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An evaluation of the Ganga river's carbon flow and its impact on India's nutritional and climate change

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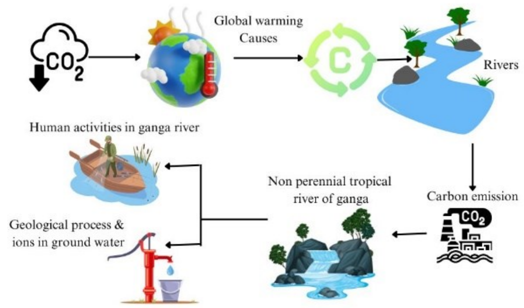
Graphical abstract



Abstract

Changes in weather patterns and the global climate are a result of global warming, which has been linked to rising carbon dioxide concentrations. Understanding the mechanisms on earth that have an impact on atmospheric carbon concentrations and their cycling—collectively referred to as the "Carbon cycle"—is essential for estimating carbon budgets. Studies on carbon budgets have largely ignored the role of inland waterways in the carbon cycle, yet rivers play an active role by absorbing/releasing carbon into the atmosphere and transferring dissolved carbon into oceans. In tropical parts of the planet, it is anticipated that water bodies, like rivers, would contribute to carbon emissions to a greater extent newline Although there are many studies on the impact of human activity on the Ganga River, there are very few that take an ecological viewpoint. In light of these facts, the following was designed as the study's hypothesis: newline The Ganga River has positive feedback as a result of human activity, which alters the environment at a level significantly greater than what has previously been projected. The current investigation was conducted in a significant tropical, non-perennial river of the Ganga. To calculate the carbon flow of the Ganga River newline, it is important to understand the interaction between geological processes and the concentration of different ions in groundwater and surface water.

Keywords: carbon emission, Ganga river, atmosphere, carbon dioxide, climate change

1. Introduction

There are major repercussions from the growing greenhouse gas emissions in South Asia and India. The Intergovernmental Panel on Climate Change (IPCC)'s third assessment report makes a rough forecast that by 2080, the area might see a temperature increase of about five degrees Celsius. The country's general economic growth as well as the country's agricultural, forestry, and coastal resources will all be significantly impacted by climate change. India must thus limit its carbon emissions if it wants to get closer to a sustainable growth path. Indian officials are now debating several approaches to limiting carbon emissions. stronger environmental policies, two of which are promoting the use of clean fuel and energy efficiency.

The degradation of the environment is sometimes viewed as an inevitable price of industrialization. On the other hand, it is seen as a barrier to emerging nations' ability to continue their path of progress. There is, however, no disputing the reality that future challenges to civilization will be caused by carbon emissions. India's carbon emissions would increase by a compound annual rate of growth (CARG) of 3.1% from 212 million tonnes in 1995 to 738 million tonnes in 2035. Carbon emissions may have a severe impact on India. Climate model results show that after doubling the concentration of carbon dioxide from that of the pre-industrial revolution, the country's average temperature will shift by 2.3 to 4.8 degrees Celsius. Let's discuss some of the reviews related to the current topic.

Rivers were only taken into consideration when calculating the budgets for the transportation of terrestrial inorganic and organic carbon to the seas. Although the weathering of rocks and terrestrial biological components is what causes the transport of carbon to oceans, rivers also operate as an atmospheric sink by consuming atmospheric carbon dioxide. The rivers also serve as a source of carbon dioxide to the atmosphere, with soil CO_2, mineral saturation, and biological inputs being possible net sources of carbon to rivers. By absorbing and emitting CO_2 into and into the atmosphere, as well as acting as conduits for terrestrial carbon to the seas, rivers become an active component in carbon budgets. As a result, rivers play a crucial role in the global carbon cycle, and quantifying their carbon budgets is crucial for determining the fluxes in terrestrial ecosystems. These, when combined with carbon fluxes on both a regional and global scale, would aid in forecasting climate feedback.

