2018; Kumar et al., 2020). The water velocity is affected during the non-monsoon season due to various Ganga barrages located in the middle stretch, *viz*. Haridwar, Bijnaur, Naraura, and Kanpur (Figure 1 and Table 1).

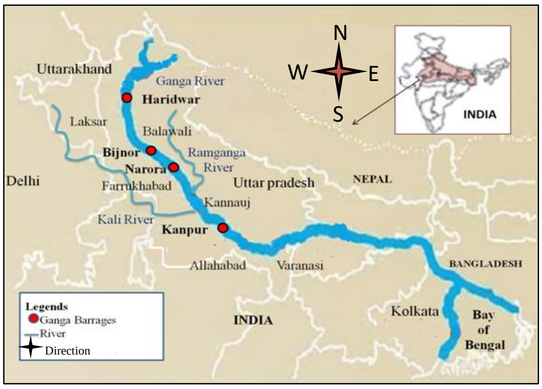

Figure 1. Location of Ganga barrages from Haridwar to Kanpur.

The basin of Ganga is more fertile and the sediment contains 0–12% of clay and the rest of 79–100% of sand (Vass et al., 2010). The river sediment helps in creating hydro-geo-morphological complexities in the river system and plays an important role in maintaining the ecological productivity and biodiversity of the river. The sediment of the middle stretch from Haridwar to Kanpur is sandier. Therefore, the middle stretch faces textural deformations and sand drift at the confluence point of the Ramganga and Kali rivers in the Kannauj district, thereby shifting the confluence point by about 1–2 km (Roy et al., 2007) (Figures 2a, b). As the river proceeds towards Kanpur where water flow is affected by the Ganga barrage thereby, continuous deposition of solid waste on the bottom affects water flow and fills up the depth of the river (Figure 2c). The deposition of solid waste in the river sediment reduces aquatic productivity and increases the possibility of flooding during the monsoon season (Roy et al., 2014).

Table 1. GPS location of Barrages along the Ganga River from Haridwar to Kanpur.

Barrages	Latitude and Longitude	Districts/ States
Bhimgoda Barrage	29°57′23″ N 78°10′49″ E	Haridwar/Uttarakhand
Madhya Ganga Barrage	29°22'26'' N 78°02'27'' E	Bijnor/Uttar Pradesh
Narora Barrage	28°11'30.12" N 78°23'58.92" E	Bulandshahar/Uttar Pradesh
Luvkush Barrage	26°30'28.08" N 80°19'0.84" E	Kanpur/Uttar Pradesh

3. Anthropogenic Activities and Their Impacts on the Ganga River

The middle stretch of Ganga from Haridwar to Kanpur receives municipal and industrial wastes from Haridwar, Bijnor, Gharhmukteswar, Anupshahr, Farrukhabad, Kannauj, and Kanpur cities and also receives toxic wastes from Ramganga and Kali rivers. This stretch is home to about 500 industries, including pulp and paper, sugar, textile, and leather, etc., including about 400 tanneries in Kanpur city, which discharge about 1000 MLD of wastewater into the main stem of Ganga either directly or through drains (Chaudhary and Walker 2019; Gupta et al., 2022). In terms of the number of industrial units, the tannery sector dominates, while in terms of wastewater generation, the pulp and paper sector dominates followed by the chemical and sugar sector. Deposition of religious wastes and anthropogenic activities at Ghatiya Ghat, Brahmavart Ghat, and Sarsaiya Ghat are greatly affecting the water quality (Figures 2d,e,f). At present, the river water is highly contaminated with toxic chemicals and microbes (Kumar et al., 2018).

Figure 2. (a) Sand bedding at the confluence point of Ganga-Ramganga near Kusumkhor, Kannauj; (b) Deposition of sand at the confluence point of Ganga- Kali River at Menhadi Ghat, Kannauj; (c) Deposition of solid waste and sand at Jajmau, Wazidpur, Kanpur; (d) Dumping of religious wastes at Ghatiya Ghat, Farrukhabad; (e) Dumping of religious wastes at Brahmavart Ghat (Bithoor), Kanpur; (f) Dumping of religious waste at Sarsaiya Ghat, Kanpur.

