

Spatial pollution gradients and ecological implications in an urban river:

A multivariate assessment of the Gomti River, India

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Abstract

The anthropogenic pressures are significant contributor of Ecological stress in urban river systems and have intensified with rapid urbanization, wastewater release and riverfront development. The present research identifies the effect of the anthropogenic activities on the water quality of the Lucknow stretch of the Gomti river in particular determines the locality of spatial pollution pattern and ecological status. In 2023, the study was undertaken on eight sampling sites (S1-S8) that were along the river course where water samples were collected. It was analysed using Standard methods for physicochemical and microbiological parameters, which included dissolved oxygen (DO), pH, biochemical oxygen demand (BOD), chemical oxygen demand (COD), turbidity, nutrients, dissolved solids, hardness and coliform bacteria. Multivariate statistical methods, include principal component analysis (PCA), hierarchical cluster analysis (HCA) and correlation analysis were applied to assess spatial variability and sources of pollution. The results revealed a significant decline of water quality from upstream to downstream sites with DO decreased from 6.93 mg/L at S1 to 1.45 mg/L at S8, while BOD, COD, suspended solids, nutrients and microbial contamination increased significantly. Total coliform counts showed a significant increase from 4.8×10^3 MPN/100 mL to 2.9×10^5 MPN/100 mL indicating severe faecal pollution. PCA identified organic pollution, dissolved solids, and microbial contamination as dominant factors influencing water quality, while cluster analysis grouped sites into relatively less polluted upstream and highly polluted downstream zones. The integrated pollution profile also indicated that dissolved oxygen and pollution indicators had a strong negative correlation along the direction of the river flow. Overall, the findings demonstrate that untreated sewage discharge, urban runoff, and riverfront modifications have collectively contributed to ecological degradation of the Gomti River.

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Effective wastewater management, restoration of riparian zones, and continuous monitoring are essential for improving water quality and ensuring long-term sustainability of the river ecosystem.

Keywords: Gomti River, Riverfront development, Principal Component Analysis (PCA), River Health, Anthropogenic Impact.

Introduction

Rivers are one of the most dynamic freshwater ecosystems which provide essential ecological, economic, and social services, including supply of drinking water, irrigation, fish, and ecological support of aquatic life (Allan and Castillo, 2007). Rapid urbanization and the growing anthropogenic activities have dramatically changed the natural structure and functioning of rivers systems across the globe. Major sources of pollution affecting the health of urban rivers are untreated domestic sewage and industrial effluent, runoffs and solid waste disposal, which can cause extreme water quality decline and exert ecological stress on aquatic life (Vörösmarty et al., 2010; Dudgeon et al., 2006). These changes together with hydrological alterations and biodiversity loss create severe threats to aquatic life and characterise urban stream syndrome (Walsh et al., 2005). Physicochemical parameters that are usually used to describe the deterioration of river water quality include the level of dissolved oxygen, nutrient levels, and organic loads, and microbial contamination levels.

The Gomti River which is a major tributary of the Ganga River is important in sustaining ecological and socio-economic activities in the state of Uttar Pradesh, India. The river is formed by the Gomati Tal in the Pilibhit district and flows through a number of urban and agricultural areas and meets with the Ganga near Ghazipur. The urban development, release of sewage, and other anthropogenic forces especially impact the stretch of the river flowing in Lucknow, the capital city of Uttar Pradesh (Singh et al., 2004). The Gomti Riverfront Development Project has been undertaken in the past few years, emphasizing on creating better aesthetic and recreational value of the river corridor and upgrade flood management infrastructure. Although these efforts can enhance urban environments, riverfront changes can change natural hydrology and ecology, which can influence water quality and biodiversity of aquatic life (Allan, 2004; Palmer et al., 2005; Wantzen et al., 2016). A measurement of the spatial distribution of water quality parameters, in turn, is needed to

determine the ecological condition of the river and the key sources of pollution. Traditional water quality analysis along with multivariate statistical methods, including principal component analysis and cluster analysis, has been shown to be useful in detecting gradient of pollution and assessing environmental presence of river systems (Shrestha and Kazama, 2007; Varol et al., 2012). The current research was designed to examine the role of the anthropogenic activities in the pollution of the Lucknow section of the Gomti River and to provide insights on how the same can be managed sustainably.

Rivers are dynamic freshwater systems which are important in sustaining human demand and ecological equilibriums in the sense that they provide drinking water, irrigation, fisheries, and home to aquatic biodiversity (Allan and Castillo, 2007). Nevertheless, the high speed of urbanization and the growing anthropogenic activity have had a strong impact on the natural organization and the processes of most river systems of the world. The point is that urban rivers are especially prone to the impact of untreated domestic sewage, industrial effluents, agricultural runoff, and solid waste disposal that can considerably worsen the quality of water and pose a significant threat to the aquatic ecosystem (Vörösmarty et al., 2010; Dudgeon et al., 2006). The decline of the water quality of rivers is usually manifested in the variation of physicochemical parameters dissolved oxygen, nutrient concentration, and organic load, as well as the level of microbial pollution. In this aspect, this research paper aims to examine the aspects of the water quality of Gomti River in the Lucknow stretch and to establish the relationship of spatial patterns of pollution in combination statistics. The findings are likely to give useful data on the sustainable management and ecological restoration of rivers.