The characteristics of the weathering products and the biogeochemical process within the watershed region are represented by the riverine carbon fluxes. The two main kinds of carbon that rivers transfer are organic and inorganic. One of the main channels for rivers to exchange carbon with the atmosphere is through gaseous carbon outflow. More frequently in tropical regions, CO_2 is released into the atmosphere through rivers due to CO_2 supersaturation in certain rivers. The inorganic riverine fluxes are made up of a mixture of material that has developed from the basin's geology, anthropogenic, biological, and atmospheric sources. Riverine carbon fluxes make up a small portion of the global carbon cycle, yet they are extremely vulnerable to local and global climatic change.

India is reportedly one of the top CO_2 emitters among the other countries, according to estimates of the carbon budgets for each nation at the global level. It's fairly well-known how much carbon is emitted from terrestrial ecosystems. Similar studies have been made to assess the contribution of CO_2 from oceans, with reasonable success. The impact of riverine catchments and inland water bodies on the carbon cycle, however, has not been adequately discussed. In tropical regions of the world, rivers and other water bodies are anticipated to contribute more significantly to carbon emissions. The maximum carbon production is found in the tropical regions (30°N - 30°S), which account for 42.7% of all land. Therefore, research on how tropical rivers affect studies of the carbon cycle is crucial and is probably going to differ greatly from rivers in non-tropical areas. In tropical areas like India, there is a need to quantify the impact of rivers on the carbon cycle. The majority of rivers that drain the southern region of India are transient and reliant on the monsoon season. The patterns of carbon flux in terrestrial ecosystems are also altered by the monsoonal pattern. Additionally, the rivers in peninsular India flow through crystalline rocks, where rock weathering would significantly affect the carbon cycle. In Indian rivers like the Brahmaputra, Narmada, Godavari, and Cauvery rivers, studies on carbon consumption have been conducted. The spatiotemporal fluctuation in DIC transport and the escape of CO2 to the atmosphere, however, have not been taken into consideration in these investigations. Additionally, no comprehensive studies have been done to comprehend how the river basin functions through time as a source or sink of carbon. Therefore, the current study was conducted to fill in the gaps in the literature regarding the evaluation of a tropical non-perennial river basin's contribution to the carbon cycle and potential connections to climate change.

(Khan *et al.* 2020) To develop an effective climate strategy to address environmental issues, an accurate carbon emissions measurement is crucial. (Saidi, *et al.* 2020) The main goal of this article is to use both completely altered ordinary least square (FMOLS) and vector error correction model (VECM) estimation techniques to show the efficacy of clean energy sources in promoting economic growth and mitigating carbon emissions in the case of 15 significant sustainable energy-consuming countries. *(Erdoğan et al. 2020)* This study's objective is to look into how innovation has affected certain sectors of carbon emissions for 14 G20 nations between 1991 and 2017.

(Wang *et al.* 2020) By concluding an examination of the short- and long-term drivers of carbon emissions, this paper aims to address ways to stop the retaliatory rise of carbon emissions after COVID-19. (Zhang *et al.* 2020) China's growth needs to assess the carbon ETS to see if it has helped the economy and environment in the seven pilot projects. (Wang *et al.* 2022) Additionally, two mediating variables—technological innovation and economic scale—as well as a moderating variable—foreign direct investment (FDI)—are taken into account to further study the influencing processes.

Additionally, increased monsoon activity is anticipated throughout the subcontinent. Climate change will have a negative impact on industries that are susceptible to the climate, such as agriculture, forestry, coastal areas, and water resources. (Zhang *et al.* 2022) The flooding of coastal regions as a result of sea level rise would be a severe effect of climate change in India. In addition to this, the rise in cyclones brought on by massive amounts of seawater will cause massive destruction to both the economy and human lives. (Sun *et al.* 2022) The precipitation pattern will have an impact on the river basin systems and the accessibility of groundwater resources in addition to the melting glaciers in the mountain areas. As a result of climate change, a shift in evapotranspiration has also been projected.

The smoky part of carbonaceous aerosols is often known as soot or BC. Due to its distinctive graphitic micro crystal-like structure, the BC significantly absorbs electromagnetic radiation in the near UV, visible, and near IR regions. As a byproduct of all combustion processes, BC is produced. (Wang *et al.* 2022) The research into estimating black carbon emissions, particularly its rise over time in a developing nation like India, is still in its early stages. (Zhang, *et al.* 2023) built an inventory of carbonaceous aerosol emissions from fossil fuels at the world scale and computed their radiative impact. Applying it to a smaller area, like India, reveals that many assumptions are made about the lack of activity data at the micro level. Recent estimates of the BC emissions from burning biofuels have been made by (Li, *et al.* 2023). They also argued that the key to reducing climate change in the South Asian area is its control.

