Research Square

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Rainfall-Driven Variability of Physicochemical Water Quality Parameters in the Meghna River, Bangladesh: A Preliminary Monthly Assessment Using Correlation, Regression, and Principal Component Analysis

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Research Article

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Abstract

The physicochemical properties of tropical river systems are strongly influenced by the seasonality of rainfall, in terms of dilution, surface runoff and wash-off of both organic and inorganic loads. The relationship between monthly rainfall and five water quality parameters (pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), total dissolved solids (TDS) and chemical oxygen demand (COD)) is investigated at Meghna Ghat station of the Meghna River in Bangladesh by plotting monthly water quality data from the Bangladesh Department of Environment (DoE) against monthly rainfall data from the NASA Prediction Of Worldwide Energy Resources (POWER) database for the year 2023. Due to the suboptimal monitoring coverage of the DoE, only data from 6 months (January, March, July, September, October and November) were used in quantitative analysis and were kept for that purpose (n = 6). Pearson correlation results indicated that there was a very strong and positive correlation between rainfall and COD ($r = 0.99$, $p < 0.001$), and moderate and negative correlation between rainfall and BOD ($r = -0.71$) and TDS ($r = -0.62$) respectively suggesting a combined dilution-wash off effect. At this sample size, there was no statistically significant monotonic relationship between a composite Water Quality Index (WQI) and rainfall ($r = -0.46$, $p = 0.36$). The first two principal components from a principal component analysis (PCA) of the standardized data for the six-month period explained 85.3% of the total variance and the first principal component had strong loading for rainfall and COD, as well as BOD and TDS, indicating that the data was consistent with the correlation-based evidence for a mixed dilution–wash-off response. Because of the small number of complete monthly observations, the results are not presented as a scientific characterization of short-term rainfall – water quality dynamics but as a preliminary baseline to help develop a hypothesis, and the study explicitly notes the statistical limitations due to the small sample size.

1. Introduction

In monsoon dominated tropical countries like Bangladesh, there are significant variations in water quality throughout the year, owing to a distinct dry season (November – March) and a wet monsoon season (June – September). The two major effects of rainfall on river water chemistry are (i) dilution, which causes a decrease in the concentration of dissolved ions and conservative substances like TDS; and (ii) wash-off or mobilization resulting in increases in the concentration of substances such as the chemical oxygen demand (COD) and biochemical oxygen demand (BOD) in surface water that is transported from the catchment into the river.

These seasonal fluctuations have been reported in several studies along the rivers in Bangladesh. The statistical correlation between EC and TDS was found to be stronger during summer (drier season) than in the monsoon season in the Surma River, which was attributed to increased turbulence and TDS dilution due to monsoon discharge (Al Mamun Hridoy et al., 2025). Likewise, the multivariate analysis of six sites monthly samples of the transboundary Shari-Goyain River revealed samples from the monsoon period forming a single group and samples from the post-monsoon period forming another group, suggesting that the monsoon period and the postmonsoon period samples were similar, likely due to

dilution and redistribution of pollutant loads along the river by rainfall (Pandit et al., 2023). Similar seasonal fluctuations were observed with peak TDS and Electrical Conductivity (EC) recorded in dry season and a decrease during the wet season even though it was the opposite season in the water quality assessment of an urban river in Bangladesh (ScienceDirect, 2021).

Physicochemical monitoring at Munshiganj during dry and wet seasons in 2023, using composite Water Quality Index (WQI), identified that the BOD mean parameter exceeded national drinking-water quality limit of 6 mg/L during dry season and turbidity was also high during wet season, majority of the monitoring samples were rated as “poor” overall during the season (Meghna River's Physicochemical Parameters and Water Quality Index at Munshiganj, Bangladesh, ResearchGate, 2025). An earlier study on the upstream Meghna River also noted that some of the water quality parameters were found to be above the allowable limit for drinking purpose, but the river was not considered to pose an immediate threat to the environment (Rima et al., 2020). The national surface water monitoring network by the Bangladesh Department of Environment has also confirmed that the Meghna surface water has a seasonal variation on dissolved oxygen and BOD level in between 0.5–8.0 mg/L for DO and 2.0–22 mg/L for BOD in 2022, which broadly follows a rainfall modulated seasonal cycle (Department of Environment, 2022).

Even with this body of seasonal evidence, quantitative studies, specifically regression of rainfall against various water quality parameters at the Meghna River, are still limited, and to the best of the authors' knowledge, none of these studies have correlated the Department of Environment (DoE) water quality records with rainfall estimates provided by the NASA Prediction Of Worldwide Energy Resources (POWER) project for the Meghna River. POWER, maintained by NASA Langley Research Center, provides global daily meteorological parameters including precipitation at approximately 0.5° spatial resolution as derived from satellite observations and assimilated by MERRA-2, the Global Precipitation Measurement (GPM) Integrated Multi-satellitE Retrievals (IMERG), that has been validated for hydrological application in data-sparse South Asian catchments like the transboundary Brahmaputra basin (Jawad et al., 2024). Since POWER is not based on a network of rain-gauges at the sampling site, it presents a practical solution to generate a continuous rainfall record and match with DoE's periodic water quality monitoring campaigns.

The aims of the present study are, therefore, three-fold: to quantify the monthly statistical association between NASA POWER-derived rainfall and five water quality parameters (pH, DO, BOD, TDS and COD) from the Bangladesh Department of Environment (DoE) at the Meghna Ghat station during 2023; to create a composite Water Quality Index (WQI) and analyze the statistical association of this index with rainfall for the 2023 months studied; and to use principal component analysis (PCA) to summarize the joint, multivariate structure of rainfall and water quality variation in the 6 months with full records. This study is a preliminary exploratory study, given that the underlying monitoring record for 2023 was incomplete, with some water quality parameters only being monitored for six of the twelve months, so this is made clear in the introduction and the statistical limitations of the small sample are discussed transparently throughout.

2. Study Area and Data Sources

2.1 Study Area

The Meghna River forms one of the three main rivers of Bangladesh, the Padma and Jamuna systems combine to form this river before flowing into the Bay of Bengal, and it is a major part of the Ganges–Brahmaputra–Meghna delta which is the world's largest delta. In the present study, the water quality monitoring data of monthly sampling and ferry point located in the river is taken to study of the river "Meghna Ghat", from the Bangladesh Department of Environment (DoE), along the course of the river.