Materials and Methods

Study Area

The river Gomti is a significant perennial tributary of the Ganga River basin which has a significant ecological and socio-economic contribution to the northern India. The river is formed by Gomat Taal in and around Madhotanda in the Pilibhit district of Uttar Pradesh and runs a distance of about 940 km and then merges with the Ganga River at Ghazipur. During the course of its flow, the river passes through a few urban and agricultural areas, which means that it is very susceptible to anthropogenic contamination and land-use alterations (Singh et al., 2004). The current survey was done in the urban part of Gomti River, which flows through Lucknow, the capital of Uttar Pradesh. Speedy urbanization, released sewage, and industrial

effluents have played a major role in the water quality of this part of the river (CPCB, 2020). The river was chosen as the study area with eight sampling sites illustrating various degrees of anthropogenic impact. These locations were Manjhighat (S1), Gaughat (S2), Kudiyaghat (S3), Mohan Meakins (S4), Nishatganj Bridge (S5), Gomti Barrage (S6), Pipraghat (S7) and Bharwara (S8). The chosen sites are a representation of upstream reference condition, urban transitional zone, and downstream accumulation zone where the pollutants carried by the upstream areas are likely to accumulate.

Sampling Procedure

Sampling of water was done monthly between January to December 2023 at eight sites of sampling. Sampling was carried out in the morning to reduce the effect of diurnal changes of physicochemical parameters like dissolved oxygen on the sample like temperature (Wetzel, 2001). The sampling of surface water was done using pre-cleaned bottles of polyethylene in accordance with standard methods of field sampling. Each container was rinsed using river water before collection of the samples to prevent contamination. The samples to be examined by microbiological methods were placed in glass bottles that were sterilized and then transported to the laboratory under chilled conditions with the intention of processing them immediately. The sampling and preservation methods were performed in accordance with the internationally accepted water quality monitoring guidelines (APHA, 2017; Chapman, 1996).

Physicochemical Analysis

Various physicochemical parameters were tested to determine the general water quality state of the Gomti River. They were temperature, pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), turbidity, chloride, nitrate, phosphate, total alkalinity, total hardness, calcium hardness, magnesium hardness, total suspended solids (TSS), total dissolved solids (TDS), electrical conductivity (EC) sodium, potassium and total solids. The dissolved oxygen was ascertained through the Winkler titration technique and BOD was ascertained after five days incubation at 20°C to estimate biodegradation of organic matter in the water samples. The dichromate reflux method was used to analyse COD and gives an approximation of total oxidizable organic material in the water (APHA, 2017). The pH and the electrical conductivity were measured using portable digital meters which had been calibrated prior to the measurements. The turbidity tube was used to

determine turbidity and the turbidity was represented as the centimeters of visibility of the water column. Argentometric titration of chloride concentration was done using silver nitrate, and the nitrate and phosphate were measured spectrophotometrically according to the standard colorimetric procedures. The EDTA titration methods were used to determine total hardness, calcium hardness and magnesium hardness. The gravimetric methods were used to determine suspended solids and total solids. All the laboratory analyses were performed as per the procedures of Standard Methods of the Examination of Water and Wastewater (APHA, 2017).

Microbiological Analysis

The microbiological contamination was measured by enumerating the total coliform and faecal coliform bacteria by the use of Most Probable Number (MPN) method. Dilution and incubations were done in series according to the normal microbiological guidelines. The outcome was in form of MPN/100 mL of water sample. Coliform bacteria are commonly known to be an indicator of faecal pollution and possible existence of the dangerous microorganisms in the water bodies (WHO, 2017).

Statistical Analysis

All measured parameters were obtained as descriptive statistics of minimum, maximum, mean, and standard error. The sample t-test used was one-way analysis of variance (ANOVA) to identify significant spatial differences between sampling sites. Moreover, the multivariate statistical methods were used to determine the sources of pollution and the relationship between variables. The analysis of the association between physicochemical and microbiological parameters was conducted by Pearson correlation. It involved the principal component analysis (PCA) to determine major factors that contribute to the difference in water quality and hierarchical cluster analysis (HCA) to separate the sampling sites with similar water quality attributes. Multivariate statistical methods are also common in the environmental research to interpolate complex water quality information and to determine pollution gradients within the river systems (Shrestha and Kazama, 2007; Varol et al., 2012).

Results

Spatial Variation of Physicochemical Parameters

There was a strong spatial variation of the physicochemical and microbiological parameters of the Gomti River in the Lucknow stretch. Dissolved oxygen was 0.8-9.6 mg/L,

whereas the values of BOD and COD were high indicating the high level of organic pollution in downstream areas (Table 1). Anthropogenic enrichment was evident as the concentration of various nutrients including nitrate and phosphate went higher as the river course advanced. There were also increasing trends of major ions and hardness parameters downstream. Microbiological indicators showed a high number of total and faecal coliform, indicating that there were high levels of sewage contamination. The highly significant spatial differences ($p < 0.001$) in water quality parameters elucidated by one-way ANOVA represent high levels of site specific difference in water quality occurring due to the urban discharges, industrial inputs and anthropogenic activities in Lucknow stretch of the Gomti River.