Unprecedented growth in human activity has had negative effects on the aquatic environment, with significant irreversible harm to the structure and functioning of the ecosystem. Despite ongoing efforts by several nations, water bodies, particularly rivers, are always coming under intense strain from numerous human-induced changes, including changing land use and demand for freshwater to meet their demands. Large amounts of pollutants are being added to the water supply through urban-industrial discharge, atmospheric deposition, and runoff containing agricultural chemicals as a result of the unchecked population growth over the past few decades, the expansion of large cities, and extensive industrialization. (Zhang, *et al.* 2022) Increases in population, water supply, sanitation, and drainage are significant effects of urbanization that have a negative impact on water resources downstream and put additional pressure on the metropolitan area's hydrology. The development of agriculture together with rising urban and industrial activity has had a negative impact on water habitats, particularly in plain regions. Poor management practices and the dumping of untreated or just partially treated home and industrial waste have caused severe environmental issues, such as pollution of the soil, sediment, and water.

The changing environmental conditions that come from the intricate interactions between terrestrial and aquatic ecosystems have a substantial impact on the quality of surface waters. Rivers are thought to be very dynamic due to repeated low or high flows, and the fluctuation changes the water quality characteristics briefly, causing an unanticipated shift in site circumstances at a particular point in time. (Wang, *et al.* 2023) Identification of the 'ecological response' of the oceanic systems to various anthropogenic perturbations is a study subject that is becoming more important in the field of aquatic pollution prevention. Understanding these reactions is one of the main issues in riverine ecology. ecological responses that support resource partitioning and ecological feedback at sediment-water and land-water interfaces generate dramatic changes. The prediction of river ecosystem responses to diverse environmental deterioration is made even more challenging by the complicated relationships between present structural and functional features. One of the primary causes of this is that, while anthropogenic activities speed up the rate of ecological deterioration, the river's ability to purify itself lessens the severity of these harmful effects. The second reason is that both the direct effects of the causative factor(s) and the indirect effects of ecosystem reactions and feedback to these degradations determine how sensitive riverine ecosystems are to them.

2. Materials and methods

2.1. Selection of sampling locations

To choose the study area sample locations, a thorough examination was done. To accurately reflect the water's natural hydrochemistry, care was made to choose places far from sewage outfalls and industrial areas. Dams, tributary confluences, and the presence of local groundwater sampling wells were all appropriately considered while choosing sample locations. Each sample site was spaced apart by preset distances of 18 to 25 kilometers along the river. The comparable groundwater samples were taken not more than 300 meters away from the river sampling sites. Using a portable GPS device from Garmin, the latitude, longitude, and elevation of each place were calculated.

2.2. Collection of water samples

The basin's monsoonal characteristics were taken into consideration for determining the precise sample window. It was decided to do sampling during these monsoons as well as during the non-monsoon time in a year since this basin experiences rainfall during two separate monsoons, the southwest monsoon from June to September and the northeast monsoon from October to December, each lasting around three months. As a result, sampling was done three times a year while taking into account changes to the monsoon pattern.

2.3. Experimental procedure

The samples were delivered to the lab, where the DIC samples were kept at 4°C for preservation. The analysis of the main ions followed APHA guidelines (APHA 1995). Samples of sodium, calcium, and potassium were examined using a Systronics 505 flame photometer. Titration was used to analyze magnesium. Sulfate and silicate were assessed using a Spectrophotometer (Systronics 905), while chloride was examined using an auto titrator (Metrohm 901). Extech II Fl 700 portable probe was used to test fluoride, while Quantalase LF 2a LED laser fluorimeter was used to quantify uranium. A Coulometer (UIC Inc CM 1505) was used to evaluate the DIC samples. An ethanol amine solution and a colorimetric indicator are placed within the coulometer cell, which is based on the colorimetric principle. Quantitative CO_2 absorption occurs when the gas stream passes through the solution; this CO_2 then combines with the ethanol amine to generate a potent titratable acid. The solution's color is restored automatically by the titration current, which electrically creates the base. The CO_2 Coulometer's operating range for a single sample is between one microgram of carbon and 10,000 micrograms of carbon. For every 15 samples, the instruments were cross-checked to preserve accuracy. To determine the accuracy of the study, the ion balance error was estimated and found to be less than 10.