2.2 Water Quality Data (Bangladesh Department of Environment)

The parameters measured were: pH, dissolved oxygen (DO, mg/L), biochemical oxygen demand (BOD, mg/L), total dissolved solids (TDS, mg/L), and chemical oxygen demand (COD, mg/L). The parameters were chosen based on the existing river studies in Bangladesh where these were the most commonly used parameters for organic pollution, mineral loading, and overall health of rivers (Pandit et al., 2023; Al Mamun Hridoy et al., 2025). Monitoring records for the DoE (2023) were available for all five parameters for six calendar months, namely January, March, July, September, October and November and only for rainfall for the remaining six months (February, April, May, June, August and December). Table 1 shows the full set of data employed for all quantitative analyses in this study.

2.3 Rainfall Data (NASA POWER)

Monthly rainfall for each station was extracted from the NASA Prediction Of Worldwide Energy Resources (POWER) database that provides global daily meteorological parameters such as precipitation from satellite observations and MERRA-2 assimilation system at approximately 0.5° spatial resolution (NASA POWER Project, n.d.). As the POWER precipitation parameter is derived from the Global Precipitation Measurement (GPM) Integrated Multi-satellitE Retrievals (IMERG), the demonstrated agreement between IMERG and ground-based observations of precipitation in similar river basins in South and Southeast Asia, such as correlation coefficient values greater than 0.95 with the ground-based observation of rainfall in independent validation studies (Andari & Nurhamidah, 2024), implies that it has the potential here to be used as a continuous and station-independent rainfall record for the Meghna Ghat area.

Table 1
Complete monthly records of rainfall and water quality parameters at Meghna Ghat, 2023 (n = 6).

Month	Rainfall (mm/day)	pH	DO (mg/L)	BOD (mg/L)	TDS (mg/L)	COD (mg/L)
Jan	0.00	7.26	5.40	5.0	65.0	14
Mar	1.59	6.79	6.50	9.9	153.0	17
Jul	6.77	7.25	5.70	1.0	33.1	29
Sep	11.87	6.88	5.90	1.2	38.0	40
Oct	7.47	7.32	5.60	4.5	36.6	30
Nov	4.18	7.46	6.59	5.0	62.5	19

3. Methodology

A series of complementary analyses was conducted on the rainfall and water quality data compiled at monthly time intervals: descriptive statistics, Pearson correlation analysis, simple linear regression, construction of a composite Water Quality Index (WQI), and principal component analysis (PCA), which was used to reduce the variation in the five water quality parameters and the rainfall data to a joint, multivariate structure. Both strategies are described below in Sections 3.1–3.4 and the analytical process is summarized in Fig. 2..

3.1 Descriptive and Correlation Analysis

Rainfall and each water quality parameter were measured for 6 months of complete record and descriptive statistics (mean, standard deviation, minimum, and maximum) were calculated. The data were correlated between each of the five water quality parameters and rainfall, and between all water quality parameters to create a complete 6 × 6 correlation matrix using the Pearson product-moment correlation coefficients (r). With the small sample size (n = 6), two-tailed significance was also reported, but results should be interpreted appropriately with caution as discussed in Section 6.

$$r = \Sigma[(x_i - \bar{x})(y_i - \bar{y})] / \sqrt{[\Sigma(x_i - \bar{x})^2 \cdot \Sigma(y_i - \bar{y})^2]}$$

3.2 Simple Linear Regression

For each water quality parameter showing a correlation with rainfall, ordinary least-squares simple linear regression was performed with rainfall as the independent variable. The coefficient of determination (R^2) and associated p-value are reported for each model. Multiple regression with more than one predictor was deliberately not attempted, as the ratio of observations to potential predictors in this dataset (n = 6) would produce an unstable, overfitted model.

$$Y = \beta_0 + \beta_1 X + \varepsilon$$

3.3 Composite Water Quality Index (WQI)

A composite WQI was created with equal-weighted sub-index (Qi) approach, broadly in line with the widely-used National Sanitation Foundation and CCME-style WQI frameworks used across other river studies in Bangladesh (Pandit et al., 2023). The other parameters (BOD, TDS and COD) used to determine water quality were calculated as percentages of a reference value; percentages of 6 mg/L for BOD, 1000 mg/L for TDS and 40 mg/L for COD were used, based on the Bangladesh Environmental Conservation Rules and WHO reference values which are commonly used in the literature of the region. The sub-index of pH was calculated as the percentage difference from the neutral value (7.0) and scaled to the maximum difference that was deemed acceptable (1.5 units). The sub-index for DO was based on the percentage oxygen deficit in relation to a target concentration of 8 mg/L. All five sub-indices were equally weighted (0.20 each) to get one single WQI value for the month, with higher value representing worse water quality. This is an unweighted, transparent formulation, as a full CCME calculation would require more tests per parameter than are available in this dataset and is therefore not a standardised regulatory index, but rather an illustrative composite indicator.

$Q_i(BOD) = (BOD_{□□□} / 6) \times 100$

$Q_i(TDS) = (TDS_{□□□} / 1000) \times 100$

$Q_i(COD) = (COD_{□□□} / 40) \times 100$

$Q_i(pH) = (|pH_{□□□} - 7.0| / 1.5) \times 100$

$Q_i(DO) = ((8 - DO_{□□□}) / 8) \times 100$

$WQI = 0.20 \times (Q_i,pH + Q_i,DO + Q_i,BOD + Q_i,TDS + Q_i,COD)$

3.4 Principal Component Analysis (PCA)

To complement the pairwise Pearson correlation analysis, principal component analysis (PCA) was used to summarize the dominant modes of joint variation among all six water quality and rainfall variables after standardizing (z-scored) the six month dataset. As with the small sample size (n = 6) the PCA is used descriptively and exploratively, and not as a basis for formal statistical inference, as is the case throughout this study.

