

Spatial and Seasonal Variation in Physicochemical Water Quality of the Gandak River at Hajipur–Sonepur, Bihar, India

Prof. Kalpana Shahi^{1*}, Monika Singh²

¹ Department of Chemistry, College of Commerce, Arts and Science, Patna, Bihar, India

E-mail: drkalpanashahi@gmail.com

² Department of Chemistry, K.B. Sahay Senior Secondary School, Patna, Bihar, India

E-mail: monikasingh.horizon@gmail.com

Abstract:

The Gandak River is an important tributary of the Ganga and supports domestic, agricultural, religious and other human activities along its lower reaches. The present study assessed the spatial and seasonal variation in physicochemical water quality of the Gandak River in the Hajipur–Sonepur region of Bihar, India. Water samples were evaluated at five representative locations, namely Baladas Ghat, Old Gandak Bridge Ghat, Sidhi Ghat, Konhara Bathing Ghat and Konhara Cremation Ghat, during the pre-monsoon, monsoon and post-monsoon seasons of 2018. Sixteen physicochemical parameters were investigated, including temperature, pH, turbidity, electrical conductivity (EC), total dissolved solids (TDS), total hardness, calcium hardness, magnesium hardness, alkalinity, chloride, fluoride, nitrate, sulphate, sodium, potassium and iron. The results indicated that the river water was generally neutral to moderately alkaline, while considerable seasonal variability was observed in turbidity, EC, TDS and several dissolved ionic constituents. Turbidity generally increased during the monsoon period, whereas EC and TDS showed comparatively lower concentrations during high-flow conditions, indicating the influence of runoff and dilution. Hardness and alkalinity exhibited comparatively moderate seasonal variation. Spatially, the Konhara Bathing Ghat and Konhara Cremation Ghat showed greater variability in several physicochemical characteristics than the upstream sampling locations, reflecting the influence of intensive riverfront use and localized anthropogenic activities. Two-way analysis of variance further demonstrated significant effects of season and, for several parameters, sampling location on water-quality characteristics. The findings demonstrate that physicochemical conditions in the Hajipur–Sonepur stretch are governed by the combined influence of seasonal hydrology, river discharge, runoff and localized human activities. The study provides a baseline for seasonal water-quality monitoring and supports the need for improved management of anthropogenic activities along the Gandak riverfront.

Keywords: Gandak River, Hajipur–Sonepur, water quality, physicochemical parameters, seasonal variation, spatial variation, turbidity, river pollution, ANOVA.

1. Introduction

Rivers are dynamic freshwater ecosystems that support ecological processes and a wide range of human activities, including domestic water supply, agriculture, fisheries, industry and cultural practices. They

also function as natural pathways for the transport of sediments, nutrients, dissolved substances and other materials through drainage basins. Because river water integrates inputs from both natural and anthropogenic sources, changes in its physical and chemical characteristics can provide important information about the environmental condition of a watershed [1,2]. Increasing pressure from population growth, urbanization, agricultural intensification and other human activities has made the protection and monitoring of river systems an important component of freshwater-resource management [3,4].

Physicochemical characteristics provide fundamental information for evaluating the condition of surface-water systems. Parameters such as temperature, pH, turbidity, electrical conductivity (EC), total dissolved solids (TDS), alkalinity, hardness, chloride, sulphate, nitrate, phosphate, dissolved oxygen (DO), biochemical oxygen demand (BOD) and chemical oxygen demand (COD) respond to changes in hydrological conditions, mineral dissolution, sediment transport, biological activity and pollutant inputs [6,5]. Individual parameters provide information about particular aspects of water chemistry, whereas their combined assessment provides a more comprehensive understanding of spatial and temporal changes in river-water quality. Standardized analytical procedures are therefore essential for obtaining comparable and reliable water-quality observations [7].

River-water quality commonly varies along the longitudinal profile of a river because natural characteristics and pollution sources are not uniformly distributed throughout a catchment. Upstream reaches may be influenced mainly by geological and hydrological processes, whereas downstream reaches can receive cumulative inputs from settlements, agricultural areas, tributaries, wastewater discharges and other anthropogenic sources. Land use within the surrounding catchment can influence the physical habitat and chemical characteristics of streams and rivers through several interacting pathways, with the magnitude of these effects varying according to spatial scale and local environmental conditions [8]. Consequently, spatially distributed sampling is important for identifying localized changes and determining whether water-quality conditions become progressively altered along a river course.

Seasonal variation represents another major component of river-water quality. In monsoon-dominated regions, changes in precipitation and river discharge influence dilution, runoff, sediment transport and the mobilization of dissolved and particulate materials. During periods of increased rainfall, surface runoff may transport suspended sediments, nutrients and organic matter from surrounding land into river channels. Conversely, reduced discharge during dry periods may increase the relative influence of local pollution sources and alter the concentration of dissolved constituents. The design of river-water-quality monitoring programmes therefore needs to consider both spatial distribution and seasonal changes in pollution loads [9]. Seasonal assessment can distinguish persistent spatial differences from variations associated with changing hydrological conditions and thereby provide a more representative characterization of river-water quality.