2.4. Gps location of the study area

Repeated data collection from Earth observation satellites occurs in a variety of spectral bands and at varied spatial and radiometric resolutions. High-quality Resourcesat-2 LISS-IV satellite images with a spatial resolution of 5.8 m and a swath size of 25 25 Km have been employed in the current work to inventory rivers. Due to the lack of cloud-free and snow-free photographs from recent years, the majority of the images utilized for inventorying were from 84% of the prior years. In the South Parganas district of the Indian state of West Bengal, the Muri Ganga River is a tributary of the Hooghly. The Hooghly divides with one channel traveling east of Sagar Island before joining the Bay of Bengal. The Baratala River or Watercourse Creek are the names of this. Locally, it is referred to as Muri Ganga (Figure 1).

Latitude: 21°39'42.77"N,

Longitude: 88° 08' 33.36" E

Figure 1. GPS Location of the study area (Muri Ganga River)

2.5. APHA standard guidelines for carbon emission

According to APHA (American Public Health Association), new regulations would significantly reduce carbon pollution from coal and gas power plants, the country's second-largest source of carbon emissions, as well as other dangerous air pollutants like particulate matter, sulphur dioxide, and nitrogen oxide. The health of our communities is already being badly impacted by climate change, which is significantly exacerbated by coal and gas power plants. Climate change poses a serious risk to the public's health due to increased air pollution, the development of vector-borne diseases, and extreme weather. According to the EPA, these regulations would, until 2042, reduce carbon pollution from the electricity industry by 600 million metric tonnes, significantly assisting the country's efforts to cut greenhouse gas emissions and combat climate change.

3. Hydrochemical process

Understanding the fluctuation of significant ions in a given region's groundwater and surface water over time and space might assist pinpoint the chemical processes that are in charge of these changes. To comprehend the problems with water quality and quantity and to establish water management methods, geochemical investigations on groundwater and surface water are crucial.

3.1. Evaporation

Evaporation would be one of the primary hydrogeochemical processes for both groundwater and surface water in the research area because it is located in the tropical region, which is known for its high temperatures. Since the evaporation process enhances the concentration of ions and salt in the soil, it raises the concentration of mineral species in water. The Na vs. Cl figure clearly shows that the majority of the samples are concentrated along the freshwater evaporation line, where evaporation directly affects the TDS by raising the Na and Cl ions.

3.2. Ion exchange process

The Gibbs plot (Gibbs, 1970) makes clear the dominance of rock-water interaction in groundwater and surface water. The Gibbs plot is a logical diagram depicting the several processes that control the hydrochemistry of both groundwater and surface water. According to the Gibbs plot, evaporation is the second most prevalent process in both groundwater and surface water, after rock-water contact. Few surface water samples showed that precipitation was the controlling mechanism.

$$\mathrm{CAI}-1' = \mathrm{Cl}-\left(\mathrm{Na}^{+}+\mathrm{K}^{+}\right)/\,\mathrm{Cl}^{-}$$

$$\mathrm{CAI}-2 = \mathrm{Cl}-\left(\mathrm{Na}^{+}+\mathrm{K}^{+}\right)/\left(\mathrm{SO_4}^{2-}+\mathrm{HCO_3}^{-}+\mathrm{CO_3}^{2-}+\mathrm{NO_3}^{-}\right)$$

Chloro-alkaline indices I and II (CAI-I and CAI-2) were proposed as base exchange indices and have since been demonstrated to be evidence for the ion exchange process between water and host rock environments. Important details on the various chemical compositions of water and how they interact with rocks are provided by CAI. Formulas are used to compute it, and all results are expressed in meq/l.