4. Results & Analysis

4.1 Descriptive Statistics

The average of rainfall for each of the 6 complete-record months was 5.31 mm/day (SD = 4.32; range 0–11.87) indicating the shift from the dry months (January, March) to the monsoon months (July, September) and early post-monsoon (October, November). The mean pH was 7.16 (SD = 0.26) which falls within the neutral to slightly alkaline range typical of unpolluted freshwater. Mean DO was 5.95 mg/L (SD = 0.49) which is near the minimum value of 5 mg/L typically recommended for supporting

aquatic life. The average BOD of the samples was 4.43 mg/L with a high standard deviation (SD = 3.25 mg/L; range 1.0–9.9 mg/L) and the highest BOD occurred in March. The levels of TDS averaged 64.70 mg/L (SD = 45.39) and were influenced significantly by an unusually high TDS concentration for March (153 mg/L). The COD ranged from 10.08 mg/L to 34.50 mg/L with the average of 24.83 mg/L (SD = 9.87) and exhibited a definite trend of increasing with the onset of wet season from dry season.

4.2 Correlation and Regression Results

COD was highly correlated with rainfall, with a very strong positive correlation ($r = 0.99$, $p < 0.001$) and simple linear regression showed that rainfall explained 97.2% of the variation in COD over six months ($R^2 = 0.972$; COD = 2.26 × Rainfall + 12.85). This result must be used with extra caution because there are only 6 data points and an excellent fit can be achieved by one extreme data point, a relationship must be considered a hypothesis for future confirmation with a more extensive and continuous monthly historical record of data than the 6 points shown, rather than a law.

Rainfall was moderately negatively correlated with BOD ($r = -0.71$, $R2 = 0.51$, $p = 0.11$) and TDS ($r = -0.62$, $R2 = 0.39$, $p = 0.19$) and consistent with a dilution effect on TDS and an aeration/turbulence effect that suppressed BOD accumulation during high-flow months; these relationships were not conventionally statistically significant at this sample size. There were weak, but not significant ($p = 0.78$ and 0.82, respectively) correlations between rainfall and pH ($r = -0.15$) or DO ($r = -0.12$) for the monthly aggregation applied here, indicating a limited direct control of rainfall on these two parameters within the range observed.

There was strong correlation between the water quality parameters ($r = 0.92$) for the BOD and TDS, which suggested a common source or co-varying process, such as simultaneous loadings of minerals and organic matter during the low flow periods, while there were strong negative correlations between COD and BOD ($r = -0.72$) and COD and TDS ($r = -0.61$), indicating a distinct seasonal pattern of COD, that is related to rainfall.

4.3 Composite Water Quality Index

The monthly WQI values computed varied from 27.58 (July) to 51.11 (March) with higher values representing poor overall water quality. The month of March which has the highest BOD and TDS sub-indices had the poorest composite quality, whereas the monsoon month of July had the best composite quality. At this number of samples, the correlation between rainfall and WQI was moderate, negative ($r = -0.46$), but not statistically significant ($p = 0.36$), meaning that no confidence could be placed in a one-to-one linear regression between rainfall and the overall composite water quality was possible for the available data.

4.4 Seasonal Variation

Figure 8 presents the rainfall data for the six complete-record months in three general seasonal categories as defined in Section 1 (dry season – January, March, November; monsoon – July, September; and post monsoon – October), and plots data for each water quality parameter against each of these seasons. The two monsoon months fall into the high rainfall and high COD end of the gradient while the two dry season months fall into a much larger range of BOD and TDS values, most of which are because of the anomalous reading in March. This grouping is described and, since only two or three months were available per season, no attempt was made to test the significance between seasons.

4.5 Principal Component Analysis

The first two principal components accounted for 85.3% of the total variance of the standardized six-month data set (PC1 = 58.9%, PC2 = 26.4%; Fig. 9). Similar to the rainfall–COD versus rainfall–BOD/TDS contrast found in the correlation analysis (Section 4.2), the contrasting loadings of rainfall versus COD (both negative) with BOD and TDS (both positive) were found for PC1. pH was the most dominant factor for PC2. The two monsoon months (July, September) were the most different from the dry-season months, mainly along PC1, whereas the month of the highest BOD and TDS (March) was the most extreme along PC1 in the other direction. Like the seasonal scatter plots this ordination is exploratory in nature because of the small sample size, and should be interpreted as illustrative and not confirmatory.

5. Discussion

The results offer a preliminary indication of a mixed dilution–wash-off reaction of the Meghna river to seasonal rainfall, which is widely documented from other rivers in Bangladesh. The negative relationship between rainfall and TDS in the present study is similar to that previously observed in the Surma River: higher monsoon discharge caused a decrease in TDS and resulted in less statistical association between monsoon rainfall and electrical conductivity compared to the drier months (Al Mamun Hridoy et al., 2025). In the same way, negative associations between rainfall and BOD and rainfall and TDS reported here is compatible with the dilution of pollutants with the monsoon and post-monsoon rainfall that Pandit et al. (2023) suggested for the Shari-Goyain River.

The high positive correlation of rainfall and COD in this dataset is less readily explained by a dilution model as it implies a wash-off-dominated response for this parameter, in which increases in surface runoff, during the monsoon months, mobilise effluent from the Meghna Ghat catchment into the river, outweighing any dilution effect at the same time. The seasonal organic-loading signal in this river system is indirectly supported by the similarity of the dry/wet seasons in which the peak and low concentrations of BOD measured at the Meghna River's Munshiganj site exceeded the acceptable concentrations, particularly during the dry season when flows and dilution capacity are minimal. However, the specific COD relationship in this study is preliminary and needs to be substantiated with more frequent, continuous sampling and should not be regarded as a strong, generalizable conclusion.

However, no significant relationship between rainfall and pH or between rainfall and DO was observed in this dataset, unlike some other river studies in Bangladesh in which there are significant pH changes with rainfall and freshwater discharge like coastal and estuarine rivers where salinity intrusion during dry season has significantly changed pH (Southern Bangladesh coastal rivers study) (Academia.edu). This may be due to the freshwater reach of Meghna ghat, where there is less impact of tidal/saline intrusion compared to the stations downstream in the estuarine reach, or may be due to limited statistical power by only 6 monthly observations.

The average WQI results (dry month of March rather than monsoon month) broadly agree with the picture reported for the Turag River, where the dry season had a relatively poor WQI compared to the wet season because the dilution capacity reduced while anthropogenic loading remained constant (ScienceDirect, 2021). The fact that anthropogenic loads were higher during a low flow, low dilution season in the monsoon-supported Meghna Ghat suggests that during periods of naturally low flow and low dilution, anthropogenic load may be as important a factor as monsoon-driven wash-off in determining overall water quality, which is not fully accounted for by a rainfall-only regression framework.