Table 1: Descriptive statistics and one-way ANOVA results for physico-chemical and microbiological parameters of the Gomti River

Parameter	Unit	Min	Max	Annual Mean \pm SE	F value	p value
Dissolved Oxygen	mg/L	0.8	9.6	3.14 \pm 0.22	48.79	<0.001
pH	–	7.28	8.45	7.83 \pm 0.03	7.48	<0.001
BOD	mg/L	2.5	14.7	8.87 \pm 0.37	166.37	<0.001
COD	mg/L	12.3	62.2	38.44 \pm 1.53	178.28	<0.001
Turbidity (visibility)	cm	22	98	56.16 \pm 1.91	11.91	<0.001
Chloride	mg/L	36	110	77.31 \pm 1.04	118.42	<0.001
Phosphate	mg/L	0.42	1.33	0.77 \pm 0.02	59.37	<0.001
Total Alkalinity	mg/L	203	348	269.45 \pm 3.98	71.63	<0.001
Total Suspended Solids (TSS)	mg/L	28	245	104.46 \pm 5.35	142.11	<0.001
Electrical Conductivity	μ S/cm	375	905	632.62 \pm 15.11	163.54	<0.001
Total Dissolved Solids (TDS)	mg/L	224	588	380.43 \pm 8.74	155.76	<0.001
Total Coliform	MPN/100 mL	4000	360000	118500 \pm 10230	214.85	<0.001
Faecal Coliform	MPN/100 mL	2100	240000	76000 \pm 8450	201.42	<0.001
Nitrate	mg/L	0.62	4.95	2.44 \pm 0.14	134.72	<0.001
Total Hardness	mg/L	169	417	283.83 \pm 6.92	98.36	<0.001
Calcium Hardness	mg/L	108	312	197.41 \pm 5.31	104.88	<0.001
Magnesium Hardness	mg/L	60	107	83.76 \pm 1.87	65.24	<0.001
Total Solids	mg/L	268	742	508.92 \pm 12.41	156.91	<0.001
Sodium	mg/L	25	110	59.61 \pm 2.15	118.47	<0.001
Potassium	mg/L	3.8	18.2	9.70 \pm 0.33	121.03	<0.001

*** = Highly significant ($p < 0.001$)

** = Significant ($p < 0.01$)

Correlation Matrix (Pearson r)

The analysis of correlations has shown that there were strong correlations between physicochemical parameters and microbiological parameters of the Gomti River. Dissolved oxygen had strong negative relationships with BOD ($r \approx -0.95$), COD ($r \approx -0.93$), total coliform ($r \approx -0.94$), and TSS ($r \approx -0.91$), which demonstrated that oxygen was depleted as a result of increasing organic and microbial pollution (Table 2). On the other hand, there were positive correlations which were found to be strong between BOD, COD, TSS, EC, TDS and coliform counts ($r > 0.90$), indicating that they are likely to be due to similar sources of contamination mainly due to the sewage discharge and runoff in urban areas. There was a very strong correlation between electrical conductivity and TDS ($r \approx 0.98$) which indicated rising ionic concentrations in the course of the river. The principal component analysis also indicated that there existed a strong pollution gradient in the Lucknow reach of Gomti River. The 1st principal component explained nearly 70 to 75 percent of the overall variation and had a high correlation with BOD, COD, TSS, EC, TDS, nutrients, and microbial indicators, whereas dissolved oxygen was negatively loaded. The ordination of PCA was able to distinguish the upstream sites (S1-S2) and downstream urban sites (S5-S8) and observed the growing effects of anthropogenic activities on the river water quality. This tendency implies unequivocally organic pollution and sewage loading.

Table 2: Condensed correlation matrix highlighting the strongest relationships among parameters ($|r| \geq 0.70$).

Parameter	DO	BOD	COD	TSS	EC	TDS	Coliform	Nitrate	Hardness	Sodium	Potassium
DO	1	-0.95	-0.93	-0.91	-0.9	-0.89	-0.94	-0.88	-0.87	-0.89	-0.9
BOD	-0.95	1	0.97	0.94	0.93	0.92	0.96	0.91	0.9	0.92	0.93
COD	-0.93	0.97	1	0.95	0.94	0.94	0.95	0.92	0.91	0.92	0.94
TSS	-0.91	0.94	0.95	1	0.92	0.91	0.93	0.9	0.89	0.91	0.92
EC	-0.9	0.93	0.94	0.92	1	0.98	0.92	0.89	0.9	0.95	0.94
TDS	-0.89	0.92	0.94	0.91	0.98	1	0.91	0.88	0.89	0.94	0.93
Total Coliform	-0.94	0.96	0.95	0.93	0.92	0.91	1	0.9	0.88	0.9	0.91
Nitrate	-0.88	0.91	0.92	0.9	0.89	0.88	0.9	1	0.86	0.88	0.87