3.3. Weathering

The majority of the main ions in both river water and groundwater are caused by the weathering of rocks. The following fundamental equations illustrate how carbonate and silicate minerals interact during rock weathering.

Carbonates: $CaCO_3 + CO_2 + HCO_3 = Ca^{2+} + 2HCO_3^-$

Silicates: $CaSiO_3 + 2CO_2 + 3H_2O = 2HCO_3^- + Ca^{2+} + H_4SiO_4$

Due to the availability of silicate minerals in the study location, silicate weathering has a strong hold over this river basin. The majority of the samples fell above the 1: 1 aquiline on the plot of Na + K vs. total cations and Ca + Mg vs. total cations, which suggests that silicate weathering contributed to the ions in those samples (Figures 4.10 and 4.11). This suggests that the research region's pyroxene and plagioclase feldspar minerals are weathering. One of the main processes that release Na and K in groundwater in aquifers of plutonic rocks is silicate weathering, and this process is probably the main one that adds Na and K to the water. Simply put, the formula for the relationship between humidity and temperature is that they are inversely proportional. The relative humidity will drop as the temperature rises, making the air drier; conversely, if the temperature drops, the air will get wet and the relative humidity will rise.

3.4. Mineral saturation indices

The existence of reactive minerals in water and their activity there can be predicted using mineral equilibrium calculations (Deutsch, 1997). The molar ratios of the ions, the EC, and the pH were used to obtain the SI values. Below formula is used to calculate the SI values.

$$\mathrm{SI} = \frac{IAP}{K_t}$$

IAP stands for the Ion Activity Product, and Kt is the equilibrium constant (a temperature-dependent parameter). It was presumed that SI's equilibrium state would be 0. Less below the equilibrium limit values signify mineral dissolution, while bigger values indicate mineral precipitation.

3.5. Soil properties

The soil types in the Ganga basin are extremely rich and diverse. The Gangetic plains offer a sizable storage area where the river may deposit layers of sediment that are thousands of meters thick to create a productive and vast plain area, in contrast to the Himalayan region's soils, which are always at risk of erosion. A mantle of residual soil with varying thickness has also been created in the Deccan plateau region due to the weathering of old rocks found in the peninsular shield. There are ten primary types of soil in the basin, of which alluvial soils (52.44%), red soils (11.80%), and medium black soils (10.78%) combined account for around 75.02% of the basin's total soil. Mountainous, sub-montane, and alluvial soils, which make up about 58% of the basin's area, exhibit extremely high erosion; red soil, which makes up 12% of the basin's area, exhibits high erosion; and mixed red-yellow and mixed red-black soils, which make up about 8% of the basin's area, exhibit moderate erosion. Similar to this, the shallow black and lateritic soils with a 6% cover area exhibit very low erodibility whereas the deep black and medium black soils, which cover approximately 14% of the basin area, indicate a low rate of erosion. The soils in the lower hilly area are of the forest and hilly type, while the soils in the lower Gangetic plains are loam to silty loam type. The soils are of glacial and fluvial-glacial origin in the upper section of the Bhagirathi and the Alaknanda, the lower hilly region, and the lower hilly region.

3.6. River water sample

Using a water depth sampler from mid-stream and from three different reach sizes (25 m, 50 m, and 75 m), respectively, the water samples from the sub-surface (15-25 cm depth) and the sediment-water interface (SWI) of the river were obtained. The samples were taken in triplicates monthly from each location in acid-rinsed plastic bottles, kept in the dark at 4°C in an ice box, and delivered to the lab for further analysis by established procedures. To prevent microbial exploitation of heavy metals, a portion of the samples was acidified right away by adding 1 ml of strong nitric acid per 100 ml sample.