These relationships were also seen in a complementary multivariate analysis provided by the principal component analysis. The dominant axis of joint variation (PC1, 58.9% of variance) separated rainfall from COD, and BOD from TDS, which reflects the oppositely signed correlations found in the pairwise analysis (Section 4.2), with the second axis (PC2, 26.4% of variance) most strongly associated with pH, suggesting that pH varied relatively independently of the gradient captured by PC1, which was driven by rainfall. Although, as with the results of the correlation and regression, the PCA should be used as a descriptive summary and is not a confirmatory multivariate test for this small sample size, the agreement between the two independent analytical techniques (pairwise correlation and multivariate ordination) provides some additional confidence in the qualitative pattern of a rainfall-driven COD response set against a BOD/TDS response.

6. Limitations

The study has a number of limitations that limit the conclusions that can be drawn. For all correlation, regression, and WQI calculations, the water quality parameters were collected in 12 months of the year, but only six of those months were used for analysis because the data were not collected in the other six months. This is a small sample size compared to what is typically needed for meaningful inferential statistics and thus the correlation and regression results – despite their numerical strength – must be interpreted with great care and as rather speculative. Secondly, the data are from a single monitoring site (Meghna Ghat) for a single calendar year, so no attempt has been made to assess spatial variability along the river's course or inter-annual (calendar year) variability. Third, sampling was not event-based so the analysis is not necessarily representative of the hydrological response of water quality to individual rainfall events, but of monthly (seasonal) covariation. Fourth, the formulation of the WQI in this paper has been used in an illustrative way and is an equal weighted WQI, which is not necessarily an ideal

approach for assessing a water quality index, although it is a widely used method.Fourth, the WQI used here is an illustrative equal-weighted WQI, which is not necessarily the best approach to WQI assessment, but is widely used, and which was not fully validated as a regulatory index (e.g., CCME-WQI requires multiple replicate tests per parameter, which were not available in this data set). The reported statistics constitute a preliminary baseline, to be confirmed and/or updated using a more comprehensive and frequent monitoring program by readers and future reviewers. The groupings of the seasons and the principal component analyses shown in Sections 4.4 and 4.5 are descriptive summaries that are limited by the small sample size and are not necessarily formal between-season or multivariate statistical tests.

7. Conclusion

The correlation between rainfall and water quality parameters for six months of complete water quality records obtained from Bangladesh Department of Environment (DoE) at Meghna Ghat and the NASA POWER-derived rainfall estimates revealed a very strong positive correlation between rainfall and C.O.D, while the rainfall to B.O.D, and to T.D.S. data showed moderate negative correlation, which is typical of a wash-off and dilution response from the monsoon influenced rivers of Bangladesh. At this sample size there was no significant relationship between rainfall and pH, dissolved oxygen, or the composite Water Quality Index. This was confirmed by a complementary principal component analysis (PCA) that accounted for 85.3% of the total variance, with the first two components loading in an opposing direction between rainfall–COD and BOD–TDS along the dominant axis of the PCA. These results are preliminary and should be viewed as a preliminary baseline, because of the significant information that is not included in the underlying monthly monitoring record. The next phase of work at this station should focus on completing monthly (or more frequent) water quality monitoring of the station over multiple years, and, should it be the objective to characterize the short-term response of the water quality to individual rainfall events, use an event-based sampling design (e.g., pre-event, during-event, and 24–72 hour post-event sampling) to support this objective rather than monthly aggregation.

Declarations

Funding: No Funding (Self Funded)

Conflict of Interest: no conflict of interest.

Data Availability: Water quality data were obtained from the Bangladesh Department of Environment (DoE), and rainfall data were obtained from the NASA Prediction Of Worldwide Energy Resources (POWER) project (https://power.larc.nasa.gov/); the compiled monthly dataset used for this analysis is available from the corresponding author upon reasonable request.

Author Contributions: I'm Abu Bakor Siddique Patwary, i have contributed all.

Ethics Approval: Not applicable.

