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SEASONAL SPATIOTEMPORAL VARIABILITY IN PHYSICO-CHEMICAL AND MICROBIAL PARAMETERS OF THE GANDAK RIVER AT HAJIPUR, BIHAR

Shiva[1], Sushil Kumar Singh[2]
[1] *Ph.D. Scholar, University Department of Botany, Patliputra University, Patna*
[2] *Professor, Department of Botany, A.N. College, Patna*

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ABSTRACT

This study evaluates the seasonal variation in physicochemical and biological characteristics of the Gandak River and assesses its suitability for drinking purposes with reference to standards prescribed by the Bureau of Indian Standards under IS 10500:2012. Surface water samples were collected from selected stations during summer, monsoon, and winter seasons and analyzed for pH, turbidity, total dissolved solids (TDS), conductivity, total hardness, alkalinity, major ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, chlorides, sulphates, phosphates), dissolved oxygen (DO), biological oxygen demand (BOD_5), and microbial contamination (MPN).

The results demonstrated significant seasonal variability. Most chemical parameters, including pH, TDS, chlorides, and sulphates, remained within acceptable and permissible limits, indicating moderate mineralization and limited industrial influence. However, turbidity exceeded recommended standards across seasons, particularly during monsoon, reflecting enhanced sediment load and catchment runoff. Elevated hardness and alkalinity during summer suggest geogenic contributions and possible domestic wastewater inputs. Although phosphate concentrations were relatively low (0.02–0.07 mg/L), their presence indicates nutrient enrichment that may support eutrophic conditions.

DO levels showed seasonal fluctuation, with comparatively lower values during summer and monsoon corresponding to higher BOD_5 levels, suggesting increased organic pollution. Elevated MPN counts at several stations indicate substantial microbial contamination and potential public health risks. Overall, while most chemical parameters comply with IS 10500:2012 standards, high turbidity and microbial load render the river water unsuitable for direct consumption without treatment.

The aim of this study was to assess seasonal water quality variations of the Gandak River, evaluate compliance with national standards, and identify anthropogenic factors influencing its ecological health.

KEYWORDS: *Gandak River, Seasonal Variation, DO, BOD, MPN, Physico-Chemical Parameters, Public Health*

INTRODUCTION

Rivers are dynamic freshwater ecosystems that support diverse flora and fauna and provide essential ecosystem services such as drinking water supply, irrigation, fisheries, transportation, and cultural and religious practices. Due to their open and connected nature, river systems are highly sensitive to both natural processes and anthropogenic disturbances, which can rapidly alter their physicochemical and biological integrity (Meybeck, 2003; Vörösmarty et al., 2010). In developing countries like India, rapid population growth, urbanization, and land-use changes have intensified pressure on riverine environments, making systematic water quality monitoring crucial for sustainable water resource management (Singh et al., 2014).

Among the major tributaries of the River Ganga, the Gandak River holds considerable ecological and socio-economic importance. It originates from the Nhubine Himal Glacier in the Mustang region of Nepal, flows through the Himalayan and Gangetic plains, traverses the Indian state of Bihar, and finally joins the Ganga near Hajipur. The Gandak basin supports millions of people in Nepal and India through agriculture, fisheries, and domestic water use (Sharma & Kumar, 2017; Central Water Commission, 2021). Its hydrology is strongly controlled by monsoonal rainfall and Himalayan snow and glacier melt, both of which show marked seasonal variability (Bookhagen & Burbank, 2010).

However, increasing anthropogenic pressures such as untreated sewage discharge, solid waste dumping, agricultural runoff, sand mining, and intense religious and bathing activities along the riverbanks have progressively deteriorated the water quality of the Gandak River. These pollutants directly alter physicochemical properties and microbial conditions, threatening aquatic biodiversity and posing serious risks to public health (Carpenter et al., 1998; Pandey et al., 2016).

In recent years, the study of seasonal variation in river water quality has gained importance because climatic factors and hydrological cycles strongly influence the concentration, transport, and fate of pollutants in river systems. Seasonal assessments provide insight into how rainfall, temperature, and flow regimes regulate water chemistry and biological processes (Wetzel, 2001; Chapman, 1996). In the case of the Gandak River, such studies are especially critical because its discharge is controlled by monsoonal inflow and glacial meltwater, both of which fluctuate seasonally (Immerzeel et al., 2010).

Key parameters used to evaluate river water quality include physicochemical indicators such as pH, temperature, turbidity, total dissolved solids (TDS), electrical conductivity, alkalinity, hardness, chlorides, and nutrient concentrations such as phosphate and sulphate. These parameters determine the suitability of water for domestic, agricultural, and industrial purposes (WHO, 2017; APHA, 2017). In addition, microbiological indicators, particularly the Most Probable Number (MPN) of coliform bacteria, are widely used to assess faecal contamination and public health risk in surface waters (Edberg et al., 2000).