The Ganga and its tributaries are heavily polluted with municipal and industrial wastes containing various salts (Gupta et al., 2009; Gupta et al., 2017; Khan et al., 2017; Singh et al., 2017; Maurya and Malik, 2019, Kumar et al., 2020). Many studies have reported that the tributaries of the Ganga are heavily polluted with various heavy metals and are being discharged into the main channel of the Ganga (Tables 2–3). These metals enter the river and accumulate in the water column, sediment, or aquatic fauna. A three-year program (2011–2013) initiated by the government to study trace and toxic metals in Indian rivers shows that the levels of As and Hg in the rivers are below the prescribed limit, while the concentration of Pb is far above the prescribed limit of the Indian standard (CWC, 2014).

Table 2. Reported heavy metal concentrations in water and sediment of the Ganga River and its tributaries.

Rivers	**Samples**	**Heavy Metal Concentration**				**References**
		Cr	Cd	Cu	Pb	
Ganga	Water (µgL^{-1})	0.00 - 108.7	NA	57.15 - 99.10	10.1 - 48.92	CWC (2014)
Ramganga	Sediment (µgg^{-1})	69.9	1.7	29.8	26.7	Pandey and Singh (2017)
	Water (µgL^{-1})	NA	0.3 - 0.12.9	NA	0.2.4 - 0.9.6	Khan et al. (2017)
	Sediment (µgKg^{-1})	NA	224-833	NA	133 - 895	
Kali	Water (µgL^{-1})	87	24	NA	0.001 - 0.34	Malik and Maurya (2014)
	Sediment (µgKg^{-1})	350 - 20110	110-3380	NA	14220 - 81530	
Yamuna	Water (µgL^{-1})	3.245 - 13.58	0.018 - 0.044	0.871 - 3.087	0.067 - 0.326	Kaur and Mehra (2012)
	Sediment (µgKg^{-1})	163000 - 817000	500 - 11800	40000 - 829000	22000 - 253000	Singh (2001)
Gomati	Water (µgL^{-1})	NA	16 - 68	29000 - 62000	31000 - 65000	Neha et al. (2017)
	Sediment (µgKg^{-1})	NA	1907 - 8390	89670 - 95350	35823 - 90920	
Ghaghara	Water (µgL^{-1})	00-10	57	47	29	Singh et al. (2016)
	Sediment (µgKg^{-1})	61250 - 87680	210 - 280	2760 - 1174.	10710 - 14260	Singh et al. (2017)

BDL: Below detection limit, NA: Not applicable

Table 3. Heavy metal concentrations at different sites of the Ganga River from Haridwar to Kanpur belt.

Sites	**Samples**	**Heavy Metal Concentration**				**References**
		Cr	**Cd**	**Cu**	**Pb**	
Haridwar	Water	0.016	BDL	BDL	0.05	Kumar et al. (2020)
	Sediment	3.75	0.25	17	1.5	
Garhmukteshwar	Water	NA	NA	0.08326	0.1024	CWC (2014)
	Water	0.1983	NA	0.10957	0.02537	
Kachlabridge	Water	0.15504	NA	0.10799	0.03378	CWC (2018)
Ghatiya Ghat	Water	0.116	0.005	0.158	0.4	Kumar et al. (2020)
Fatehgarh (Farrukhabad)	Sediment	24.5	1.35	21.2	55.5	
	Water	0.17524	NA	NA	0.01461	CWC (2018)
Singirampur	Water	0.02	BDL	0.075	0.075	Kumar et al. (2020)
(Farrukhabad)	Sediment	4.25	0.35	11	12.5	
Kusumkhor	Water	0.165	0.002	0.0205	0.45	
(Kannauj)	Sediment	21.05	1	26	50	
Mehandi Ghat	Water	0.0705	0.0025	0.105	0.555	
(Kannauj)	Sediment	20.3	4.15	12.4	58	
Nanamau	Water	0.0205	BDL	0.026	0.055	
(Bilhaur)	Sediment	3.6	BDL	3.3	7.5	
Brahmavart Ghat (Bithoor)	Water	0.0305	0.005	0.055	0.06	
	Sediment	11.25	0.1	11.55	6.5	
Kanpur	Water	0.36691	NA	0.0871	0.01503	CWC (2014)
	Water	NA	NA	NA	0.02516	CWC (2018)
Sarsaiya Ghat	Water	0.135	0.0025	0.0275	0.075	Kumar et al. (2020)
(Civil line, Kanpur)	Sediment	41.1	6.75	31.05	12.5	
Siddhanath Ghat	Water	0.261	0.002	0.062	0.065	
(Jajmau)	Sediment	83	9.7	35.6	12.5	