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Figures

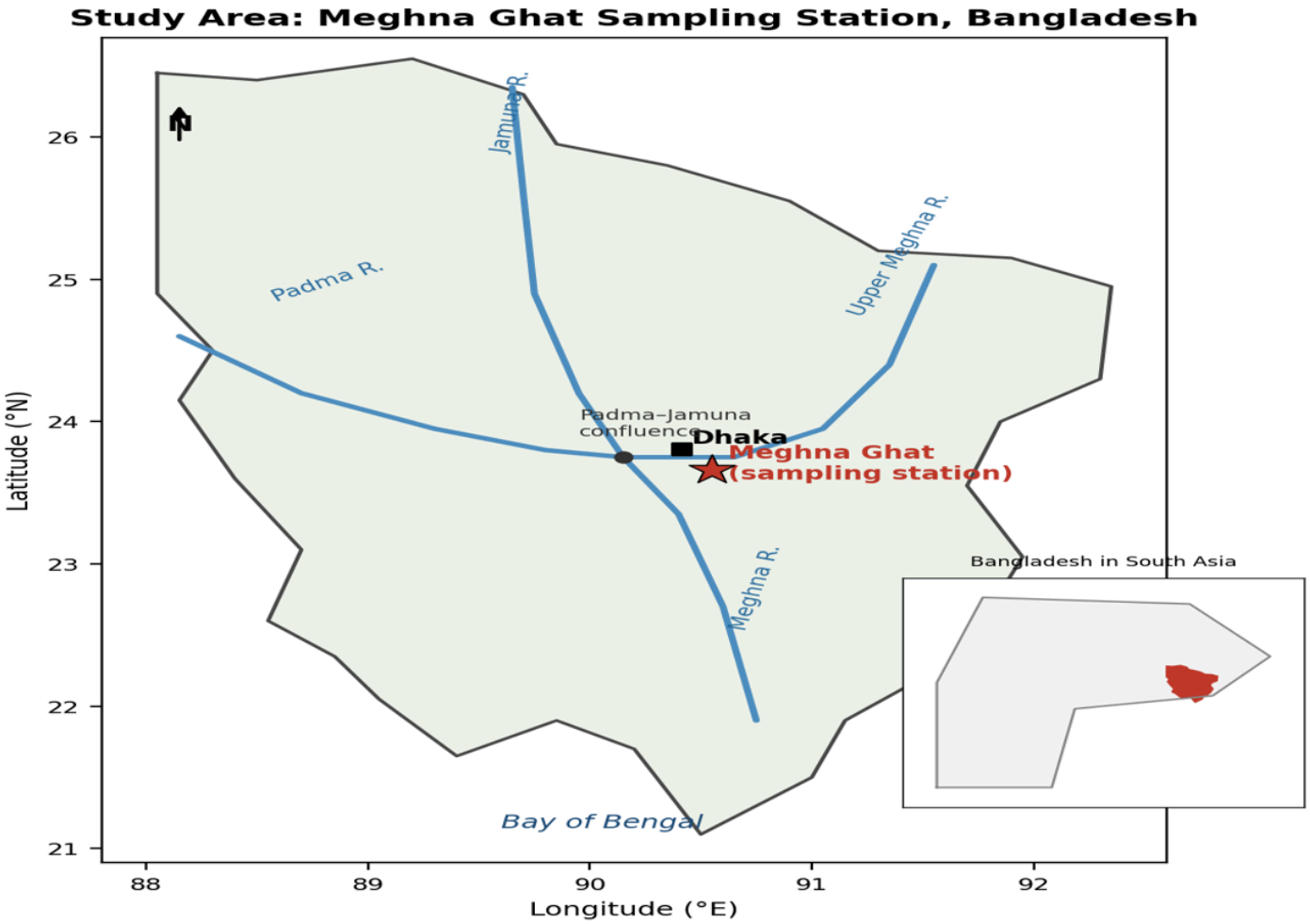


Figure 1

Schematic location map of the study area, showing the Meghna River system and the Meghna Ghat sampling station relative to Dhaka and the Padma–Jamuna confluence (base map generalized; not to precise cartographic scale).

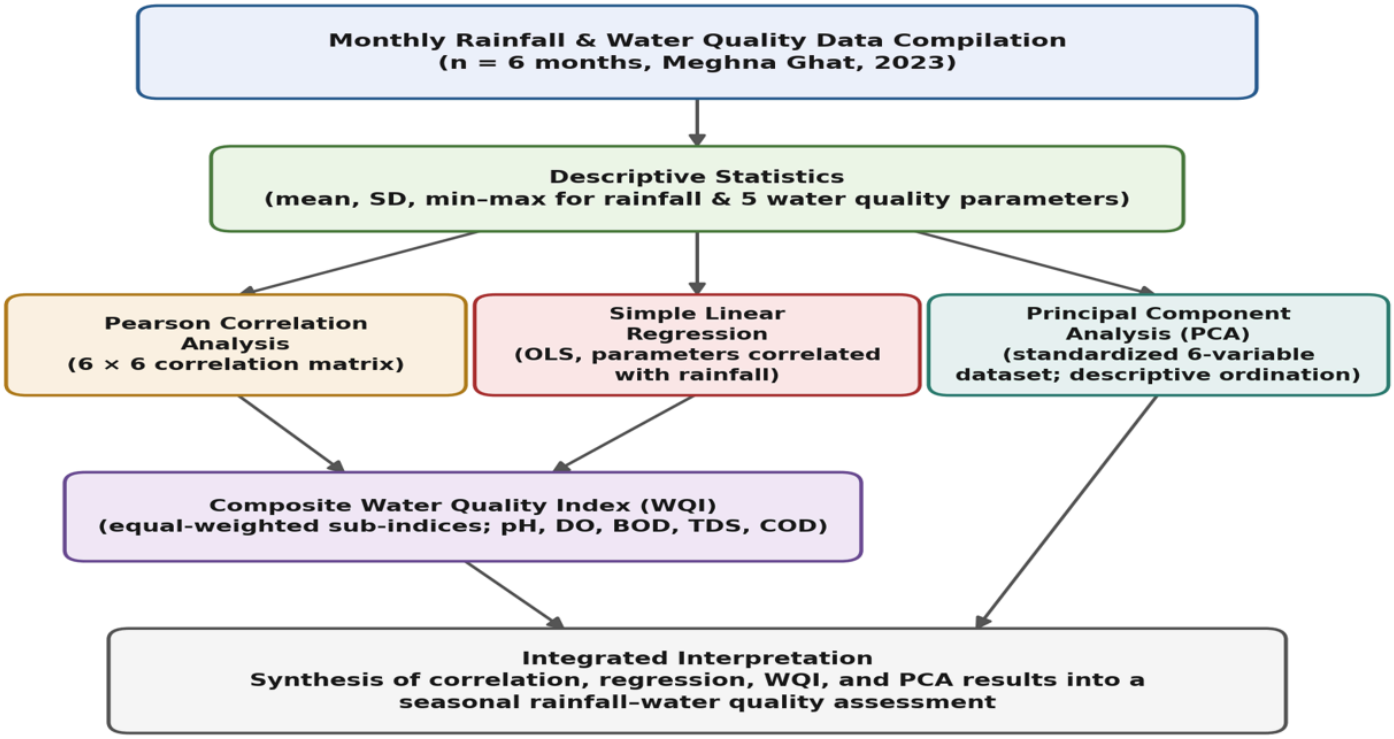


Figure 2

Overview of the analytical workflow applied in this study, from data compilation through descriptive statistics, Pearson correlation, simple linear regression, principal component analysis (PCA), and composite Water Quality Index (WQI) analyses, converging on an integrated interpretation.