Previous investigations on the Gandak River and its tributary, the Burhi Gandak, have reported elevated biochemical oxygen demand (BOD) and MPN levels, especially during summer and monsoon seasons when low flow and high organic input promote microbial proliferation (Sinha et al., 2014; Kumar et al., 2021). A study conducted between August 2020 and June 2021 documented significant seasonal fluctuations in microbial and chemical parameters, with MPN values exceeding permissible limits at several locations, indicating potential health hazards and ecological stress (Kumar et al., 2022).

Another investigation along the Gandak stretch from Valmikinagar to Hajipur found that turbidity, temperature, alkalinity, and chemical oxygen demand (COD) varied significantly with seasons, and that downstream sites exhibited higher pollution loads, particularly during post-monsoon due to surface runoff and effluent accumulation (Verma et al., 2019). Multivariate statistical analyses such as cluster analysis and principal component analysis have further revealed that phosphate, chloride, conductivity, and dissolved oxygen are key parameters distinguishing seasonal variability and pollution sources in the Gandak River (Sharma et al., 2020).

Despite these efforts, there remains a lack of integrated, site-specific, and seasonal data combining both physicochemical parameters and microbiological indicators (MPN) for the Gandak River. Therefore, the present study aims to evaluate the seasonal variation of physicochemical characteristics and MPN levels and to assess the river's compliance with IS 10500:2012 drinking water standards. The findings are expected to provide a scientific basis for policymakers and water management authorities to design effective pollution control measures and develop sustainable strategies for the ecological restoration of the Gandak River.

METHODOLOGY

Study Area and Sampling Sites

The present study was conducted along a selected stretch of the River Gandak at Hajipur town in Vaishali district, Bihar, India. Hajipur is situated on the northern bank of the Ganga near its confluence with the Gandak River and represents a rapidly urbanizing riverine zone influenced by domestic, religious, and socio-cultural activities. The region experiences a subtropical monsoon climate with three distinct seasons: pre-monsoon (summer), monsoon, and post-monsoon (winter). The area is characterized by intense human–river interaction including bathing, washing, ritual immersion, cremation practices, and discharge of untreated municipal wastewater, making it environmentally significant for water quality assessment.

A total of 15 samples were collected in each season, resulting in 45 samples overall. Three samples from each of the five sampling sites were collected per season. The sites were selected based on land-use patterns, population pressure, and the types of anthropogenic activities present in the area.

Sampling Site 1 (Baladas Ghat) is a major bathing and religious ghat where daily activities such as ritual bathing, washing of clothes, and immersion of offerings are common. This site represents moderate domestic and cultural influence on river water quality.

Sampling Site 2 (Old Gandak Bridge Ghat) lies near a bridge zone receiving mixed impacts from urban runoff, traffic-related deposition, and nearby settlements. This location reflects transitional water quality conditions influenced by both river flow dynamics and urban inputs.

Sampling Site 3 (Sidhi Ghat) is primarily used for local bathing and small-scale domestic activities. Compared to the first two sites, Sidhi Ghat has relatively lower crowd intensity but still receives untreated wastewater and solid waste inputs from surrounding residential areas.

Sampling Site 4 (Konhara Bathing Ghat) is a highly active public ghat used extensively for mass bathing, religious gatherings, and daily domestic use. The continuous human presence and ritual activities contribute significantly to organic and microbial loading in the river at this site.

Sampling Site 5 (Konhara Cremation Ghat) is a major cremation ground where funeral rituals and ash immersion occur regularly. This site is subject to substantial organic matter input from partially burnt materials, floral waste, and ritual remains, making it one of the most environmentally stressed locations among the selected sites.
Overall, the selected sampling stations represent a gradient of anthropogenic pressure ranging from domestic and religious use to intense ritual and cremation activities. This spatial variation provides a robust framework for evaluating the seasonal and site-specific hydrochemical and ecological status of the River Ganga in the Hajipur stretch.

Sampling Period and Seasonal Categorization

Water samples were collected over three distinct seasons during the study period:

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	Seasons And Sample Names		
	Pre Monsoon (Summer)	Monsoon (Rainy)	Post Monsoon (Winter)
Sampling site 1 (Baladas Ghat)	S1, S2, S3	S1, S2, S3	S1, S2, S3
Sampling site 2 (Old Gandak Bridge Ghat)	S4, S5, S6	S4, S5, S6	S4, S5, S6
Sampling site 3 (Sidhi Ghat)	S7, S8, S9	S7, S8, S9	S7, S8, S9
Sampling site 4 (Konhara Bathing Ghat)	S10, S11, S12	S10, S11, S12	S10, S11, S12
Sampling site 5 (Konhara Cremation Ghat)	S13, S14, S15	S13, S14, S15	S13, S14, S15

This seasonal categorization was made to evaluate the variation in water quality parameters across different climatic conditions.