BDL: Below detection limit, NA: Not Applicable

Indiscriminate use of organochlorine pesticides like dichloro-diphenyl-trichloroethane (DDT), Aldrin, Dieldrin, benzene hexachloride (BHC), Hexachlorocyclohexane (HCH), etc. in both agriculture and health sectors. The Ganga basin has led to bio-concentration and bio-magnification of these toxic chemicals in fish and other endangered animals like Ganges dolphins (Malik and Maurya, 2014). The agricultural sector discharges about 134.8 million tons of waste into the river basin. Similarly, 2,573 tons of pesticides, mainly DDT and BHC-Y, are applied annually for pest control. The Ganges basin receives about 200 tons of gross biological oxygen demand (BOD) pollution per day. However, it is still relatively localized and concentrated in urban centers such as Haridwar, Kanpur, Varanasi, and Diamond Harbour near Kolkata.

The well-developed ecosystem of Ganga has greater aquatic biodiversity. The greater biodiversity of an aquatic ecosystem indicates a healthy environment (Lu et al., 2015). About 2000 species live in the Ganga River including fish and fisheries, zooplankton, phytoplankton, and some important species like Gangetic turtles (*Nilssonia gangetica*), dolphins (*Platanista gangetica gangetica*), crocodiles (*Gavialis gangeticus*), etc. (ZSI, 1991). The dams restrict the migration of this aquatic flora and fauna. The use of various fertilizers and pesticides such as DDT, Linuron, Benomyl, Atrazine, etc. in the river basin affects the health of eggs and juveniles. Over-exploitation of commercially important aquatic species and depletion of their natural habitats due to high levels of pollution in the Ganga has led to their decline. Several species like Dolphin (*Platanista gangetica gangetica*), Crocodile (*Gavialis gangeticus*), Ganges turtle (*Batagur kachuga*), and some fish species like Magur (*Clarias batracus*), Golden mahseer (*Tor putitora*), Hilsa (*Tenualosa ilisha*), Ganges shark (*Glyphis gangeticus*) and Ganges stingray (*Himantura fluviatilis*), etc. have been listed in the Red Data Book under the categories of least concern and critically endangered (NMCG, 2011).

4. Major Threats to the Ecology of the Ganga River

The major threats disturbing the ecological integrity of the river are the discharge of untreated municipal and industrial wastes, dumping of solid wastes, annual floods, and various anthropogenic and religious activities along the Ganga River which destroy the river water quality, natural habitat, and aquatic biodiversity. Habitat modification in the Ganga River is mainly caused by damming, water diversion for irrigation, deforestation, and mining. Such physical modification in river habitats may lead to species extinction. Constructions of dams on rivers restrict the aquatic species migration and displace the population from their normal spawning grounds and separate them into two smaller groups. Deforestation leads to the degradation of catchment areas due to soil erosion which causes sedimentation and siltation in the river body. It is not only affecting the breeding ground of aquatic organisms but also causes the gill closing of small fishes. Aquatic habitat was degraded at Kanpur by direct entry of municipal wastes at Sarsaiya ghat and tannery effluent at Wazidpur, Jajmau, Kanpur that resulted in the death of fishes and other aquatic fauna in the Ganga River (Figure 3a,b).

Figure 3. (a) habitat degradation due to direct entry of tannery effluent at Wazidpur, Kanpur; (b) fish death at Sarsaiya Ghat, Kanpur due to poor water quality.

4. Strategies for Ganga River Conservation

The Ganga Conservation Strategy can be achieved through the following measures which will prevent direct discharge of liquid and solid wastes from all point and non-point sources.

4.1. For Liquid Waste

The direct discharge of untreated sewage and industrial effluents into the river basin must be prevented by using a high-capacity sewage treatment plant (STP) that removes chemical pollutants and solid waste from sewage and industrial effluents.