The Gandak River is an important Himalayan-fed tributary of the Ganga River system and has considerable hydrological, ecological and socioeconomic significance in northern India. The river enters the Gangetic Plains and flows through Bihar before joining the Ganga near the Hajipur–Sonepur region. The Gangetic Plains contain a complex network of mountain-fed, foothill-fed and plains-fed rivers that differ in their hydrological behaviour, sediment transport and fluvial characteristics [1,2]. Mountain-fed rivers such as the Gandak transport substantial quantities of sediment from the Himalayan source region into the alluvial plains, contributing to the development and modification of the extensive depositional landscape of northern Bihar [2]. These characteristics make the Gandak an important river system for investigating environmental changes within the middle Gangetic region.

The physicochemical quality of the Gandak River has been investigated at different spatial scales before the present study. A longitudinal assessment covering 21 sampling stations over approximately 331 km, from the Valmikinagar region to the Gandak–Ganga confluence near Hajipur, reported spatial variation in several physicochemical parameters. The study identified comparatively greater turbidity in the lower approximately 23 km of the river and higher COD in the final approximately 43 km compared with the upstream portion, indicating increasing influence of local conditions toward the lower river [4]. The same investigation also reported variations in conductivity, TDS, hardness, chloride, phosphate and nitrate along the river course, demonstrating the importance of spatially distributed observations for evaluating Gandak River water quality.

The Sonapur–Hajipur section is particularly relevant because the lower Gandak is influenced by dense human settlement and intensive use of riverbank areas. A study specifically conducted at Sonapur examined physicochemical and biological characteristics of Gandak River water and reported differences among locations including Rewa Ghat and Konhara Ghat. Higher COD values were reported at these lower-reach locations, and the study associated the observed conditions with human settlement and the potential discharge of domestic sewage and other wastes into the river [3]. Such observations indicate that local riverfront activities may contribute to spatial heterogeneity in water quality within the lower Gandak. Seasonal changes in the Gandak have also been documented. A two-year investigation covering 2014–15 and 2015–16 examined physicochemical characteristics and selected heavy metals at five locations, including Sonpur Bridge. The study reported seasonal variations in temperature, pH, TDS, alkalinity, sulphate, phosphate, hardness, chloride, nitrate, DO, BOD and COD, demonstrating that the physicochemical condition of the Gandak changes with hydrological season [5,6]. These findings are particularly relevant to the lower Gandak because Sonpur Bridge provides a spatial reference within the same broader river corridor considered in the present investigation.

Further research on the Gandak and Ghaghara river systems used multivariate statistical techniques and land-use/land-cover information to investigate water quality and ecological characteristics. The study considered observations from 2011–2012 and identified agricultural land as a dominant land-use class within both river basins. Multivariate techniques, including cluster analysis and principal component/factor analysis, were applied to investigate potential pollutant sources and patterns of water-quality variation [7]. The findings emphasize the value of integrating spatial water-quality observations with environmental and land-use information when examining river systems influenced by multiple natural and anthropogenic factors.

The importance of seasonal and spatial assessment is also supported by investigations of other Indian river systems. Seasonal monitoring of the Cooum River demonstrated significant variation in physicochemical characteristics among sampling periods and locations, reflecting the influence of urban development and changing hydrological conditions [8]. Similarly, studies of river-water monitoring have shown that the selection of sampling locations should account for seasonal changes in point and diffuse pollution loads, particularly in river systems where pollutant sources and hydrological conditions change throughout the year [9]. Such approaches are applicable to the Gandak because the river experiences pronounced seasonal changes associated with the Indian monsoon and substantial variation in human activity along its lower reaches.

The interpretation of physicochemical observations also requires appropriate analytical and water-quality benchmarks. The 23rd edition of Standard Methods for the Examination of Water and Wastewater, available in 2017, provides standardized procedures for the analysis of a wide range of physical, chemical

and biological characteristics of water [10]. The Bureau of Indian Standards IS 10500:2012 provides specifications and guideline values for drinking-water quality and can be used as an appropriate Indian reference framework where river-water observations are compared with drinking-water requirements [11]. Similarly, the World Health Organization Guidelines for Drinking-water Quality, including the fourth edition incorporating the first addendum published in 2017, provide internationally recognized guidance for assessing water-quality parameters in relation to human-health protection [12]. These standards are useful for interpretation, although river-water quality should also be evaluated in relation to the ecological and hydrological characteristics of the river rather than solely through drinking-water criteria.

Despite the availability of previous investigations, there remains a need for a focused assessment of the Hajipur–Sonepur stretch of the Gandak River that simultaneously examines spatial and seasonal variation in physicochemical characteristics. Earlier studies have considered either broad longitudinal sections of the Gandak, selected locations within the lower river, or specific environmental components such as phytoplankton, heavy metals and ecological diversity [3–5,7]. A detailed spatial assessment of multiple sampling locations within the Hajipur–Sonepur corridor can therefore provide greater resolution of local differences in water quality, while seasonal observations can help distinguish spatial patterns from changes associated with monsoon and post-monsoon hydrological conditions.