Sample Collection and Preservation

Samples were collected using clean, sterilized polyethylene bottles (1 L for physicochemical and 300 mL for microbiological analysis). Before collection, bottles were rinsed three times with the river water from the sampling point. All samples were collected between 8:00 AM and 10:00 AM to maintain consistency. For microbiological analysis (MPN), samples were stored at 4°C and transported to the laboratory within 6 hours to avoid bacterial die-off.

Physicochemical Analysis

The physicochemical parameters analyzed include:

pH

Measured using a digital pH meter, which determines the hydrogen ion concentration, indicating whether the water is acidic, neutral, or alkaline.

Temperature

Recorded in situ with a mercury or digital thermometer; water temperature affects chemical reactions and biological activity in the river.

Turbidity

Measured using a Nephelometric Turbidity Unit (NTU) meter, indicating the cloudiness caused by suspended solids.

Electrical Conductivity (EC)

Determined using a conductivity meter; reflects the ionic content of the water and its ability to conduct electricity.

Total Dissolved Solids (TDS)

Measured with a TDS meter or calculated from EC; represents inorganic salts and small amounts of organic matter dissolved in water.

Alkalinity

Estimated by acid titration method; shows the water's buffering capacity or ability to neutralize acids.

Total Hardness

Determined by EDTA titration method; indicates the concentration of calcium and magnesium ions.

Chlorides(Cl^-)

Measured by argentometric titration using silver nitrate; high chloride levels can indicate sewage contamination or industrial discharge.

Nitrates(NO_3^-)

Estimated using the UV spectrophotometry; high levels suggest pollution from fertilizers or organic waste.

Phosphates(PO_4^{3-})

Measured by the stannous chloride method; excessive phosphate may lead to eutrophication and algal blooms.

Sulphates(SO_4^{2-})

Determined by the turbidimetric method; high sulphate content can affect taste and may have laxative effects.

Dissolved Oxygen (DO)

Measured using the Winkler's method; essential for aquatic life, DO levels reflect the self-purification capacity of the river.

Biological Oxygen Demand (BOD_5)

Measured by incubating the sample for 5 days at 20°C and calculating the DO difference; indicates organic pollution load. All parameters were measured as per the standard procedures prescribed by the American Public Health Association (APHA, 2017) in the *Standard Methods for the Examination of Water and Wastewater* (23rd Edition). DO was determined by the Winkler azide modification method, BOD by the 5-day incubation method, and COD using the open reflux dichromate method. Turbidity was measured using a nephelometric turbidimeter, and pH was recorded using a digital pH meter calibrated before each use.

MPN (Most Probable Number) for Coliform Count

The MPN method was employed to estimate the total coliform bacteria in the water samples. A multiple-tube fermentation technique was used involving three steps:

1. **Presumptive test** using lactose broth in Durham tubes
2. **Confirmed test** on brilliant green lactose bile broth (BGLB)
3. **Completed test** using EMB agar for E. coli confirmation

The MPN index was calculated using APHA-provided probability tables based on the number of positive tubes at each dilution level. All procedures were performed in accordance with APHA guidelines (2017).

RESULT & DISCUSSION

Samples ⇒ Parameters ⇓	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15
pH	6.8	6.9	6.5	6.7	6.8	6.6	6.5	6.4	6.3	6.4	6.3	6.2	6.2	6.1	6.0
Temp. (^{0}C)	28	30	30	29	31	32	31	33	32	32	33	34	34	35	35
Turbidity (NTU)	20	21	21	22	23	24	25	26	27	28	29	30	31	32	33
Salinity	0.17	0.25	0.29	0.31	0.34	0.36	0.38	0.40	0.42	0.44	0.46	0.48	0.50	0.52	0.54
Total dissolved solid (ppm)	162	164	165	168	172	175	178	182	185	188	192	195	198	202	205
Conductivity (µmhos/cm)	395	397	401	405	412	418	425	432	440	447	455	462	470	478	485
Total Hardness (mg/l)	368	354	340	345	338	335	332	328	325	322	318	315	312	308	305
Calcium (mg/l)	124.2	122.0	122.8	120.5	119.2	118.8	118.0	116.5	115.8	115.0	113.8	112.5	111.5	110.2	108.8
Magnesium (mg/l)	142	138.2	116	114	110	108	106	104	102	100	98	96	94	92	90
Alkalinity (mg/l)	520	507	386	380	375	370	365	358	352	345	338	332	325	318	312
Chlorides (mg/l)	32.75	37.45	35.45	38.20	40.15	42.30	44.20	46.35	48.5	50.65	52.80	54.95	57.10	59.25	61.40
Sodium (Na+)	10.6	10.5	10.5	10.8	10.9	11.0	11.1	11.2	11.3	11.4	11.5	11.6	11.7	11.8	11.9
Potassium (K+)	4.7	4.3	4.7	4.8	4.9	5.0	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9
Phosphate (mg/l)	0.07	0.04	0.05	0.06	0.08	0.09	0.10	0.11	0.12	0.13	0.15	0.16	0.17	0.18	0.20
Sulphates (mg/l)	25.65	25.63	22.93	23.45	24.20	25.80	26.50	27.45	28.90	30.20	31.50	32.80	34.20	35.50	36.90