4.2. For Solid Waste

Technological approaches are necessary to remove submerged materials like sand beds and solid waste garbage from the river surface, which improves the river flow. At present, many machines like earth-movers, sand extractors, and marine dredgers are in use which can clean the surface pollution of rivers and can collect tons of garbage at a time. Sluice gates should be opened to release the right amount of water to improve the water flow and prevent the deposition of garbage on the river surface. It is necessary to strictly enforce the laws for the benefit and welfare of the river. Along with this, awareness should be created among the common people through social media, the internet, and other sources.

4.3. Traditional Approaches

Near urban areas, a cemented canal should be constructed on both sides of the river from the beginning of the cities to the end, so that the wastewater from the non-point sources could be prevented from directly entering the river (Figure 4). Several large cemented tanks should be constructed inside the canal at a distance of about 2-3 km so that the solid waste materials would settle down in the tank. Then the solid wastes will be removed with the help of machines and converted into organic fertilizer for agriculture. At the end of the urban areas, a high-capacity STP should be set up on a cemented canal which will purify the chemicals from the water and this water should either be released into the river or should be used for field irrigation and industries. In our earlier efforts for maintaining water quality and conserving the river basin, we focused only on technological approaches and neglected the traditional approaches. As a result, none of them were effective in achieving the desired goals of improving the water quality and flow of Ganga water. Several projects have been initiated by the central government of India to clean the Ganga and its tributaries. The Ministry of Government of India sanctioned 2000 crore rupees for the 'Namami Gange' mission during the annual budget session 2016-2017, but this mission also suffered from many drawbacks. This mission was successful only in ghat development but not in improving water quality and river flow. The Government of India has established the National Ganga River Basin Authority (NGRBA) to maintain the Ganga River basin, water quality, and ecological flows.

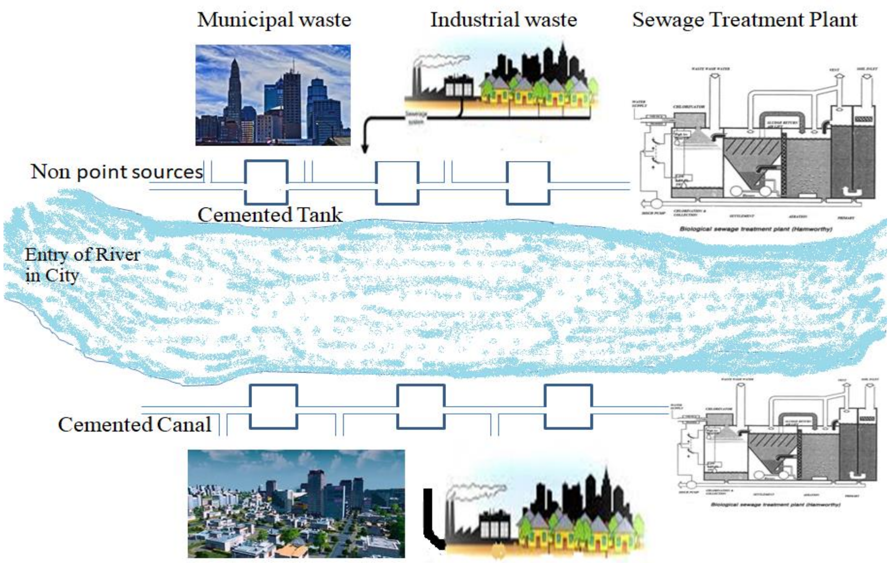

Figure 4. Prevent entry of point and non-point pollution sources in Ganga River by wall boundaries of cemented canal and tank.

5. Conclusion

This review summarizes the present scenario of the Ganga River concerning the construction of various barrages and anthropogenic activities in the middle stretch of the Ganga River. Literature reports and field surveys suggest that the middle stretch of the Ganga River from Farrukhabad to Kanpur is heavily polluted with municipal and industrial solid wastes, which are destroying the ecological integrity of the Ganga River. The river flow is mainly affected by the barrages located at Haridwar, Bijnor, Narora, and Kanpur city resulting in deposition of solid waste and restricting the migration of aquatic fauna. Therefore, it is necessary to open the barrage channels from time to time and release the water so that the river maintains its ecological integrity and self-purification. The conservation strategies of Ganga River will help to prevent solid waste dumping and awareness programs that will help to reduce the use of chemical fertilizers and pesticides along the river basin are important. Scientific research for regular monitoring and strict law enforcement is necessary to achieve sustainable ways for improving the integrity of the Ganga River. Both technological and traditional approaches should be incorporated to improve the water quality and natural habitat of the river. The Government of India has launched various programs for cleaning the Ganga River but these programs have only succeeded in developing the ghats. The main objectives of the programs to clean the river basin, improve water quality, protect water flow by removing solid waste, and prevent direct discharge of untreated industrial effluents into the river could not be achieved. This is possible only by creating awareness among the common people and also protecting other polluted tributaries through these projects.