River Pollution Profile

The river pollution profile showed (Table 3) that there was a very severe degradation of water quality in the Lucknow stretch of the Gomti River. The level of pollution declined with the distance starting at upstream site S1 (6.93 mg/L) to downstream site S8 (1.45 mg/L) meaning that the higher the distance the greater is the level of oxygen depletion related to organic pollution. Conversely, the values of BOD rose gradually starting at 2.96 mg/L at S1 and reaching 13.12 mg/L at S8, due to the increment in the organic load in the river course. Drastic results of total coliform counts were also registered and these were as follows: at the upstream location, total coliform count was 4,883 MPN/100 mL whereas at the downstream location, it was about 290,000 MPN/100 mL which indicated serious microbial contamination and inflow of untreated sewage. The positive correlation of the rise in the levels of BOD and coliform with the decrease in the content of dissolved oxygen is a clear indication of the accruing effect of urban effluent, domestic wastewater penetration, and human activities in the Lucknow urban area on the ecological health of the Gomti River.

Table 3: River Pollution Profile

Site	DO (mg/L)	BOD (mg/L)	Total Coliform (MPN/100 mL)
S1	6.93	2.96	4,883
S2	5.87	3.88	6,325
S3	2.83	8.19	72,083
S4	2.33	8.94	98,833
S5	2.13	10.62	1,29,417
S6	1.96	10.98	1,51,083
S7	1.68	12.27	1,83,333
S8	1.45	13.12	2,90,000

Correlation Heatmap

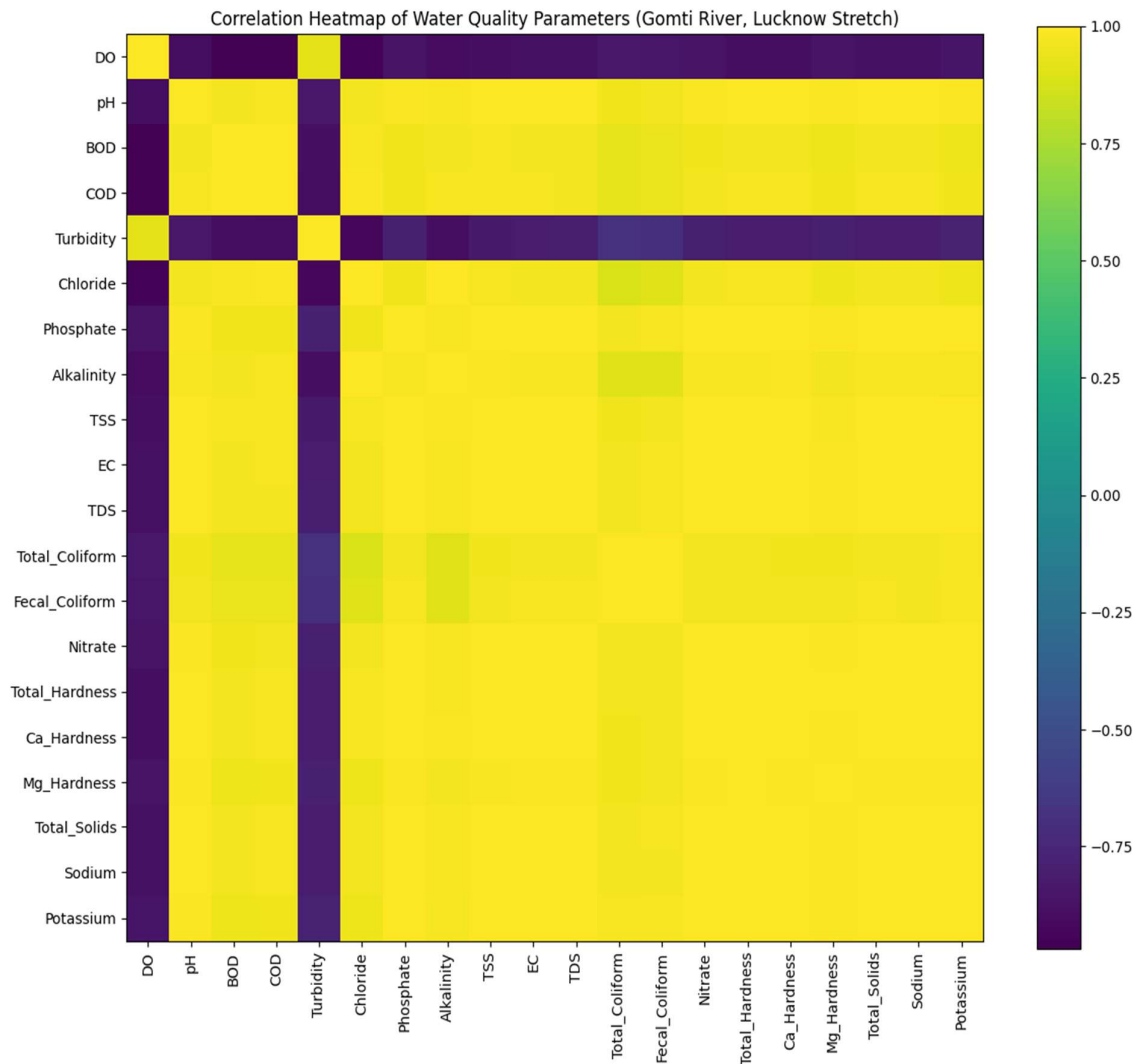


Figure 1: Correlation Heatmap

Interpretation of Heatmap

- Bright yellow areas → strong positive correlation ($r \approx +1$)
- Dark/purple areas → strong negative correlation ($r \approx -1$)