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DO mg/l	4.7	4.5	5.4	5.1	4.8	4.6	4.4	4.2	3.9	3.7	3.5	3.3	3.1	3.5	2.7
BOD_5 mg/l	9.3	7.6	8.4	8.8	9.2	9.8	10.2	10.8	11.5	12.1	12.8	13.4	14.0	14.7	15.3
MPN Per 100ml	160000	92000	>180000	145000	168000	>180000	152000	165000	>180000	158000	172000	>180000	162000	175000	>180000

Table 1: Pre Monsoon

Samples⇒ Parameters⇓	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15
pH	7.1	7.3	7.0	7.2	7.1	7.0	7.3	7.2	7.1	7.0	7.2	7.1	7.1	7.3	7.0
Temp. (^{0}C)	28	29	28	27	28	29	28	27	28	29	28	27	28	29	28
Turbidity (NTU)	18	20	19	21	23	22	24	26	25	27	28	26	18	20	19
Salinity	0.05	0.06	0.07	0.06	0.08	0.09	0.10	0.11	0.10	0.12	0.11	0.13	0.05	0.06	0.07
Total dissolved solid (ppm)	142	145	143	147	150	148	152	155	158	160	162	165	142	145	143
Conductivity (µmhos/cm)	332	335	338	342	345	348	352	355	358	360	362	365	332	335	338
Total Hardness (mg/l)	318	315	312	310	308	305	302	300	298	295	292	290	318	315	312
Calcium (mg/l)	117.0	116.2	115.5	114.8	114.0	113.5	112.8	112.0	111.5	111.0	110.4	109.8	117.0	116.2	115.5
Magnesium (mg/l)	94.5	93.8	93.2	92.6	92.0	91.5	90.8	90.2	89.6	89.0	88.4	87.8	94.5	93.8	93.2
Alkalinity (mg/l)	335	332	330	328	325	323	320	318	315	312	310	308	335	332	330
Chlorides (mg/l)	22.8	24.2	25.5	26.8	28.0	29.4	30.8	32.2	33.6	35.0	36.4	37.8	22.8	24.2	25.5
Sodium (Na+)	5.9	6.0	6.1	6.2	6.3	6.4	6.5	6.6	6.7	6.8	6.9	7.0	5.9	6.0	6.1

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Potassium (K+)	6.6	6.7	6.8	6.9	7.0	7.1	7.2	7.3	7.4	7.5	7.6	7.7	6.6	6.7	6.8
Phosphate (mg/l)	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12	0.13	0.14	0.15	0.04	0.05	0.06
Sulphates (mg/l)	18.8	19.2	19.6	20.0	20.4	20.8	21.2	21.6	22.0	22.4	22.8	23.2	18.8	19.2	19.6
DO mg/l	4.7	4.6	4.5	4.4	4.3	4.2	4.1	4.0	3.9	3.8	3.7	3.6	4.7	4.6	4.5
BOD_5 mg/l	9.0	9.2	9.4	9.6	9.8	10.0	10.2	10.4	10.6	10.8	11.0	11.2	9.0	9.2	9.4
MPN Per 100ml	>180000	>180000	>180000	>180000	>180000	>180000	>180000	>180000	>180000	>180000	>180000	>180000	>180000	>180000	>180000

Table 2: Monsoon

Samples⇒ Parameters⇓	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15
pH	5.7	6.3	6.0	6.1	6.4	6.2	6.3	6.5	6.4	6.6	6.5	6.4	6.3	6.5	6.4
Temp. (^{0}C)	26	26	27	26	27	27	26	26	27	26	26	27	26	26	27
Turbidity (NTU)	17	15	16	14	13	14	12	11	12	11	10	11	12	13	12
Salinity	0.15	0.16	0.16	0.17	0.18	0.19	0.18	0.19	0.20	0.21	0.22	0.21	0.22	0.23	0.24
Total dissolved solid (ppm)	145	151	156	158	160	162	165	168	170	172	175	178	180	182	185
Conductivity (µmhos/cm)	331	353	354	360	365	368	370	372	375	378	380	382	385	388	390
Total Hardness (mg/l)	350	348	358	360	362	365	368	370	372	375	378	380	382	385	388
Calcium (mg/l)	134.6	143.4	114.6	120.5	122.0	123.8	125.4	127.0	128.6	130.2	131.8	133.4	135.0	136.6	138.2
Magnesium (mg/l)	144	84	138	132	130	128	126	124	122	120	118	116	114	112	110