Author Contributions: Conceptualization, Dinesh Kumar; Data curation: Dinesh Kumar and Awadhesh Kumar; Investigation, Dinesh Kumar; Methodology, Dinesh Kumar; Resources; Software, Supervision, D.S. Malik and Varsha Gupta; Validation, D.S. Malik and Varsha Gupta; Visualization, Rajesh Sharma; Writing-original draft, Dinesh Kumar; Writing- review & editing, Rajesh Sharma. All authors have read and agreed to the published version of the manuscript.

Funding: University Grants Commission (UGC), New Delhi, India provided financial assistance to Dinesh Kumar.

Acknowledgment: Dinesh Kumar is immensely grateful to the University Grants Commission for providing financial assistance in the form of a fellowship. The authors express their heartfelt gratitude to the government authorities involved in pollution control and biodiversity conservation efforts for the Ganga River, who have documented their work in the form of scientific publications.

Conflicts of Interest: The authors declare no conflict of interest.

Institutional/Ethical Approval: Not applicable.

Data/Supplementary Information Availability: Not applicable.

References

Chaudhary, M., & Walker, T. R. (2019). Ganga River pollution: Causes and failed management plans (correspondence on Dwivedi (2018). Ganga water pollution: a potential health threat to inhabitants of Ganga basin). *Environment International*, 117, 327–338. https://doi.org/10.1016/j.envint.2019.02.033

CPCB (2016). ENVIS Ganga Bulletin. Central Pollution Control Board 'Parivesh Bhawan', East Arjun Nagar, Shahdara, Delhi, India. Available at: https://cpcb.nic.in/openpdffile.php?id=TGF0ZXN0RmlsZS9MYXRlc3RfMTIzX1NVTU1BUlIfQk9PS19GUy5wZGY (accessed on 5 May 2023).

CPCB (2021). Annual report. Central Pollution Control Board, River Development and Ganga Rejuvenation, New Delhi, India. Available at: https://shorturl.at/emxY3 (accessed on 5 May 2023).

CPCB (2022). National Water Quality Monitoring Network. Central Pollution Control Board, Ministry of Environment Forest and Climate Change (MoEFCC), New Delhi, India. Available at: https://cpcb.nic.in/wqm/nwmp_monitoring_network.pdf (accessed on 5 May 2023).

CWC (2014). Status of trace and toxic metals in Indian River. Government of India Ministry of water resources central water commission, pp. 1-185. Available at: https://nwm.gov.in/sites/default/files/waterwiki/5.pdf (accessed on 5 May 2023).

CWC (2018). Status of trace and toxic metals in Indian River. Government of India Ministry of water resources central water commission, pp. 1-225. Available at: http://www.indiaenvironmentportal.org.in (accessed on 5 May 2023).

Delpla, I., Jung, A. V., Baures, E., Clement, M., & Thomas, O. (2009). Impacts of climate change on surface water quality in relation to drinking water production. *Environment International*, 35(8), 1225-1233. https://doi.org/10.1016/j.envint.2009.07.001

Feuchtmayr, H., Moran, R., Hatton, K., Connor, L., Heyes, T., Moss, B., & Atkinson, D. (2009). Global warming and eutrophication: effects on water chemistry and autotrophic communities in experimental hypertrophic shallow lake mesocosms. *Journal of Applied Ecology*, 46(3), 713-723. https://doi.org/10.1111/j.1365-2664.2009.01644.x

Gupta, A., Rai, D. K., Pandey, R. S., & Sharma, B. (2009). Analysis of some heavy metals in the riverine water, sediments and fish from river Ganges at Allahabad. *Environmental monitoring and assessment*, 157, 449-458. https://doi.org/10.1007/s10661-008-0547-4