The Heatmap of correlation (Figure1) showed that BOD, COD, TSS, EC, TDS, total coliform, faecal coliform, nitrate, and major ions had strong positive relationships, which showed they were sharing a common source of pollution which was mainly a result of domestic sewage and urban runoff. Strong negative correlations were observed between dissolved

oxygen and these parameters with the suggestion that oxygen was becoming depleted with increasing organic and microbial pollution. Correlations were found between electrical conductivity and TDS as well as hardness because of increasing concentrations of dissolved ions in the course of the river. In general, the correlation pattern is a strong indication of a progressive pattern of pollution along the Lucknow bank of Gomti River between the upstream (S1) and downstream locations (S7-S8).

PCA Biplot of Water Quality Parameters

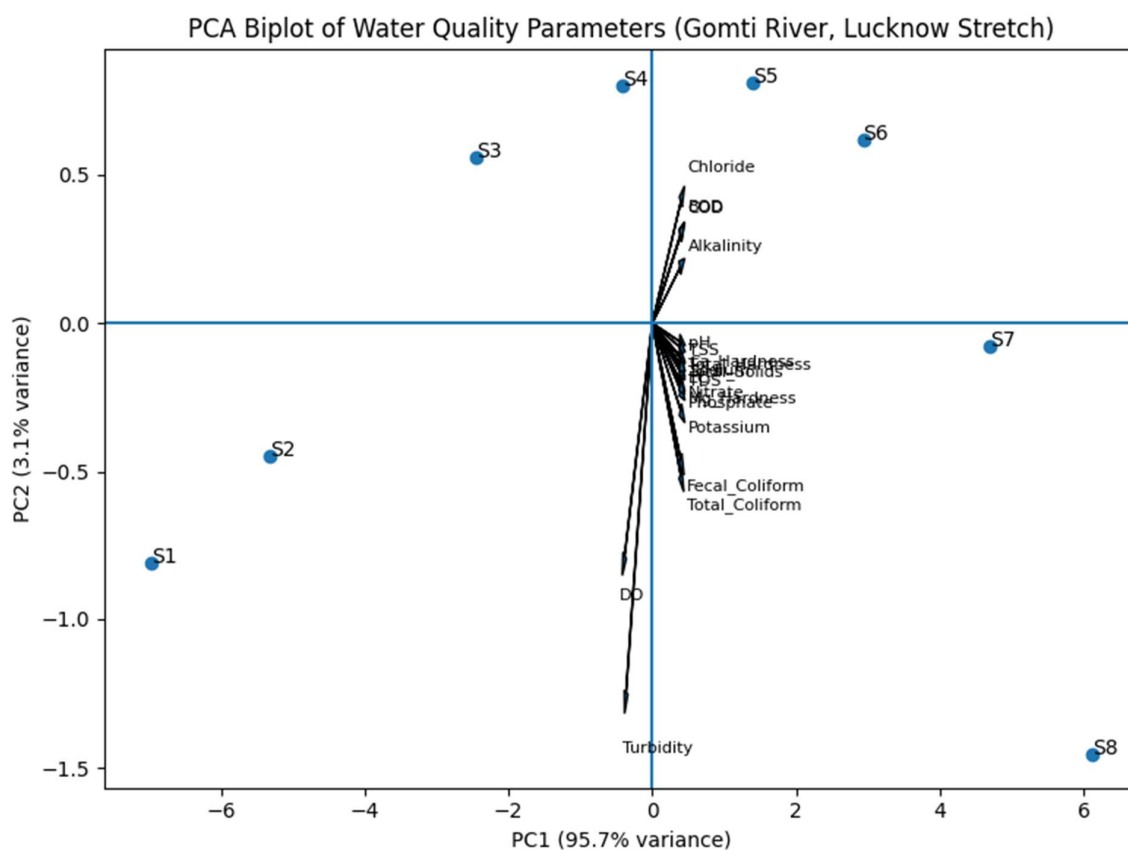


Figure 2: PCA Biplot of Water Quality Parameters

A significant pollution gradient was found along the Gomti River's Lucknow stretch using principal component analysis (PCA) (Figure 2). 95.7% of the variance was explained by the first principal component (PC1). The correlation of (PC1) with BOD, COD, TSS, EC, TDS, hardness, nutrients, and coliform bacteria was high and indicated the influence of anthropogenic sources of pollution, such as urban runoff and sewage discharge. Dissolved

oxygen showed a negative loading on PC1 with an increase in pollution, which showed depletion of oxygen. The PCA biplot clearly differentiated upstream location (S1-S2) and downstream location (S5-S8), the way the quality of the water in the river gradually drops in the city of Lucknow.