4. Result and discussion

The river contains nutrients and carbon. Downstream of the cities, there was an increase in the concentrations of dissolved organic carbon (DOC), total organic carbon, and nutrients (NO_3^-, NH_4^+, and PO_4^{3-}). The carbon and nutrients displayed an upward tendency over time. The DOC values varied from 4.39 mg L^{-1} to 15.03 mg L^{-1}, with Nawabganj (Nwbj) Site having the lowest values and Jajmau (Jjmu) Site having the highest. Similar trends were seen in the concentrations of TOC (8.12 mg L^{-1} to 33.03 mg L^{-1}), NO_3^- (230.97 g L^{-1} to 419.65 g L^{-1}), NH_4^+ (25.47 g L^{-1} to 48.89 g L^{-1}), and PO_4^{3-} (46.64 g L^{-1} to 180.65 g L^{-1}). In contrast to carbon and nutrients, dissolved silica (DSi) had little change on a regional scale and exhibited a spatial and temporal trend. (Figure 2) Downstream of the cities, the concentration decreased, with values ranging from 350.06 g L^{-1} (Jjmu Site) to 486.19 g L^{-1}

Other physicochemical aspects of river water, such as pH, conductivity, salinity, and total dissolved solids (TDS), varied according to location and time, with Jjmu Site experiencing the highest levels and Nwbj Site experiencing the lowest, and increased with time in a manner akin to nutrients. Similar to how cations like Na^+, K^+, Ca^{2+}, and Mg^{2+} grew, so did anions like CO_3^- and HCO_3^- and free CO_2 in downstream cities (Table 1). The results from the trajectory analyses are provided as the means of four successive years of research since between-year variations were not statistically significant. Downstream point sources for nutrients and carbon had inconsistent patterns. However, the results were greater at the Assi drain (Asdr) than those downstream of the Wazidpur drain (Wpdr). The concentrations of DOC and TOC exhibited a falling trend downstream of both drains. Downstream of the drains, nutrients like NH_4^+ and PO_4^{3-} exhibited a dropping tendency, but DSi showed an opposing trend. Asdr had greater DSi and PO_4^{3-} concentrations than Wpdr did whereas Wpdr had higher NH_4^+ concentrations (Figure 4.1.2). Similar to this, the NO_3^- content varied from 49.28 to 148.53 g L^{-1} (Wpdr) and 87.36 to 465.89 g L^{-1} (Asdr). The NO_3^- at Asdr deviated from the steady upward or downward trend of carbon and other nutrients on a regional scale. Up to 400 m, it had an upward tendency, which was followed by a descending trend after Asdr. For Wpdr, an upward trend was seen up to 700 m, after which the concentration began to fall (Figure 3).

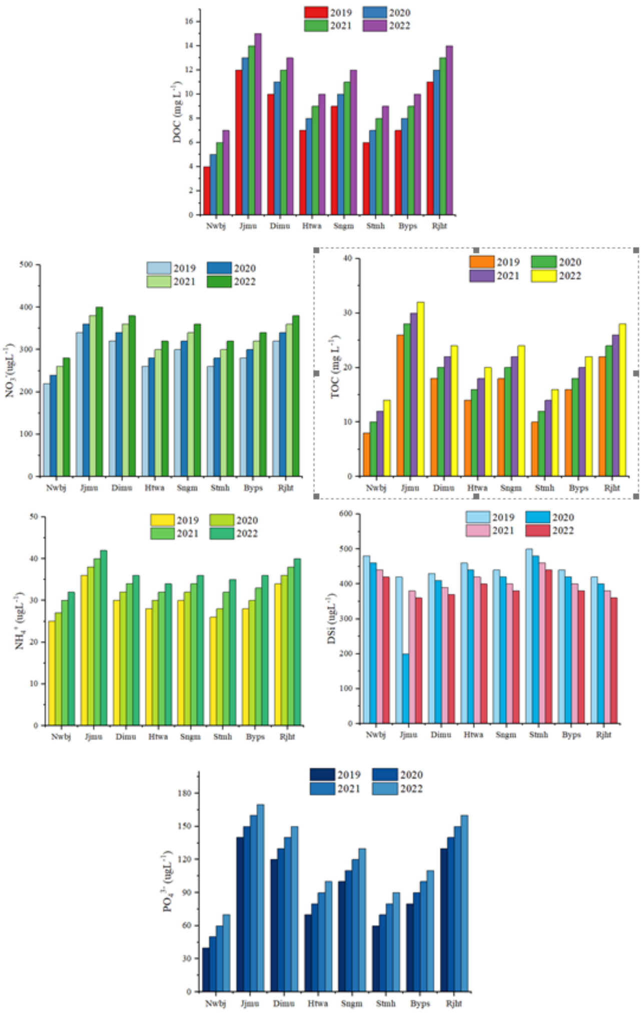


Figure 2. Organic carbon and nutrient concentration in the main study stretch of the Ganga River. Values are mean (n = 48)±1SD.