Gupta, V., Kumar, D., Dwivedi, A., Vishwakarma, U., Malik, D. S., Paroha, S., & Gupta, N. (2022). Heavy metal contamination in river water, sediment, groundwater and human blood, from Kanpur, Uttar Pradesh, India. *Environmental Geochemistry and Health*, 45, 1807-1818. https://doi.org/10.1007/s10653-022-01290-0

Gurjar, S. K., & Tare, V. (2019). Spatial-temporal assessment of water quality and assimilative capacity of river Ramganga, a tributary of Ganga using multivariate analysis and QUEL2K. *Journal of Cleaner Production*, 222, 550-564. https://doi.org/10.1016/j.jclepro.2019.03.064

Gurjar, S. K., Shrivastava, S., Suryavanshi, S., & Tare, V. (2022). Assessment of the natural flow regime and its variability in a tributary of Ganga River: Impact of land use and land cover change. *Environmental Development*, 44, 100756. https://doi.org/10.1016/j.envdev.2022.100756

Hellmann, J. J., Byers, J. E., Bierwagen, B. G., & Dukes, J. S. (2008). Five potential consequences of climate change for invasive species. *Conservation Biology*, 22(3), 534-543. https://doi.org/10.1111/j.1523-1739.2008.00951.x

Jain, C. K., & Singh, S. (2020). Impact of climate change on the hydrological dynamics of Ganga River, India. *Journal of Water and Climate Change*, 11(1), 274-290. https://doi.org/10.2166/wcc.2018.029

Kaur S., & Mehra P. (2012) Assessment of heavy metals in summer and winter season in river Yamuna segment flowing through Delhi, India. *Journal of Environment and Ecology,* 3, 149-165. https://doi.org/10.5296/jee.v3i1.2675

Khan, M. Y. A., Gani, K. M., & Chakrapani, G. J. (2017). Spatial and temporal variations of physicochemical and heavy metal pollution in Ramganga River-a tributary of River Ganges, India. *Environmental Earth Sciences*, 76, 1-13. https://doi.org/10.1007/s12665-017-6547-3

Kumar, D., Malik, D. S., & Gupta, V. (2017) Fish metallothionien gene expression: A good bio-indicator for assessment of heavy metal pollution in aquatic ecosystem. *International Research Journal of Environmental Sciences,* 6, 14-18.

Kumar, D., Malik, D. S., & Gupta, V. (2018). Seasonal assessment of surface water quality in the middle stretch of Ganga River for suitability of fish and human health. *Journal of Experimental Zoology India*, 21(2), 667-677.

Kumar, D., Malik, D. S., Kumar, N., Gupta, N., & Gupta, V. (2020). Spatial changes in water and heavy metal contamination in water and sediment of Ganga River in the river belt Haridwar to Kanpur. *Environmental Geochemistry and Health*, 42(7),2059-2079. https://doi.org/10.1007/s10653-019-00471-8

Kundzewicz, Z. W., Mata, L. J., Arnell, N. W., Döll, P., Jimenez, B., Miller, K., & Shiklomanov, I. (2008). The implications of projected climate change for freshwater resources and their management. *Hydrological Sciences Journal*, 53(1), 3-10. https://doi.org/10.1623/hysj.53.1.3

Landis, W. G., Durda, J. L., Brooks, M. L., Chapman, P. M., Menzie, C. A., Stahl Jr, R. G., & Stauber, J. L. (2013). Ecological risk assessment in the context of global climate change. *Environmental Toxicology and Chemistry*, 32(1), 79-92. https://doi.org/10.1002/etc.2047

Lu, Y., Wang, R., Zhang, Y., Su, H., Wang, P., Jenkins, A., & Squire, G. (2015). Ecosystem health towards sustainability. *Ecosystem Health and Sustainability*, 1(1),1-15. https://doi.org/10.1890/EHS14-0013.1

Malik, D. S., & Maurya, P. K. (2014). Heavy metal concentration in water, sediment, and tissues of fish species (*Heteropneustis fossilis* and *Puntius ticto*) from Kali River, India. *Toxicological & Environmental Chemistry*, 96(8), 1195-1206. https://doi.org/10.1080/02772248.2015.1015296