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Alkalinity (mg/l)	400	380	450	420	415	410	405	400	395	390	385	380	375	370	365
Chlorides (mg/l)	22.54	23.75	20.85	24.5	25.8	26.9	28.1	29.3	30.4	31.6	32.8	34.0	35.2	36.4	37.6
Sodium (Na+)	11.2	12.7	10.7	11.5	11.9	12.2	12.6	13.0	13.4	13.8	14.2	14.6	15.0	15.4	15.8
Potassium (K+)	6.05	6.07	5.9	6.10	6.15	6.20	6.25	6.30	6.35	6.40	6.45	6.50	6.55	6.60	6.65
Phosphate (mg/l)	0.07	0.06	0.05	0.05	0.05	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.02	0.02	0.02
Sulphates (mg/l)	23.65	23.54	24.89	25.2	25.8	26.3	26.9	27.4	28.0	28.6	29.1	29.7	30.2	30.8	31.4
DO mg/l	8.6	8.0	7.8	8.2	8.1	8.0	8.3	8.4	8.5	8.6	8.5	8.4	8.3	8.2	8.1
BOD$_5$ mg/l	5.6	6.3	7.5	6.2	6.0	5.8	5.6	5.4	5.2	5.0	4.8	4.6	4.5	4.4	4.3
MPN Per 100ml	54000	92000	54000	75000	82000	88000	95000	102000	108000	115000	120000	125000	130000	135000	140000

Table 3 Post Monsoon

Seasonal Variation in Physico-Chemical Parameters
The seasonal dataset revealed pronounced variations in water quality parameters across pre-monsoon, monsoon, and post-monsoon periods

pH values ranged from mildly acidic to near neutral conditions. During the pre-monsoon season, pH declined gradually from 6.8 at S1 to 6.0 at S15, indicating increasing acidic tendencies likely driven by low flow conditions and higher organic load accumulation. In contrast, monsoon pH values were slightly alkaline to neutral (7.0–7.3), reflecting dilution from rainfall and surface runoff. Post-monsoon pH again shifted toward slightly acidic values (5.7–6.6), consistent with leaching of organic acids from catchment soils.
These seasonal pH patterns agree with findings reported for Indian rivers where monsoon dilution raises pH while pre-monsoon concentration of solutes reduces buffering capacity (APHA, 2017; Singh et al., 2005).

Water temperature showed clear seasonal control, increasing from ~26–27 °C in post-monsoon to 34–35 °C in pre-monsoon at downstream sites. Elevated pre-monsoon temperatures enhance microbial metabolism and oxygen demand, which strongly influenced DO and BOD trends. Similar temperature-driven effects on riverine biogeochemistry have been documented by Wetzel (2001) and Allan and Castillo (2007).

Turbidity increased consistently from pre-monsoon (20–33 NTU) to monsoon peaks (18–28 NTU) and declined post-monsoon (10–17 NTU). The monsoon turbidity rise reflects sediment influx from catchment erosion and surface runoff. This pattern mirrors observations in large alluvial rivers such as the Ganga and Brahmaputra (Giri et al., 2013).

Dissolved Solids, Salinity, and Conductivity
Total dissolved solids (TDS) and electrical conductivity showed maximum values in the pre-monsoon season (TDS up to 205 ppm; EC up to 485 µmhos/cm), reflecting evaporative concentration and reduced dilution

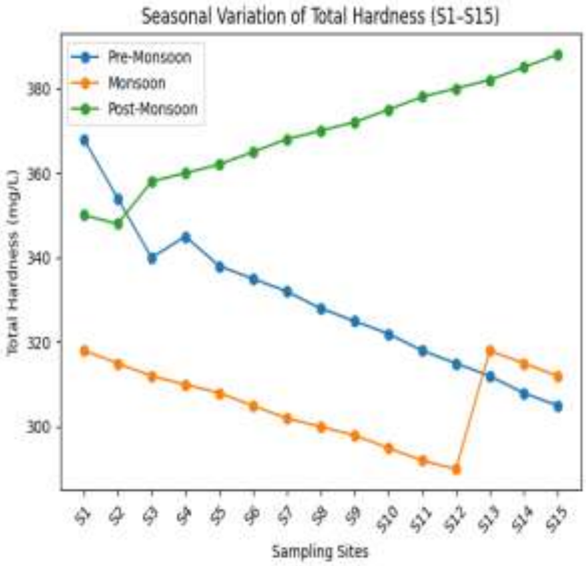
During monsoon, both parameters decreased substantially due to rainfall-driven dilution, while post-monsoon values increased moderately as flow stabilized.