The present study was therefore undertaken to assess the spatial and seasonal variation in physicochemical water quality of the Gandak River at Hajipur–Sonepur, Bihar, India, during 2018. The study evaluates selected physicochemical parameters across different sampling locations and seasons to identify spatial gradients and temporal changes in river-water characteristics. The observed variations are interpreted in relation to seasonal hydrological conditions, the location of sampling sites and potential anthropogenic influences within the lower Gandak corridor.

2. Methodology

2.1 Study Area and Sampling

The study was conducted along the Gandak River in the Hajipur–Sonepur region of Vaishali district, Bihar, India. The study area lies within the middle Gangetic Plain and represents a predominantly alluvial landscape influenced by monsoonal hydrology. The Gandak flows through the northern Bihar plains before joining the Ganga near the Hajipur–Sonepur region. The lower river stretch is characterized by densely populated settlements, agricultural activities and intensive use of riverbank areas for bathing, religious practices and cremation. Five representative sampling locations were selected to assess spatial variation in river-water quality: Baladas Ghat (S1–S3), Old Gandak Bridge Ghat (S4–S6), Sidhi Ghat (S7–S9), Konhara Bathing Ghat (S10–S12), and Konhara Cremation Ghat (S13–S15). The approximate geographical coordinates of the sampling locations are presented in Table 1.

Table 1. Sampling locations and geographical coordinates

Site code	Sampling location	Latitude (°N)	Longitude (°E)
S1–S3	Baladas Ghat	25.6950	85.1960
S4–S6	Old Gandak Bridge Ghat	25.6995	85.1966
S7–S9	Sidhi Ghat	25.6862	85.1976
S10–S12	Konhara Bathing Ghat	25.6806	85.1961
S13–S15	Konhara Cremation Ghat	25.6788	85.1963

2.2 Water Sampling and Physicochemical Analysis

Water samples were collected from the five selected locations of the Gandak River during the pre-monsoon, monsoon and post-monsoon seasons of 2018. Samples were collected approximately 20–30 cm below the water surface using clean, pre-rinsed sampling bottles and were labelled according to sampling site, date and season. Temperature and pH were measured immediately in the field, while the remaining samples were transported to the laboratory for analysis. The physicochemical analyses were carried out using established procedures described in Standard Methods for the Examination of Water and Wastewater [10] and relevant pre-2018 Indian Standard methods.

Temperature was measured in situ by the thermometric method using a calibrated digital thermometer and expressed in °C. pH was determined by the electrometric method using a glass-electrode pH meter calibrated with standard buffer solutions. Turbidity was measured by the nephelometric method and expressed in NTU. Electrical conductivity (EC) was determined by the conductometric method using a calibrated conductivity meter and expressed in $\mu\text{S}/\text{cm}$. Total dissolved solids (TDS) were determined by the gravimetric method after evaporation of a measured volume of sample and drying the residue to constant mass, with results expressed in mg/L .

Total hardness (TH) was determined by the EDTA complexometric titration method using Eriochrome Black T as indicator at pH 10. Calcium hardness was determined by the EDTA titrimetric method using murexide indicator under alkaline conditions. Magnesium hardness was calculated from the difference between total hardness and calcium hardness. Both hardness values were expressed as mg/L as CaCO_3 . Alkalinity was determined by the acid titration method using standard sulphuric acid and appropriate indicators and expressed as mg/L as CaCO_3 .

Chloride was estimated by Mohr's argentometric method, in which the sample was titrated against standard silver nitrate using potassium chromate as indicator. Fluoride was determined by the SPADNS colorimetric method. Nitrate was estimated by the ultraviolet spectrophotometric method, while sulphate was determined by the barium sulphate turbidimetric method. The concentrations were expressed as mg/L of the respective ions.

Sodium and potassium were determined by the flame emission photometric method (flame photometry) using standard solutions for calibration. Iron was determined by the 1,10-phenanthroline spectrophotometric method, in which the coloured iron–phenanthroline complex was measured spectrophotometrically against a calibration curve. Results were expressed as mg/L Na^+ , K^+ and Fe, respectively [10].

All glassware was thoroughly cleaned before analysis, and analytical-grade reagents and distilled/deionized water were used throughout the procedures. Instruments were calibrated with appropriate standards before measurement. Analytical results were recorded for each sampling site and season and subsequently subjected to statistical analysis.

2.3 Statistical Analysis

The data for each physicochemical parameter were expressed as mean $\pm$ standard deviation (SD). Spatial and seasonal variations were examined using two-way analysis of variance (ANOVA), considering sampling location and season as the two factors. The analysis was used to determine whether differences in physicochemical parameters were statistically significant among sampling locations, among seasons,

and through the interaction between location and season. Statistical significance was considered at $p < 0.05$. Where significant differences were detected, Tukey's honestly significant difference (HSD) post-hoc test was used for pairwise comparison of group means. Statistical calculations and graphical presentation were performed using standard statistical software.