Maurya, P. K., & Malik, D. S. (2019). Bioaccumulation of heavy metals in tissues of selected fish species from Ganga river, India, and risk assessment for human health. *Human and Ecological Risk Assessment: An International Journal*, 25(4), 905-923. https://doi.org/10.1080/10807039.2018.1456897

Neha, Kumar, D., Shukla, P., Kumar, S., Bauddh, K., Tiwari, J., & Kumar, N. (2017). Metal distribution in the sediments, water and naturally occurring macrophytes in the river Gomti, Lucknow, Uttar Pradesh, India. *Current Science*, 113(8), 1578-1585.

NMCG (2011). Biodiversity conservation programme, National mission for clean Ganga, Department of water resources, River Development and Ganga rejuvenation, Government of India. Available at: https://nmcg.nic.in/NamamiGanga.aspx (accessed on 10 May 2023).

Pandey, G., Madhuri, S. (2014). Heavy metals causing toxicity in animals and fishes. *Research Journal of Animal*, *Veterinary* and *Fishery Sciences*, 2, 17-23.

Pandey, J., & Singh, R. (2017). Heavy metals in sediments of Ganga River: up-and downstream urban influences. *Applied Water Science*, 7, 1669–1678. https://doi.org/10.1007/s13201-015-0334-7

Pathak, D., Whitehead, P. G., Futter, M. N., & Sinha, R. (2018). Water quality assessment and catchment-scale nutrient flux modeling in the Ramganga River Basin in north India: An application of INCA model. *Science of the Total Environment*, 631, 201-215. https://doi.org/10.1016/j.scitotenv.2018.03.022

Roy, N. G., & Sinha, R. (2007). Understanding confluence dynamics in the alluvial Ganga–Ramganga valley, India: An integrated approach using geomorphology and hydrology. *Geomorphology* 92, 182-197. https://doi.org/10.1016/j.geomorph.2006.07.039

Roy, N. G., & Sinha, R. (2014). Effective discharge for suspended sediment transport of the Ganga River and its geomorphic implication. *Geomorphology*, 227,18–30. https://doi.org/10.1016/j.geomorph.2014.04.029

Sabine, C. L., Feely, R. A., Gruber, N., Key, R. M., Lee, K., Bullister, J. L., & Rios, A. F. (2004). The oceanic sink for anthropogenic CO_2. *Science*, 305(5682), 367-371. https://doi.org/10.1126/science.1097403

Singh, H., Pandey, R., Singh, S. K. & Shukla, D.N. (2017). Assessment of heavy metal contamination in the sediment of the River Ghaghara, a major tributary of the Ganga River in Northern India. *Applied Water Science*, 7, 4133–4149. https://doi.org/10.1007/s13201-017-0572-y

Singh, H., Raghuvanshi, D., Pandey, R., Yadav, A., Tripathi, B., Kumar, P., & Shukla, D. N. (2016). Assessment of seven heavy metals in water of the river Ghaghara, a major tributary of the Ganga in Northern India. *Advances in Applied Science Research*, 7(5), 34-45.

Stagl, J. C., & Hattermann, F. F. (2016). Impacts of climate change on riverine ecosystems: alterations of ecologically relevant flow dynamics in the Danube River and its major tributaries. *Water*, 8(12), 566. https://doi.org/10.3390/w8120566

Tare, V., Yadav, A. V. S., & Bose, P. (2003). Analysis of photosynthetic activity in the most polluted stretch of Ganga River. *Water Research*, 37, 67-77. https://doi.org/10.1016/s0043-1354(01)00385-2

Varsha, G., Malik, D. S., & Dinesh, K. (2017). Risk assessment of heavy metal pollution in middle stretch of Ganga River: an introspection. *International Research Journal of Environmental Sciences*, 6(2), 62-71.

Vass, K. K., Mondal, S. K., Samanta, S., Suresh, V. R., & Katiha, P. K. (2010). The environment and fishery status of the River Ganges. *Aquatic Ecosystem Health & Management*, 13(4), 385-394. https://doi.org/10.1080/14634988.2010.530139

ZSI (1991). Faunal Resources of Ganga, Part I Calcutta: Zoological Survey of India, pp. 145.