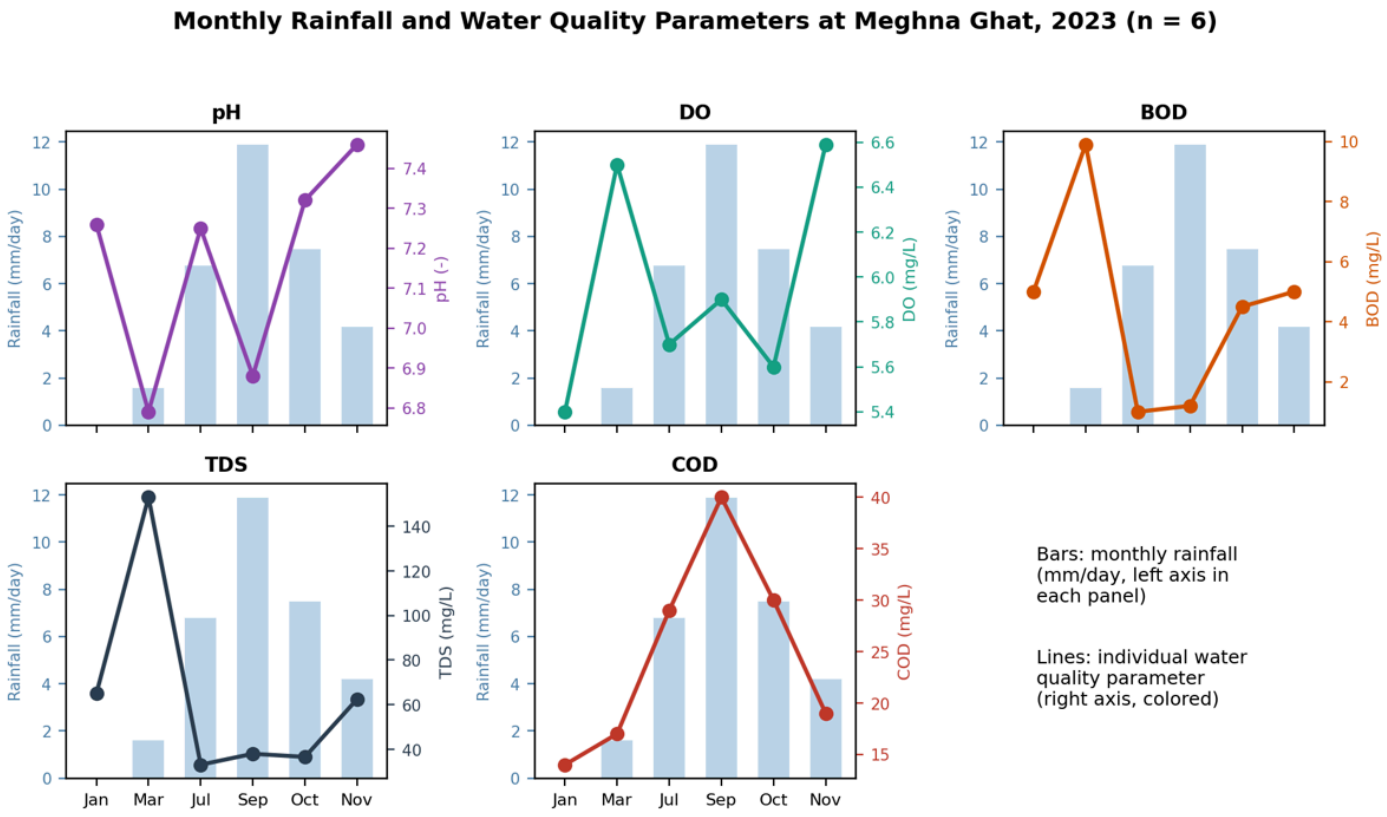


Figure 3

Monthly time series of rainfall (bars, left axis in each panel) and pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), total dissolved solids (TDS), and chemical oxygen demand (COD) (lines, right axis) at Meghna Ghat, 2023 (n = 6).

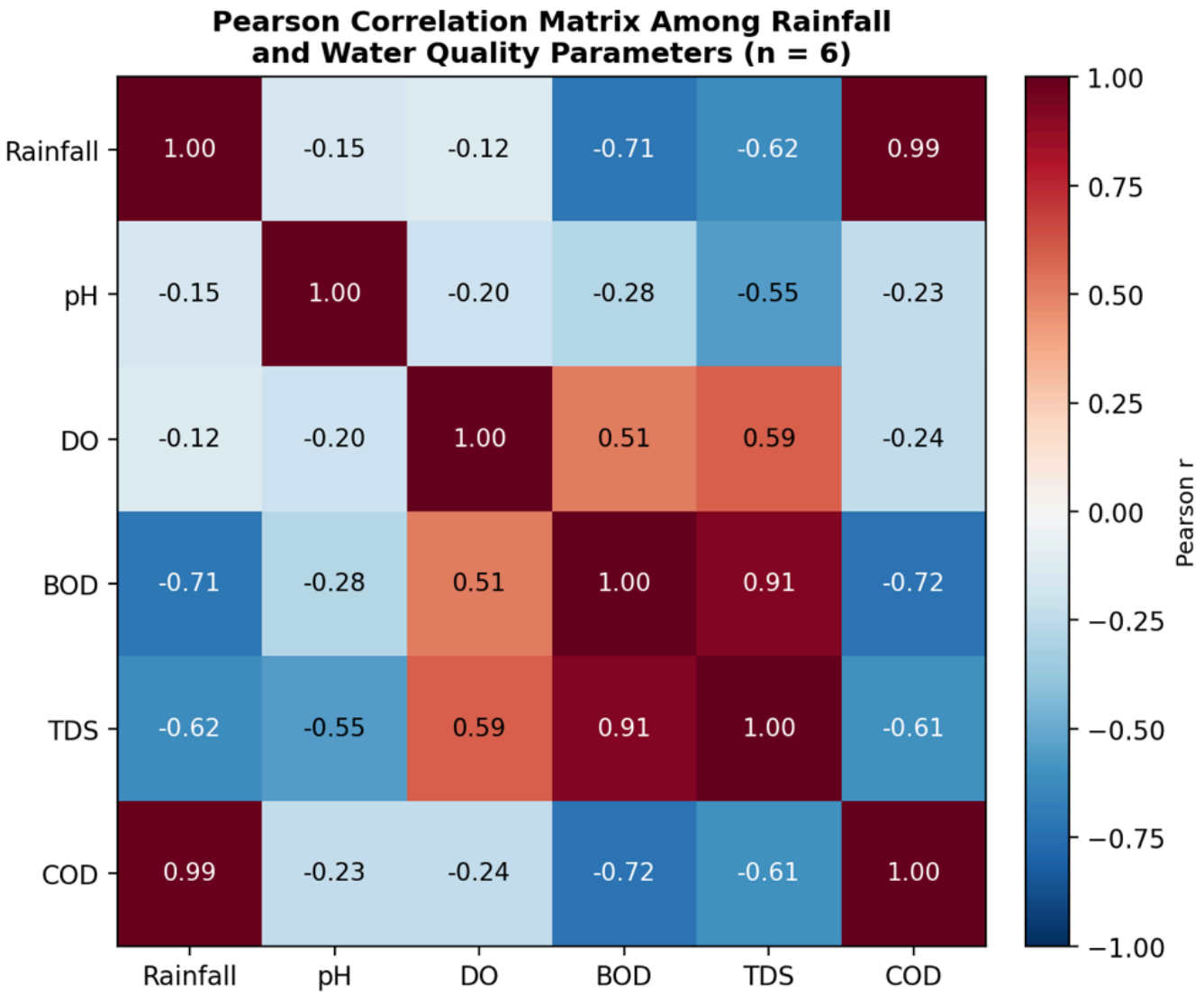


Figure 4

Pearson correlation matrix among rainfall and water quality parameters (pH, DO, BOD, TDS, COD) at Meghna Ghat, 2023 (n = 6).