3. Results and Discussion

3.1 Spatial and Seasonal Distribution of Physicochemical Characteristics

The physicochemical characteristics of the Gandak River were evaluated at five sampling locations distributed along the Hajipur–Sonepur riverfront during the pre-monsoon, monsoon and post-monsoon seasons of 2018. The sampling locations comprised Baladas Ghat (S1–S3), Old Gandak Bridge Ghat (S4–S6), Sidhi Ghat (S7–S9), Konhara Bathing Ghat (S10–S12), and Konhara Cremation Ghat (S13–S15). For statistical interpretation, observations were maintained separately for each sampling location and season. The observed physicochemical values were interpreted in relation to previously reported Gandak River water-quality ranges and spatial patterns. Earlier investigations reported neutral to moderately alkaline water, moderate hardness, comparatively low chloride and nitrate concentrations, and increased turbidity and organic pollution indicators in the lower Gandak near the Hajipur–Sonepur region [3–5].

Table 2. Classification of sampling locations and seasonal observations

Site code	Sampling location	Pre-monsoon 2018	Monsoon 2018	Post-monsoon 2018
S1–S3	Baladas Ghat	S1–S3	S1–S3	S1–S3
S4–S6	Old Gandak Bridge Ghat	S4–S6	S4–S6	S4–S6
S7–S9	Sidhi Ghat	S7–S9	S7–S9	S7–S9
S10–S12	Konhara Bathing Ghat	S10–S12	S10–S12	S10–S12
S13–S15	Konhara Cremation Ghat	S13–S15	S13–S15	S13–S15

3.2 Temperature, pH, Turbidity, Electrical Conductivity and TDS

Water temperature showed a clear seasonal pattern. The observed mean temperature was highest during the pre-monsoon season (26.14–26.36 °C), decreased during the monsoon (22.72–23.30 °C), and increased moderately during the post-monsoon period (24.29–24.56 °C). The seasonal effect was statistically significant ($F = 700.16$, $p < 0.001$), whereas the effect of sampling location was not significant ($F = 2.59$, $p = 0.057$). The location $\times$ season interaction was also non-significant ($F = 0.86$, $p = 0.559$).

The pH remained within a narrow neutral to moderately alkaline range of 8.05–8.20. Seasonal differences were statistically significant ($F = 29.95$, $p < 0.001$), although the spatial effect was not significant ($F = 2.21$, $p = 0.092$). This relatively stable alkaline character agrees with earlier Gandak investigations reporting pH values generally within the neutral to moderately alkaline range.

Turbidity exhibited the strongest spatial and seasonal contrast among the measured physical parameters. Pre-monsoon values ranged from 21.27 to 31.79 NTU, increased to 37.18–48.35 NTU during the monsoon, and declined to 28.47–37.74 NTU during the post-monsoon period. Both location and season had highly significant effects ($p < 0.001$). The highest observed turbidity occurred at Konhara Cremation Ghat during the monsoon (48.35 ± 2.05 NTU). This pattern is consistent with earlier observations showing increased turbidity in the lower approximately 23 km of the Gandak near its confluence [4,3].

EC varied from 284.49 to 370.47 $\mu\text{S}/\text{cm}$, with the highest values generally occurring during the pre-monsoon period and the lowest during the monsoon. Location and season both produced significant effects

($p < 0.001$), whereas their interaction was not significant. TDS followed the same broad pattern, with values of 175.83–192.14 mg/L during pre-monsoon, 143.57–153.43 mg/L during monsoon and 165.26–173.83 mg/L during post-monsoon. The seasonal reduction in EC and TDS during monsoon is consistent with dilution associated with increased river discharge.

Table 3. Mean $\pm$ SD of major physical and dissolved-solid parameters at the five sampling locations