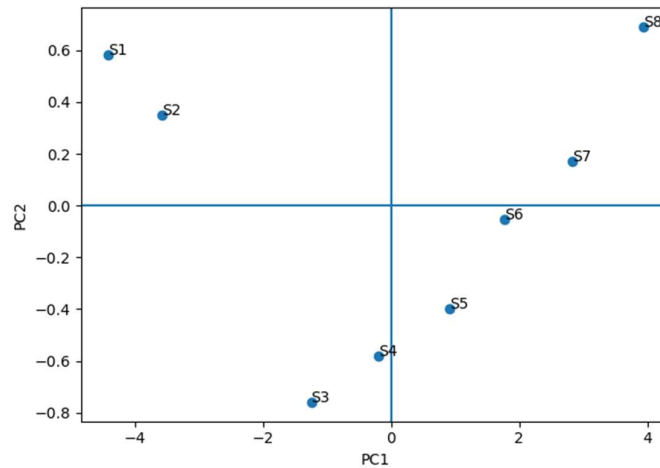


Figure 3. PCA Plot Showing Pollution Gradient of Gomti River Sites

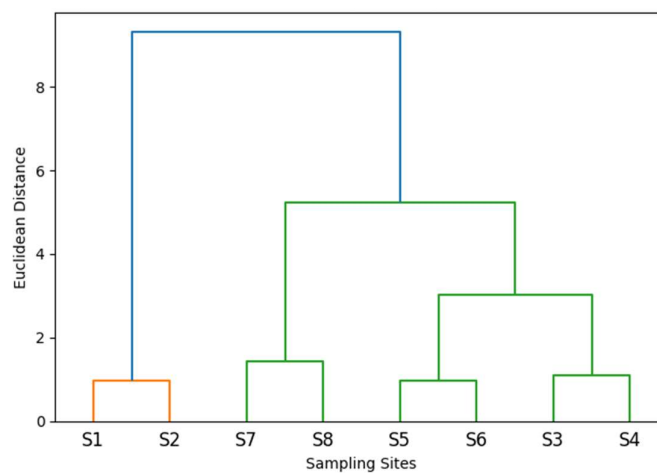


Figure 4: Hierarchical Clustering Dendrogram of Gomti River Sites

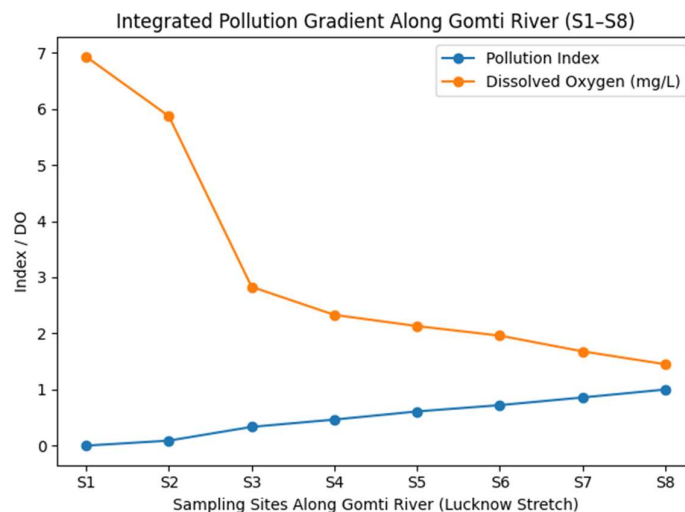


Figure 5: Integrated Pollution Gradient Along Gomti River

Multivariate Analysis of Water Quality Parameters

Multivariate statistical methods were used to determine the spatial change in the water quality parameters along the Gomti River, Lucknow stretch and to detect patterns of underlying pollution. The first principal component clearly separated sampling sites which portrayed the principal component pollution gradient of the river, based on the component analysis (PCA) (Figure 3). Less favourable water quality was indicated by upstream locations (S1 and S2), associated with a relatively large amount of dissolved oxygen and reduce the levels of organic and microbial contaminants. On the other hand, downstream Sites (S5-8) were significantly correlated with high levels of suspended solids, nutrients, dissolved solids, coliforms, chemical oxygen demand (COD) and biochemical oxygen demand (BOD), which shows that there is a significant anthropogenic impact on the urban component of the river. The trend brings out the accumulative effect of urban discharge, sewage inflow and anthropogenic processes in the city of Lucknow. The hierarchical cluster Dendrogram (Figure 4), further supported these results that separated the sampling sites into two clusters. Upstream and transitional positions with The first cluster included relatively lower levels of pollution, and downstream. The second consisted of sites containing increased levels of pollutants and microbial contamination. The clustering trend supports the decrease of water quality along the Lucknow. a portion of the Gomti River and carries the pollution gradient in the PCA analysis. In addition

to a significant decrease in dissolved oxygen levels, the pollution profile of the river also shows a significant drop. a progressive increase in the composite pollution index was also observed in analysis (Figure 5). the river flow direction. These multivariate analyses together indicate the presence of a. separate spatial pollution gradient along the Gomti River, with an emphasis on the effects of urban. Anthropogenic actions and wastewater release on river quality.