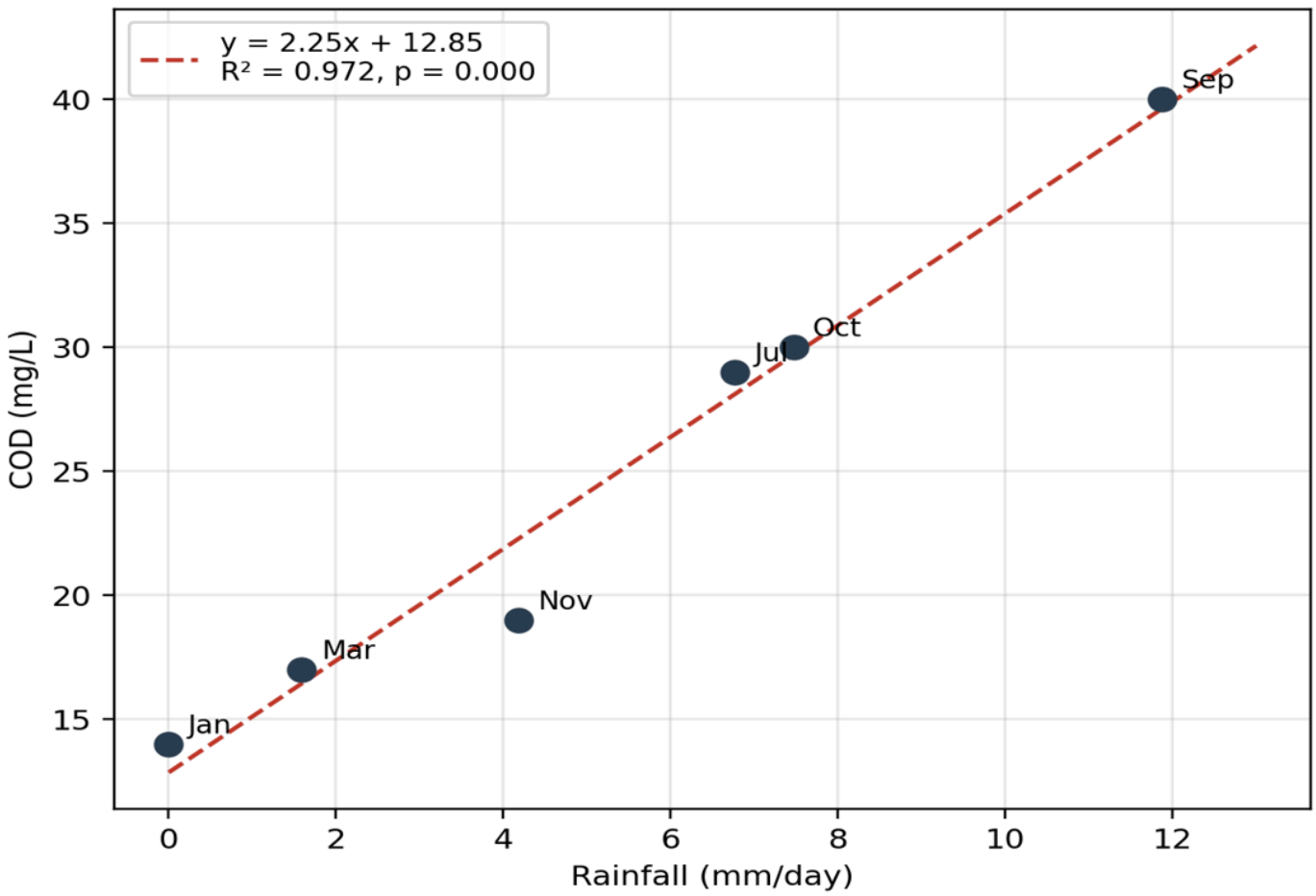


Figure 5

Relationship between monthly rainfall and chemical oxygen demand (COD) at Meghna Ghat, 2023.