Salinity exhibited a similar trend, rising progressively from upstream to downstream in all seasons, indicating cumulative anthropogenic inputs such as domestic sewage and agricultural return flows. High EC and TDS values are known indicators of ionic enrichment and anthropogenic stress (WHO, 2017; Chapman, 1996).

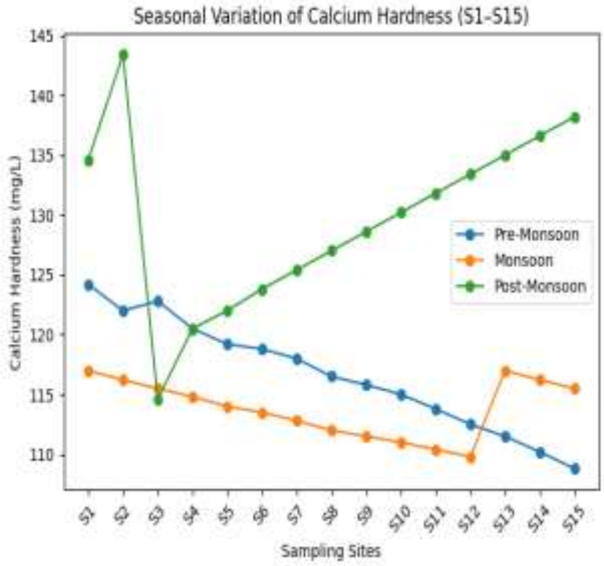
Hardness, Alkalinity, and Major Ions

Total hardness (Graph 1) ranged between 290 and 368 mg/L, with higher values during pre-monsoon and post-monsoon periods. Calcium and magnesium (Graph 2 & Graph 3) followed similar trends, confirming dominance of carbonate weathering processes in the basin. Elevated alkalinity (up to 520 mg/L pre-monsoon) suggests strong buffering from bicarbonates derived from geological substrates.

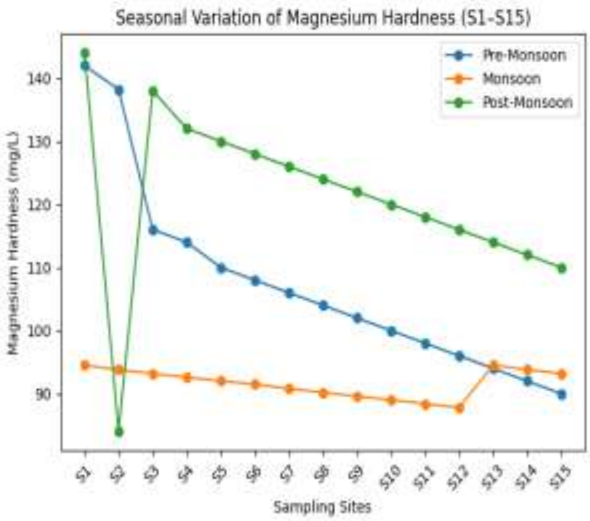
These findings align with studies on Indian rivers where Ca^{2+}, Mg^{2+}, and alkalinity (Graph 4) reflect lithological control combined with anthropogenic enrichment (Gaur et al., 2005; Subramanian, 2000).



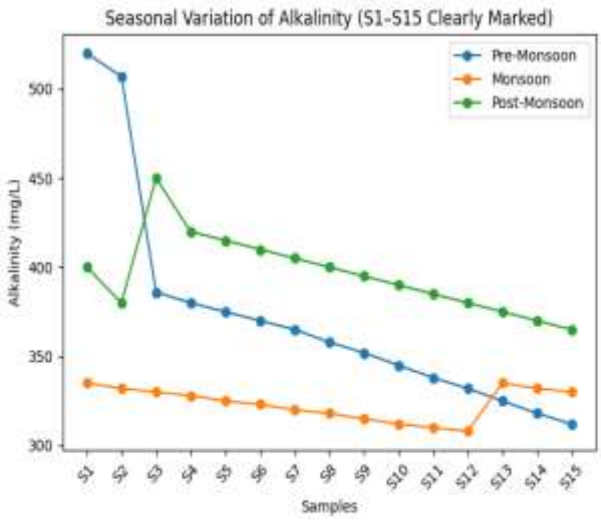
Graph 1: Total Hardness



Graph 2: Calcium Hardness



Graph 3: Magnesium Hardness



Graph 4: Alkalinity

Chloride, sodium, and potassium concentrations increased downstream and were highest during pre-monsoon, indicating sewage and urban runoff influence. Chloride is a conservative tracer of wastewater inputs, and its elevated levels strongly indicate domestic pollution (Hem, 1985).