Table 1. Physico-chemical characteristics of river water along the study gradient.

Parameters	Nwbj	Jjmu	Dim	Htwa	Sngm	Samh	Byps	Riht
pH	7.4-7.8	79-8.5	7.7-82	7.5-7.9	7.8-8.3	7.4-7.8	7.6-8.1	7.9-8.5
Conductivity ($\mu S\ cm^{-1}$)	292-329	396-499	344-421	324-375	356-446	308-356	335-391	372-482
Salinity (ppm)	91-150	123-189	107-169	99-160	110-174	96-155	103-164	115-178
TDS (ppm)	210-300	321-484	289-383	249-363	296-435	228-335	268-388	308-472
Na^+ (ppm)	18.16-29.63	36.24-49.83	28.14-36.94	22.69-34.19	31.08-41.32	20.53-31.08	25.67-37.81	32.35-45.49
K^+ (ppm)	5.01-8.12	6.97-1183	5.91-9.68	5.47-8.68	6.07-10.13	5.28-8.26	5.78-9.01	634-11.06
Ca^{2+} (ppm)	25.28-35.13	35.68-48.39	30.69-42.76	28.84-39.93	31.89-44.13	27.13-37.04	29.96-41.32	32.19-45.37
Mg^{2+} (ppm)	21.16-24.21	47.53-52.69	32.64-36.71	26.53-29.61	37.51-42.93	23.32-26.83	28.61-31.74	42.63-47.36
CO_3^- (ppm)	0.26-2.36	1.67-5.21	0.92-3.86	0.67-3.01	1.00-4.21	0.44-261	0.83-3.49	1.08-4.72
HCO_3^- (ppm)	2.31-50.09	6.13-112.32	4.62-85.39	3.86-73.71	491-91.39	3.09-64.57	4.26-79.68	5.36-100.54
Free CO_2 (ppm)	0.19-1.24	1.98-5.39	1.04-2.96	0.58-1.94	1.26-3.62	0.32-1.67	0.86-249	1.52-4.58

Table 2. Range of correlations* (Pearson's) between variables measured for the main stem of the Ganga River

	Land-water interface (LWI)				
	Organic carbon	**Nutrients**	**Heavy metals**	**EE activities**	
Organic carbon	River water	0.98 to 0.99	0.92 to 0.99	0.90 to 0.97	-0.24 to -0.98
Nutrients		0.94 to 0.99	0.94 to 0.99	0.91 to 0.98	-0.23 to -0.98
Heavy metals		0.90 to 0.96	0.90 to 0.99	0.97 to 0.99	-0.35 to -0.99
Organic carbon	Riverbed sediment	0.98 to 0.99	0.93 to 0.99	0.88 to 0.97	-0.17 to -0.98
Nutrients		0.93 to 0.99	0.93 to 0.99	0.91 to 0.99	-0.25 to -0.99
Heavy metals		0.87 to 0.95	0.87 to 0.99	0.97 to 0.99	-0.45 to -0.95
EE activities		-0.14 to -0.98	0.19 to -0.99	0.22 to -0.97	-0.62 to 0.99

4.1. Atmospheric deposition of carbon and nutrients

Along the study gradient, distinct spatial and temporal changes in atmospheric deposition (AD) were observed. The rate of carbon and nutrient deposition was lowest at Nwbj Site and greatest at Jjmu Site, and it grew steadily over time, demonstrating that these elements increased as urban-industrial influence downstream of the cities increased. The ranges for the AD-NO_3^-, -NH_4^+, -PO_4^{3-}, and -OC were, respectively, 3.63 to 13.60, 1.98 to 6.42, 0.39 to 1.87, and 3.68 to 12.40 Kg h^{-1} $season^{-1}$. Seasonally, the winter season had the largest depositions, and the wet season had the lowest (Figure 4).