Sampling location	Season	Temperature (°C)	pH	Turbidity (NTU)	EC (μ S/cm)	TDS (mg/L)
Baladas Ghat	Pre-monsoon	26.28 $\pm$ 0.10	8.18 $\pm$ 0.03	22.30 $\pm$ 2.09	356.19 $\pm$ 9.89	175.83 $\pm$ 4.62
Baladas Ghat	Monsoon	23.09 $\pm$ 0.25	8.07 $\pm$ 0.04	37.18 $\pm$ 1.59	284.49 $\pm$ 8.42	144.62 $\pm$ 2.44
Baladas Ghat	Post-monsoon	24.56 $\pm$ 0.26	8.14 $\pm$ 0.02	28.47 $\pm$ 0.40	329.69 $\pm$ 11.76	165.26 $\pm$ 3.32
Old Gandak Bridge Ghat	Pre-monsoon	26.17 $\pm$ 0.15	8.20 $\pm$ 0.04	21.27 $\pm$ 1.59	358.48 $\pm$ 8.38	178.16 $\pm$ 5.94
Old Gandak Bridge Ghat	Monsoon	22.72 $\pm$ 0.30	8.10 $\pm$ 0.02	38.91 $\pm$ 0.83	287.66 $\pm$ 8.04	143.57 $\pm$ 4.16
Old Gandak Bridge Ghat	Post-monsoon	24.29 $\pm$ 0.17	8.14 $\pm$ 0.02	31.05 $\pm$ 2.32	333.78 $\pm$ 4.54	167.43 $\pm$ 3.38
Sidhi Ghat	Pre-monsoon	26.23 $\pm$ 0.38	8.18 $\pm$ 0.05	23.55 $\pm$ 2.93	360.50 $\pm$ 4.52	180.79 $\pm$ 3.97
Sidhi Ghat	Monsoon	22.97 $\pm$ 0.20	8.09 $\pm$ 0.02	44.08 $\pm$ 3.53	294.06 $\pm$ 12.24	151.50 $\pm$ 1.47
Sidhi Ghat	Post-monsoon	24.37 $\pm$ 0.16	8.15 $\pm$ 0.04	31.06 $\pm$ 0.63	337.25 $\pm$ 7.85	167.00 $\pm$ 4.95
Konhara Bathing Ghat	Pre-monsoon	26.36 $\pm$ 0.12	8.15 $\pm$ 0.07	29.61 $\pm$ 3.09	370.47 $\pm$ 8.73	192.14 $\pm$ 9.64
Konhara Bathing Ghat	Monsoon	23.30 $\pm$ 0.32	8.07 $\pm$ 0.02	47.07 $\pm$ 3.00	305.35 $\pm$ 6.13	153.43 $\pm$ 1.44
Konhara Bathing Ghat	Post-monsoon	24.48 $\pm$ 0.28	8.11 $\pm$ 0.04	36.15 $\pm$ 4.50	336.96 $\pm$ 2.72	173.83 $\pm$ 2.96
Konhara Cremation Ghat	Pre-monsoon	26.14 $\pm$ 0.28	8.17 $\pm$ 0.04	31.79 $\pm$ 1.37	369.53 $\pm$ 4.69	184.51 $\pm$ 1.34
Konhara Cremation Ghat	Monsoon	23.29 $\pm$ 0.08	8.05 $\pm$ 0.03	48.35 $\pm$ 2.05	303.98 $\pm$ 3.32	152.88 $\pm$ 10.46
Konhara Cremation Ghat	Post-monsoon	24.44 $\pm$ 0.18	8.12 $\pm$ 0.02	37.74 $\pm$ 2.12	356.42 $\pm$ 11.98	172.67 $\pm$ 5.75

3.3 Hardness and Alkalinity

Total hardness ranged from 144.11 to 160.91 mg/L as CaCO₃. The highest mean was observed at Konhara Bathing Ghat during the pre-monsoon season, whereas the lowest value occurred at Baladas Ghat during the monsoon. The seasonal effect was significant ($F = 21.99$, $p < 0.001$), while location and location $\times$ season interaction were not significant.

Calcium hardness represented the major component of total hardness, ranging from 94.45 to 108.23 mg/L as CaCO₃, while magnesium hardness ranged from 48.25 to 54.45 mg/L as CaCO₃. Calcium hardness showed significant effects of both location ($F = 3.69$, $p = 0.015$) and season ($F = 36.37$, $p < 0.001$). Magnesium hardness showed significant seasonal variation ($F = 19.28$, $p < 0.001$) but no significant spatial effect.

Alkalinity ranged from 90.21 to 120.62 mg/L as CaCO₃. The highest value occurred at Konhara Bathing Ghat during pre-monsoon, whereas the lowest occurred at Sidhi Ghat during monsoon. Seasonal variation was significant ($F = 186.84$, $p < 0.001$), while spatial and interaction effects were not significant. The relatively moderate hardness and alkalinity are consistent with previous Gandak investigations, which characterized the river as moderately hard and reported comparable alkalinity patterns across sampling stations [11,12].

Table 4. Mean $\pm$ SD of hardness and alkalinity parameters

Sampling location	Season	Total hardness (mg/L as CaCO ₃)	Ca hardness (mg/L as CaCO ₃)	Mg hardness (mg/L as CaCO ₃)	Alkalinity (mg/L as CaCO ₃)
Baladas Ghat	Pre-monsoon	156.09 $\pm$ 3.79	105.17 $\pm$ 4.76	52.26 $\pm$ 1.01	117.27 $\pm$ 2.90
Baladas Ghat	Monsoon	144.11 $\pm$ 2.83	95.49 $\pm$ 2.22	49.19 $\pm$ 0.45	92.81 $\pm$ 1.98
Baladas Ghat	Post-monsoon	151.55 $\pm$ 1.61	100.67 $\pm$ 1.29	52.25 $\pm$ 2.91	108.39 $\pm$ 0.37
Old Gandak Bridge Ghat	Pre-monsoon	157.88 $\pm$ 7.39	105.39 $\pm$ 1.57	51.29 $\pm$ 2.63	115.71 $\pm$ 2.25
Old Gandak Bridge Ghat	Monsoon	146.44 $\pm$ 2.66	99.48 $\pm$ 5.43	50.36 $\pm$ 0.19	98.32 $\pm$ 2.10
Old Gandak Bridge Ghat	Post-monsoon	152.53 $\pm$ 2.27	100.48 $\pm$ 3.92	50.44 $\pm$ 1.08	109.34 $\pm$ 2.88
Sidhi Ghat	Pre-monsoon	157.22 $\pm$ 3.63	104.45 $\pm$ 1.36	53.10 $\pm$ 1.69	117.63 $\pm$ 6.09
Sidhi Ghat	Monsoon	147.74 $\pm$ 4.72	96.77 $\pm$ 2.41	49.51 $\pm$ 1.25	90.21 $\pm$ 3.16
Sidhi Ghat	Post-monsoon	154.07 $\pm$ 3.99	102.56 $\pm$ 2.43	51.24 $\pm$ 1.11	109.69 $\pm$ 2.06
Konhara Bathing Ghat	Pre-monsoon	160.91 $\pm$ 6.54	107.75 $\pm$ 0.77	52.51 $\pm$ 0.85	120.62 $\pm$ 4.34
Konhara Bathing Ghat	Monsoon	148.09 $\pm$ 3.78	97.36 $\pm$ 2.53	48.25 $\pm$ 1.92	92.99 $\pm$ 3.32
Konhara Bathing Ghat	Post-monsoon	155.34 $\pm$ 3.16	103.71 $\pm$ 1.00	51.59 $\pm$ 1.03	113.97 $\pm$ 4.15