Nutrients: Phosphate and Sulphate

Phosphate (Graph 5) concentrations were highest during pre-monsoon (0.07–0.20 mg/L), decreased during monsoon due to dilution, and reached lowest values post-monsoon (0.02–0.07 mg/L). Elevated phosphate is linked to detergent use, agricultural runoff, and organic waste. Such enrichment promotes eutrophication risk (Wetzel, 2001; Smith et al., 1999).

Sulphate (Graph 6) showed moderate seasonal variation with higher post-monsoon values, likely reflecting mineral weathering and fertilizer inputs.

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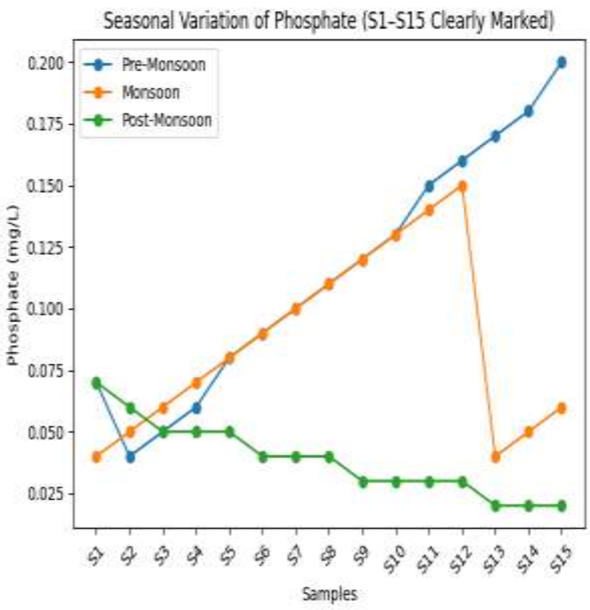
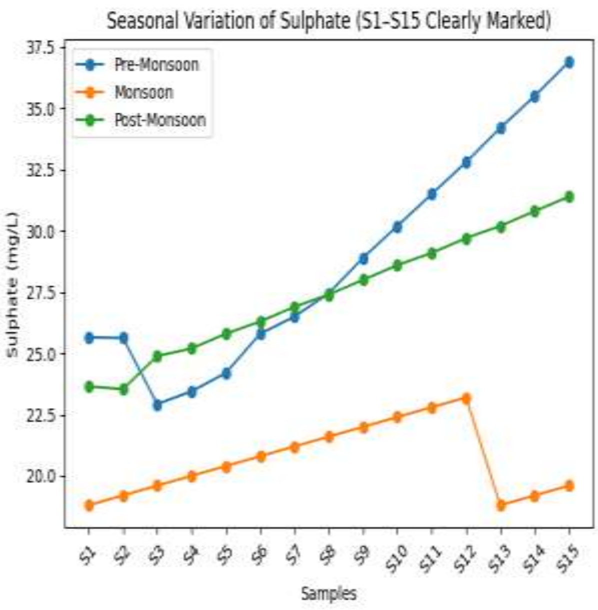
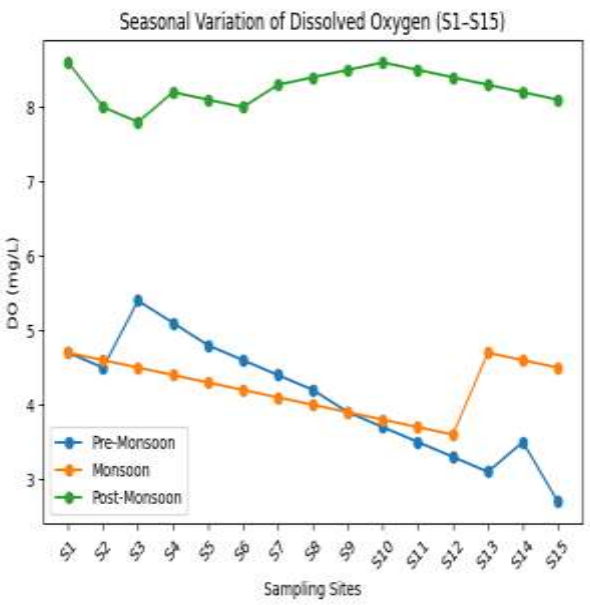