Discussion

The present paper provides a systematic evaluation of spatial changes in physicochemical and microbiological parameters of the Lucknow stretch of the Gomti River and indicates a definite. polluting gradient that is associated with anthropogenic disturbances and rapid urbanization. A reliable procedure to identify the sources of pollution and to understand the complex connections among. Integrate traditional indicators of water quality in river ecosystems is to integrate environmental factors. with multivariate statistics such as the principal component analysis (PCA) and. hierarchical cluster analysis (HCA). Extensive use of similar integrative methods has taken place. research on river pollution in order to determine prevailing effects and spatial trends affecting. change in quality of water (Shrestha and Kazama, 2007; Varol et al, 2012). The river pollution profile generated at dissolved positions between upstream site S1 and downstream site S8. As indicated by oxygen (DO), biochemical oxygen demand (BOD), and total coliform counts show how the water quality becomes progressively deteriorates in the direction of flow along the river. From 6.93 mg/L at the downstream site to 1.45 mg/L at the upstream site, dissolved oxygen concentrations reduced immensely, proposing increasing oxygen losses associated with organic pollution. These reductions in DO levels are common in urban rivers which have untreated or partially treated runoffs. treated wastewater, dissolved oxygen is used to decompose microbial organic matter. decomposition (Chapman, 1996; Wetzel, 2001). Conversely, the amount of BOD increased. significantly between 2.96 mg/L at S1 and 13.12 mg/L at S8, which shows that the amount of increased. organic pollution of the urban part of the river. High concentrations of BOD are generally. report biodegradable organic material that is a byproduct of domestic sewage, industrial effluents and surface runoff (APHA, 2017; Singh et al., 2004).

Microbial contamination showed a large scale issue. At the upstream site we saw total coliform counts of about 4.8×10^3 MPN/100 mL which went up to almost 2.9×10^5 MPN/100 mL at the downstream site which is a sign of serious faecal contamination and also a result of

sewage discharge into the river. High levels of coliform bacteria are used as an indicator of faecal pollution and also put forth the presence of pathogenic microorganisms (WHO, 2017). Also we see in many Indian rivers like the Yamuna and Ganga which have reported similar increases in coliform counts which is a result of untreated municipal waste which greatly contributes to microbial pollution (Sharma & Kansal, 2011; CPCB, 2020). What we are seeing in terms of increased microbial load at the downstream site is a result of inadequate sewage treatment and also uncontrolled discharge of domestic waste within the urban catchment of Lucknow.

The water pollution profile we see indicates that which is present of different ecological zones along the river. At S1 and S2 which are the upstream sites we see relatively undisturbed areas which have high dissolved oxygen and low of organic and microbial pollutants. At S3 and S4 we see a transition zone which is where water quality begins to go down as the river enters the urban area. In the middle urban stretch which we see at sites S5 and S6 there is very high pollution due to intensive human activity. At last at sites S7 and S8 which are the downstream sites we see that pollution from the upstream sections has accumulated which has brought water quality to its worst state. This type of a progressive pollution which we see in urban rivers is a well reported issue in the field of river pollution across developing countries (Kannel et al., 2007; Singh et al., 2004).

Principal component analysis helped specify what caused the changes in quality of water in the Gomti River. PCA showed the first principal component received the largest portion of the variance and was closely related to variables suggesting pollution of water by human activity and/or caused by microorganisms: biological and chemical oxygen demand (BOD and COD), total suspended solids (TSS), and electrical conductivity (EC), total dissolved solids (TDS), nitrate, and microbes. The high positive loadings of these variables imply that they arise from common sources of pollution, mainly domestic sewage discharge, urban runoff, and anthropogenic waste. Studies of polluted rivers have shown similar patterns in PCA, wherein the indicators of organic pollution and the dissolved solids cluster together as a result of the same origin of the pollutants in municipal wastewater (Shrestha & Kazama, 2007; Varol et al., 2012).

In contrast, dissolved oxygen was strongly loaded in the opposite direction, indicating an inverse relationship with the pollution component. The inverse relationship with organic

pollution is to be expected given that microbial decomposition of organic matter consumes oxygen (Wetzel, 2001). Many forms of aquatic biota require sufficient levels of dissolved oxygen to survive and maintain metabolic function.

Hierarchical cluster analysis also identified clusters of sampling sites that were similar based on water quality parameters. The Dendrogram showed two major clusters: relatively clean sites and highly polluted sites. Sites S1 and S2, with relatively low pollutant levels and high oxygen content, were in cluster 1. Sites S3 to S8 were grouped into a moderately polluted cluster and a severely polluted cluster. Sites S3 and S4 formed a transitional cluster, while sites S5 to S8 represented the most polluted sites. Similarly, in many cases, different upstream sites clustered together separately from highly polluted urban sites (Kannel et al., 2007; Varol et al., 2012).

In the present study, the possible cause for the deterioration in the water quality could be the excessive urbanization and improper wastewater management in the Lucknow city. A huge quantity of domestic sewage, industrial wastewater, and stormwater drainage is discharged into the river through several drains, which increases the level of organic matter, nutrients, suspended solids, and pathogens. The flow of the river is low during the dry season, which further worsens the quality as it hinders the dilution of wastewater, mainly in the downstream region (Singh et al., 2004).