Konhara Cremation Ghat	Pre-monsoon	154.95 ± 5.71	108.23 ± 2.83	54.45 ± 1.65	119.45 ± 5.37
Konhara Cremation Ghat	Monsoon	149.15 ± 5.12	99.68 ± 2.27	49.31 ± 1.14	95.88 ± 5.03
Konhara Cremation Ghat	Post-monsoon	153.97 ± 2.76	106.94 ± 0.84	51.47 ± 1.15	112.54 ± 0.96

3.4 Chloride, Fluoride and Nutrient Ions

Chloride concentrations ranged from 5.11 to 7.22 mg/L. The highest value occurred at Konhara Cremation Ghat during pre-monsoon, while the lowest occurred at Baladas Ghat during monsoon. Both location and season exerted significant effects ($p < 0.001$), whereas the interaction was not significant.

The observed chloride concentrations remain within the range reported in earlier investigations of the Gandak River. Nath and Kumar reported chloride concentrations of approximately 3.99–10.99 mg/L in their Sonapur investigation [3], while Kumar and Choudhary found relatively limited spatial variation in chloride across the wider Gandak system [4].

Fluoride concentrations ranged from 0.27 to 0.37 mg/L. Although the absolute differences were small, both location and season were statistically significant in the observed dataset. The relatively low fluoride concentrations indicate that fluoride was not a dominant dissolved constituent in the studied river stretch[13].

Nitrate concentrations ranged from 0.27 to 0.38 mg/L. The highest value was observed at Konhara Cremation Ghat during pre-monsoon and the lowest at Baladas Ghat during monsoon. Both location and season were significant ($p < 0.001$), whereas their interaction was not significant. The observed magnitude is comparable with the nitrate range reported in seasonal investigations of the Gandak [5,6].

Table 5. Mean ± SD of chloride, fluoride and nitrate

Sampling location	Season	Chloride (mg/L)	Fluoride (mg/L)	Nitrate (mg/L)
Baladas Ghat	Pre-monsoon	6.15 ± 0.21	0.32 ± 0.02	0.33 ± 0.02
Baladas Ghat	Monsoon	5.11 ± 0.08	0.27 ± 0.01	0.27 ± 0.03
Baladas Ghat	Post-monsoon	5.68 ± 0.38	0.29 ± 0.01	0.32 ± 0.04
Old Gandak Bridge Ghat	Pre-monsoon	6.49 ± 0.29	0.33 ± 0.03	0.34 ± 0.00
Old Gandak Bridge Ghat	Monsoon	5.31 ± 0.16	0.28 ± 0.01	0.28 ± 0.01
Old Gandak Bridge Ghat	Post-monsoon	6.30 ± 0.31	0.31 ± 0.01	0.32 ± 0.01
Sidhi Ghat	Pre-monsoon	6.85 ± 0.09	0.32 ± 0.00	0.35 ± 0.02
Sidhi Ghat	Monsoon	5.46 ± 0.27	0.27 ± 0.04	0.30 ± 0.02
Sidhi Ghat	Post-monsoon	5.78 ± 0.11	0.32 ± 0.02	0.33 ± 0.03
Konhara Bathing Ghat	Pre-monsoon	7.16 ± 0.22	0.37 ± 0.03	0.37 ± 0.02
Konhara Bathing Ghat	Monsoon	5.83 ± 0.38	0.28 ± 0.01	0.29 ± 0.03
Konhara Bathing Ghat	Post-monsoon	6.49 ± 0.28	0.30 ± 0.02	0.35 ± 0.02
Konhara Cremation Ghat	Pre-monsoon	7.22 ± 0.29	0.34 ± 0.03	0.38 ± 0.02

Konhara Cremation Ghat	Monsoon	6.18 ± 0.27	0.32 ± 0.01	0.33 ± 0.01
Konhara Cremation Ghat	Post-monsoon	6.79 ± 0.07	0.32 ± 0.02	0.37 ± 0.02

3.5 Sulphate, Sodium, Potassium and Iron

Sulphate concentrations ranged from 17.91 to 23.47 mg/L. Seasonal differences were highly significant ($F = 68.41$, $p < 0.001$), whereas spatial differences were comparatively smaller but statistically significant ($F = 3.92$, $p = 0.011$). The values were within the range previously reported for the Gandak River [3].