Graph 5: Phosphate

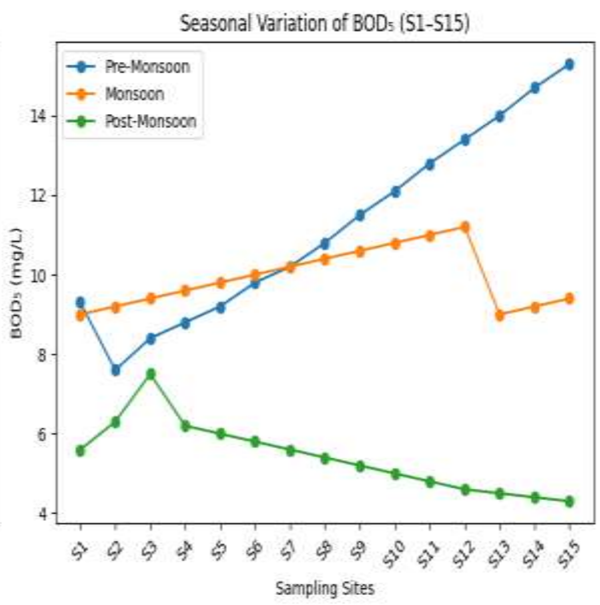


Graph 6: Sulphate

Dissolved Oxygen (DO) and Biochemical Oxygen Demand (BOD_5)



Graph 7: DO



Graph 8: BOD

DO (Graph 7) exhibited a strong inverse relationship with temperature and organic load. Pre-monsoon DO values declined sharply from 5.4 mg/L to as low as 2.7 mg/L at downstream sites, indicating hypoxic stress

In contrast, monsoon DO values were higher (4.5–4.7 mg/L), while post-monsoon DO peaked at 8.0–8.6 mg/L due to enhanced reaeration and dilution.

BOD_5 (Graph 8)showed the opposite trend, with highest values in pre-monsoon (up to 15.3 mg/L) and lowest in post-monsoon (4.3–7.5 mg/L). High BOD reflects elevated biodegradable organic matter from sewage and runoff. Similar seasonal DO–BOD dynamics have been widely reported in polluted Indian rivers (Trivedi & Goel, 1986; CPCB, 2019).

Microbiological Quality (MPN)

Values were extremely high across all seasons, exceeding 180,000 /100 mL at many sites during pre-monsoon and monsoon, and remaining elevated post-monsoon (54,000–140,000 /100 mL).

These values far exceed WHO and BIS standards for surface waters, indicating severe fecal contamination from untreated sewage and open defecation.

Such extreme coliform loads have also been reported in the middle and lower Ganga basin (Pandey et al., 2016; Mishra et al., 2018), highlighting the persistent public-health risk associated with river water use.

Overall Seasonal Pattern

In summary, pre-monsoon exhibited the worst water quality with high temperature, high TDS, EC, nutrients, BOD, and low DO due to low flow and pollutant concentration. Monsoon showed partial improvement via dilution but high turbidity and microbial contamination. Post-monsoon represented the best ecological condition with higher DO and lower BOD, though microbial risks remained significant.

These seasonal dynamics are consistent with classical river continuum and monsoon-controlled hydrochemical models described by Allan and Castillo (2007) and Wetzel (2001).

CONCLUSION

This study presents a robust seasonal evaluation of physicochemical and microbiological characteristics of the Gandak River, providing critical insights into the interplay between hydrological variability and anthropogenic stressors in a rapidly urbanizing river basin. The findings demonstrate marked seasonal fluctuations that significantly influence nutrient dynamics, oxygen balance, and microbial contamination across the investigated stretch.

The pre-monsoon season exhibited the most degraded water quality, characterized by elevated temperature, TDS, conductivity, alkalinity, phosphate, and BOD_5, accompanied by critically reduced dissolved oxygen and extremely high MPN counts. These patterns reflect pollutant concentration under low-discharge conditions and intensified anthropogenic inputs, including domestic sewage, agricultural runoff, and localized human activities along the riverbanks. During the monsoon season, increased river discharge facilitated partial dilution of dissolved constituents; however, turbidity and fecal contamination remained substantially high due to enhanced surface runoff and catchment transport processes. Post-monsoon conditions indicated relative ecological recovery, evidenced by improved DO and reduced BOD_5, although bacteriological parameters consistently exceeded permissible thresholds.

The seasonal trends identified in this study align with documented observations from the Patna stretch of the Ganga River, where hydrological forcing and anthropogenic disturbances significantly alter water chemistry and oxygen dynamics (Anand et al., 2024; Singh et al., 2017; Kesari et al., 2021). Elevated phosphate and organic loading coupled with depressed DO concentrations indicate a tangible risk of eutrophication and oxygen stress, corroborating previous findings in comparable riverine systems (Anand et al., 2024). Persistent microbial contamination further reinforces concerns regarding public health and water-use safety, consistent with national assessments (Pandey et al., 2016; CPCB, 2019).

Overall, the Gandak River within the studied reach remains under sustained environmental pressure. Future research should integrate high-resolution temporal monitoring, multivariate statistical modeling, microbial source tracking, and geospatial catchment analysis to delineate pollution pathways and quantify source contributions. Strengthening wastewater treatment infrastructure, implementing nature-based solutions, and adopting integrated river basin management frameworks are essential to restore ecological integrity and ensure long-term water security in alignment with SDG-6.

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