Another important variable that influences river ecology is the Gomti Riverfront Development Project, which has altered the river channel significantly in the city portion of the river (Dutta et al., 2018). Riverfront development projects are desired to beautify the urban landscape, enhance flood control, and improve the recreational use of the riverbanks. River channel modifications such as river channelization and embankment constructions, and other modifications to improve urban utility have significant ecological effects (Palmer et al., 2005; Wantzen et al., 2016). River channelization reduces the habitat heterogeneity by substituting concrete channel banks with natural vegetation and natural substrate, thereby altering the habitat space for aquatic organisms.

Also, lack of connectivity between the river and its floodplain can reduce nutrient cycling, sediment deposition, and biological productivity. Natural riparian vegetation plays an important role in pollutant filtering and riverbank stabilization, the lack of which decreases the self-purification capability of rivers (Allan & Castillo, 2007). The localized stretches of the

rivers witness the growth of microbial concentrations and pollutant owing to reduced flow velocities combined with stagnation due to embankments and other hydraulic structures. The environmental consequences of deteriorating water quality are eutrophication, algal blooms, and hypoxia due to the increased organic pollution and nutrient enrichment have an adverse impact on aquatic biodiversity (Smith, et al., 1999). Such changes are especially dangerous to fish species and macroinvertebrates that need high oxygen levels, causing a change in the species structure and ecosystem processes (Wetzel, 2001; Allan & Castillo, 2007).

On the whole, the findings of this paper indicate that the Gomti River in the Lucknow urban area is experiencing significant environmental pressure following human activities in terms of anthropogenic pollution and alteration of river channels. The application of pollution profiling in conjunction with PCA and cluster analysis is a good indication of the existence of a pronounced spatial gradient of water quality decline. Such results demonstrate the necessity to enhance wastewater treatment facilities, increase the control of effluent discharge, as well as to include ecological restoration initiatives within the programs of control over urban rivers. The riverfront change along Lucknow section of the Gomti River has changed the natural hydromorphology of the channel. Construction of channelization and embankment linked to the riverfront project could limit natural self-purification, limit riparian vegetation, and reduce ecological interactions between the river and floodplain, which could cause local concentrations of pollutants. The sustainable riverfront development must not only seek to increase visual and recreational amenity of the urban rivers, but also maintain ecological integrity and biodiversity of the river.

Conclusion

The current research gives a detailed evaluation of water quality in the Lucknow area of the Gomti River and shows a definite spatial gradient of pollution by urbanization and anthropogenic forces. Physicochemical and microbiological parameters analysis revealed the gradual decrease in the water quality as upstream and downstream positions. The level of dissolved oxygen decreased drastically along the river path and the level of Biochemical oxygen demand, nutrient content, suspended solids and microbial indicator like total and faecal coliforms rose significantly. These trends show rising organic pollution and sewage pollution in the urban section of the river. These observations were further reinforced with multivariate statistical techniques. Principal component analysis revealed that the main factors that affect

the water quality variation are organic pollution, dissolved solids and microbial contamination. The hierarchical cluster analysis was used to cluster the sampling sites into the relatively clean upstream areas, moderately polluted transitional and severely polluted downstream areas. The river pollution profile diagram was a good demonstration of an inverse relationship between dissolved oxygen and pollution indicators as the river flow progressed. The results imply that the degradation of the ecological state of the river has been caused by rapid urbanization, discharge of untreated sewage, and hydromorphological changes related to the Gomti Riverfront development. The ecologically sensitive riverfront planning, better wastewater treatment and the replenishment of riparian buffers should incorporate into the river management process in order to increase the ability of the river to self-purify and safeguard the long-term ecological health of the Gomti River ecosystem. When these pressures are not eliminated, there is the risk that the ecological integrity and aquatic biodiversity of the river face additional threats. Thus, to guarantee the long-term sustainability of the Gomti River ecosystem, the integrated river basin management strategies are important in advancing pollution reduction and ecological restoration.

Implications of the Policy and Management

Findings of this report indicate that there are some critical policy and management issues to consider in enhancing the ecological health of Gomti River. To begin with, it is important to enhance the wastewater treatment plant to minimize the release of untreated domestic sewage and industrial effluents in the river. The operation and maintenance of sewage treatment plants should be emphasized to be operated effectively to allow them to meet the required environmental standards. Second, ecological restoration principles need to be put into the urban riverfront development projects instead of only concentrating on the aesthetic improvements. The natural self-purification ability of the river and the aquatic biodiversity can be improved by restoring natural riparian vegetation, establishing buffer zones, and increasing the heterogeneity of the habitat. Third, ongoing monitoring programs with conventional indicators of water quality and multivariate statistical analysis must be applied to monitor trends of pollution and assess the effectiveness of management interventions. These monitoring systems would allow early notification of environmental degradation and would facilitate in taking evidence-based decisions. Lastly, there should be the promotion of awareness campaigns in the community and involvement of the people in order to promote sustainability

of water usage and waste management. The combination of scientific studies with policy design and social participation will be important to recover and preserve the ecological integrity of the Gomti River.

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