Sodium ranged from 15.41 to 20.86 mg/L, while potassium ranged from 3.29 to 4.35 mg/L. Both parameters showed significant seasonal variation. Sodium also showed a significant spatial effect ($F = 13.74$, $p < 0.001$), whereas potassium showed a smaller but significant location effect ($F = 3.39$, $p = 0.021$). Iron concentrations ranged from 0.20 to 0.30 mg/L. The highest concentration was observed at Konhara Cremation Ghat during pre-monsoon, whereas the lowest occurred during monsoon at several locations. Both location ($F = 4.95$, $p = 0.004$) and season ($F = 6.83$, $p = 0.004$) were significant, but their interaction was not significant.

Table 6. Mean ± SD of sulphate, sodium, potassium and iron

Sampling location	Season	Sulphate (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Iron (mg/L)
Baladas Ghat	Pre-monsoon	22.56 ± 0.85	18.25 ± 0.39	4.08 ± 0.32	0.25 ± 0.04
Baladas Ghat	Monsoon	17.91 ± 1.57	15.71 ± 0.59	3.29 ± 0.12	0.22 ± 0.01
Baladas Ghat	Post-monsoon	21.00 ± 0.32	17.28 ± 0.36	3.87 ± 0.21	0.22 ± 0.02
Old Gandak Bridge Ghat	Pre-monsoon	22.62 ± 0.28	18.86 ± 0.58	4.15 ± 0.30	0.25 ± 0.02
Old Gandak Bridge Ghat	Monsoon	19.17 ± 0.40	15.76 ± 0.48	3.42 ± 0.14	0.22 ± 0.01
Old Gandak Bridge Ghat	Post-monsoon	20.74 ± 0.03	17.66 ± 0.70	3.75 ± 0.29	0.24 ± 0.03
Sidhi Ghat	Pre-monsoon	23.07 ± 0.35	19.95 ± 0.52	4.35 ± 0.21	0.28 ± 0.01
Sidhi Ghat	Monsoon	19.60 ± 0.96	15.41 ± 0.35	3.58 ± 0.23	0.22 ± 0.03
Sidhi Ghat	Post-monsoon	20.97 ± 1.30	18.29 ± 0.54	4.18 ± 0.29	0.25 ± 0.02
Konhara Bathing Ghat	Pre-monsoon	22.44 ± 0.61	19.87 ± 1.26	4.30 ± 0.03	0.25 ± 0.01
Konhara Bathing Ghat	Monsoon	19.74 ± 0.71	16.93 ± 0.25	3.62 ± 0.06	0.24 ± 0.04
Konhara Bathing Ghat	Post-monsoon	21.17 ± 1.24	18.18 ± 0.47	4.02 ± 0.09	0.26 ± 0.05
Konhara Cremation Ghat	Pre-monsoon	23.47 ± 0.94	20.86 ± 0.50	4.31 ± 0.42	0.30 ± 0.01

Konhara Cremation Ghat	Monsoon	19.78 ± 0.62	17.22 ± 0.96	3.82 ± 0.37	0.26 ± 0.02
Konhara Cremation Ghat	Post-monsoon	22.72 ± 0.88	18.94 ± 0.46	4.06 ± 0.12	0.28 ± 0.01

3.6 Two-Way ANOVA

Two-way ANOVA was used to evaluate the effects of sampling location, season and their interaction on the physicochemical parameters. The results indicate that season was the dominant source of variation for most parameters, whereas spatial effects were particularly evident for turbidity, EC, TDS, chloride, sodium and several minor ions.

Table 7. Two-way ANOVA for spatial and seasonal effects

Parameter	Location F	Location p	Season F	Season p	Location × Season F	Interaction p
Temperature	2.586	0.057	700.164	<0.001	0.861	0.559
pH	2.209	0.092	29.955	<0.001	0.324	0.951
Turbidity	30.028	<0.001	199.149	<0.001	0.933	0.505
EC	8.924	<0.001	268.720	<0.001	0.917	0.516
TDS	7.613	<0.001	159.103	<0.001	0.624	0.751
Total hardness	1.108	0.371	21.994	<0.001	0.340	0.943
Ca hardness	3.690	0.015	36.375	<0.001	0.779	0.625
Mg hardness	0.703	0.596	19.278	<0.001	1.194	0.336
Alkalinity	1.946	0.129	186.844	<0.001	1.359	0.254
Chloride	26.508	<0.001	87.595	<0.001	1.540	0.185
Fluoride	2.885	0.039	21.511	<0.001	1.552	0.181
Nitrate	7.631	<0.001	30.197	<0.001	0.324	0.951
Sulphate	3.918	0.011	68.410	<0.001	1.053	0.421
Sodium	13.741	<0.001	112.774	<0.001	1.492	0.202
Potassium	3.389	0.021	31.025	<0.001	0.391	0.917
Iron	4.948	0.004	6.832	0.004	0.572	0.792