An accurate indicator of river health is the land-water interface. This study demonstrated that fluctuations in riverbed silt, LWI characteristics, and water quality along the main river stem as well as downstream from both point sources were synchronous with one another and displayed varying and significant human activity influences. The substantial positive correlations between the high concentrations of NH_4^+, PO_4^{3-}, TOC, and heavy metals at Jjmu, Rjht, and at the drain mouth in all three sets of the database (Tables 4.2.1, 4.2.2, and 4.2.3) highlighted their similar source of origin. Similar to this, heavy metal pollution that is harmful limits the growth of phytoplankton. These findings demonstrate the limitations of establishing nutrient-productivity links based only on water quality metrics.

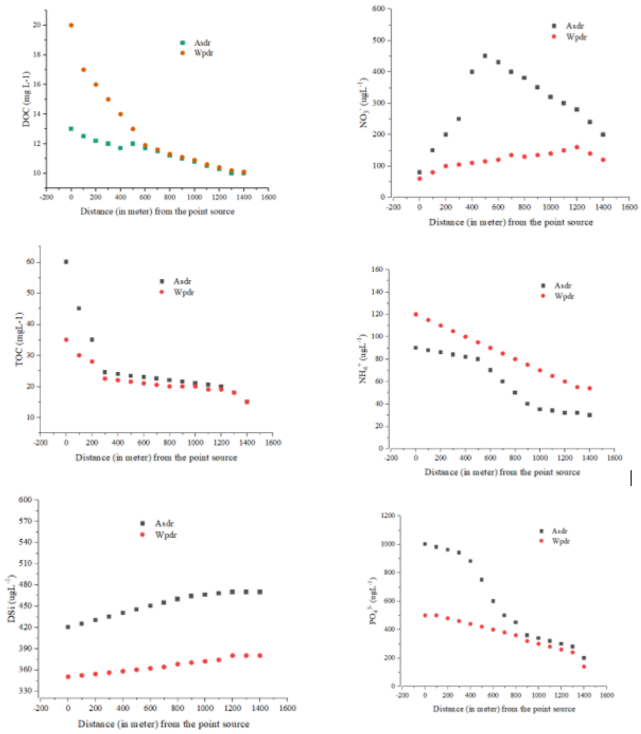


Figure 3. Organic carbon and nutrient concentration in river water downstream point sources. Asdr: Assi drain; Wpdr: Wazipdpur drain.

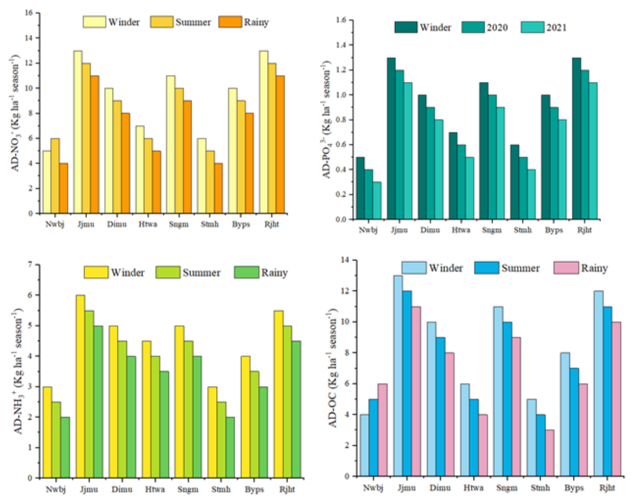


Figure 4. Atmospheric deposition of organic carbon and nutrients in the main study stretch of the Ganga River. Values are mean (n = 12)±1SD.Conclusion

The Ganga River has been the subject of several research, however, information from an ecological standpoint is quite limited. The river is more susceptible to changing from one stable condition to another due to several human disturbances in the form of various point and non-point sources. In an ecological analysis of the Ganga River, this research highlights the following problems:

1. There is no simple, inexpensive, and low-variance approach for assessing and monitoring the river.

2. There are no reports on the evolving condition of ecosystem functioning that couple human disturbances, environmental feedbacks, and their effects on the river's ecological resilience.

3. The lack of a multi-temporal and multi-scale data base for analysing ecosystem responses to metal contamination and eutrophy.

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