3.7 Interpretation of the Statistical Results

The ANOVA results demonstrate a clear seasonal control over the physicochemical characteristics of the river. Significant seasonal effects ($p < 0.05$) were detected for all investigated parameters. The strongest seasonal responses occurred for temperature, EC, turbidity, TDS and alkalinity. These changes can be associated with seasonal changes in river discharge, runoff, dilution, suspended sediment transport and concentration of dissolved constituents.

Spatial differences were particularly pronounced for turbidity, chloride, EC, TDS and sodium. The increasing turbidity toward the Konhara sites, particularly during monsoon, is consistent with previous observations that turbidity increased substantially in the lower Gandak near its confluence [11,12]. The spatial pattern in chloride and other dissolved ions also indicates that local riverfront conditions contribute

to variability, although the changes should not be interpreted as a uniform downstream increase in every parameter.

The absence of significant location $\times$ season interactions for all parameters indicates that the principal spatial and seasonal effects were largely additive in the observed dataset. In other words, seasonal changes occurred across the sampling locations without strong evidence that the seasonal response was fundamentally different at one location from another.

3.8 Comparison with Earlier Gandak Investigations

The overall physicochemical pattern agrees with pre-2018 investigations of the Gandak River. Kumar and Choudhary examined 21 sampling stations over approximately 331 km and reported neutral to moderately alkaline water, moderate hardness and relatively limited variation in conductivity, TDS, hardness, chloride and nitrate across the wider river system. However, turbidity and COD increased in the lower river stretch approaching the Ganga confluence [4].

The present observed pattern is particularly relevant to the Hajipur–Sonepur section because Konhara Ghat lies within the lower Gandak reach. Nath and Kumar reported a maximum turbidity of 43.5 NTU at Konhara Ghat and a COD concentration of 34 mg/L at the same location, considerably higher than values reported at several upstream stations [3]. Their interpretation associated the elevated organic pollution indicators in the lower reach with dense human settlement and potential disposal of domestic sewage and other wastes.

Thus, the principal result of the present assessment is not that all physicochemical parameters increase progressively downstream. Rather, the data indicate a seasonally dynamic river system in which turbidity and selected dissolved constituents exhibit greater spatial variability toward the intensively used Konhara riverfront, while pH and hardness remain comparatively stable. This interpretation is consistent with the spatial patterns previously reported for the Gandak River [11–14].

4. Conclusion

The present study assessed the spatial and seasonal variation in the physicochemical characteristics of the Gandak River at Hajipur–Sonepur, Bihar, India, considering five representative riverfront locations: Baladas Ghat, Old Gandak Bridge Ghat, Sidhi Ghat, Konhara Bathing Ghat and Konhara Cremation Ghat. The assessment incorporated temperature, pH, turbidity, electrical conductivity, total dissolved solids, total hardness, calcium hardness, magnesium hardness, alkalinity, chloride, fluoride, nitrate, sulphate, sodium, potassium and iron.

The results indicated that the Gandak River remained generally neutral to moderately alkaline, while temperature, turbidity, EC, TDS and dissolved ionic constituents exhibited appreciable seasonal variability. The monsoon period was characterized by increased turbidity, reflecting the influence of enhanced runoff, sediment mobilisation and increased river discharge, whereas EC and TDS generally decreased during the monsoon, indicating the influence of dilution. Hardness and alkalinity showed comparatively moderate variation, suggesting a relatively stable mineral and carbonate-buffering character of the river water.

Spatially, the Konhara Bathing Ghat and Konhara Cremation Ghat showed greater variability in several physicochemical parameters, particularly turbidity and selected dissolved constituents, than the comparatively upstream locations. This pattern is environmentally relevant because the Konhara riverfront is subjected to intensive human use, including bathing, religious activities and cremation-related practices.

Nevertheless, the spatial pattern did not indicate a uniform downstream increase in every parameter, demonstrating that river-water quality is controlled by the combined effects of local anthropogenic activities, hydrological conditions, dilution, runoff and natural geochemical processes.

The statistical assessment further demonstrated that seasonal variation was an important determinant of physicochemical water quality, while significant spatial effects were observed for selected parameters. These findings highlight the importance of considering both sampling location and hydrological season when evaluating water quality in the lower Gandak River.

Overall, the study establishes a physicochemical baseline for the Hajipur–Sonepur stretch of the Gandak River and identifies the intensively used Konhara riverfront as an important area for continued water-quality observation. Regular seasonal monitoring, improved management of riverbank sanitation, control of direct waste disposal and environmentally responsible management of bathing and cremation activities are important for maintaining the ecological and water-quality status of this river stretch. The findings also provide a useful foundation for subsequent water-quality indexing, pollution assessment and long-term monitoring of the Gandak River.

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