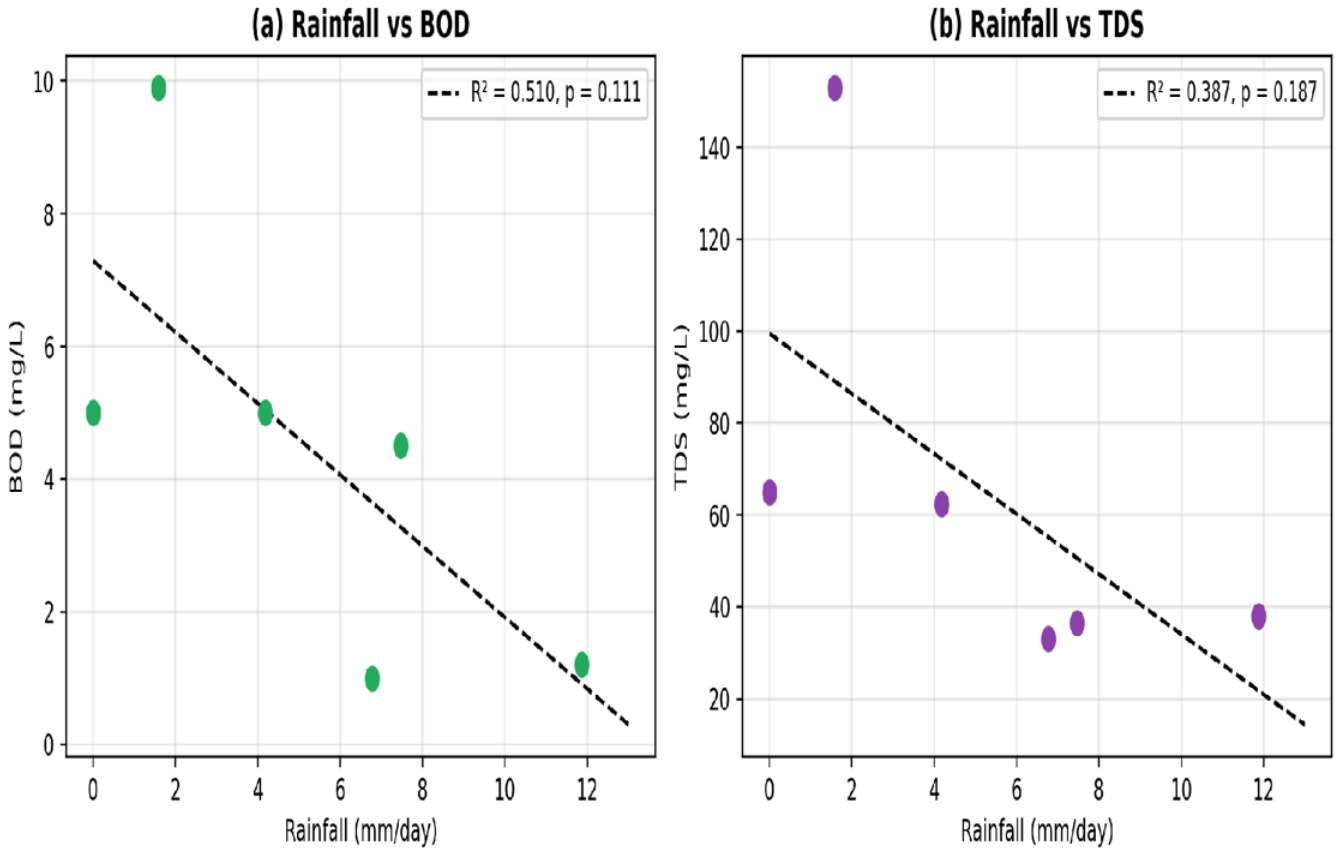


Figure 6

Relationship between monthly rainfall and (a) BOD and (b) TDS at Meghna Ghat, 2023.

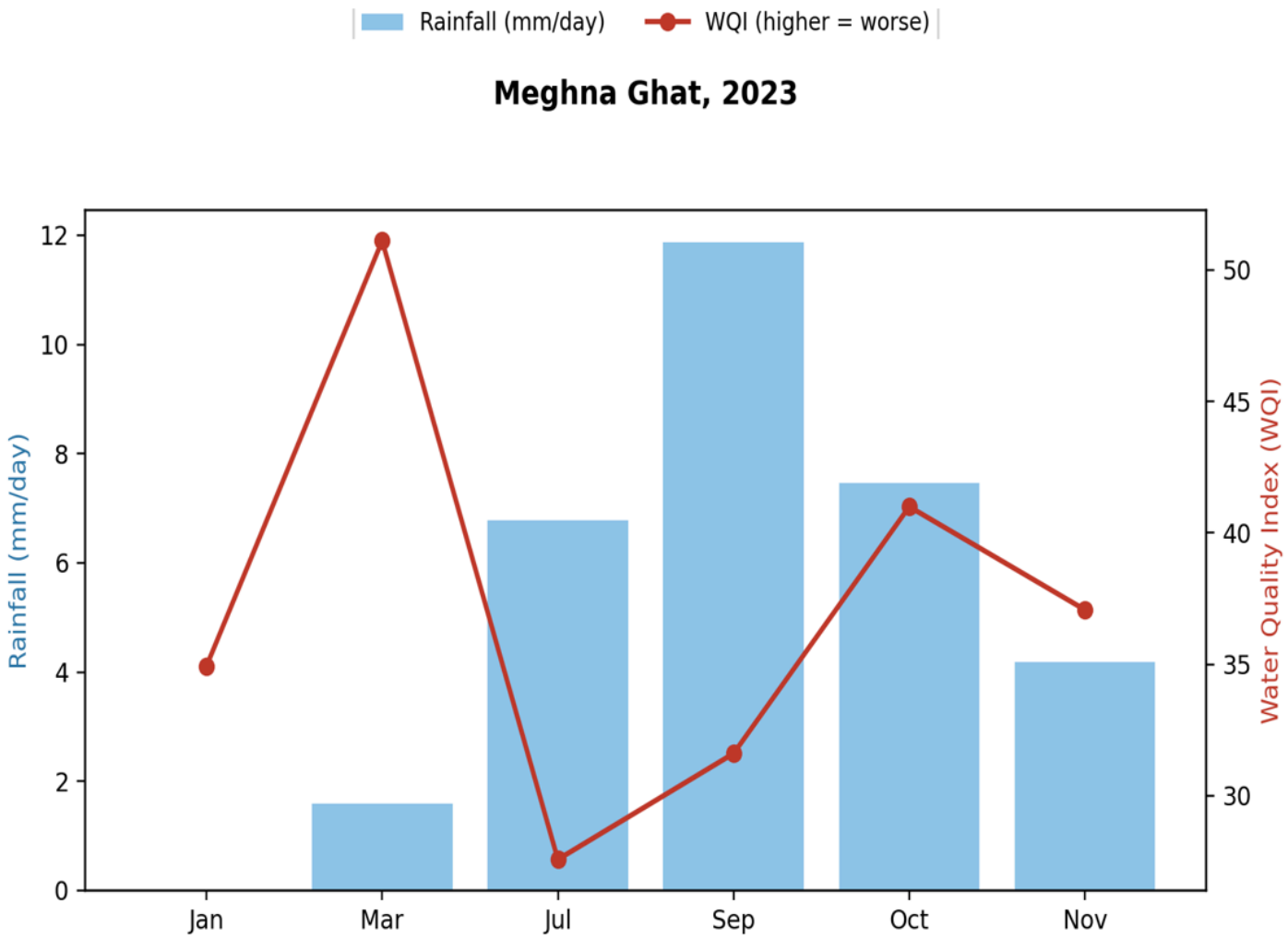


Figure 7

Monthly rainfall and composite Water Quality Index (WQI) at Meghna Ghat, 2023 (higher WQI indicates poorer quality).

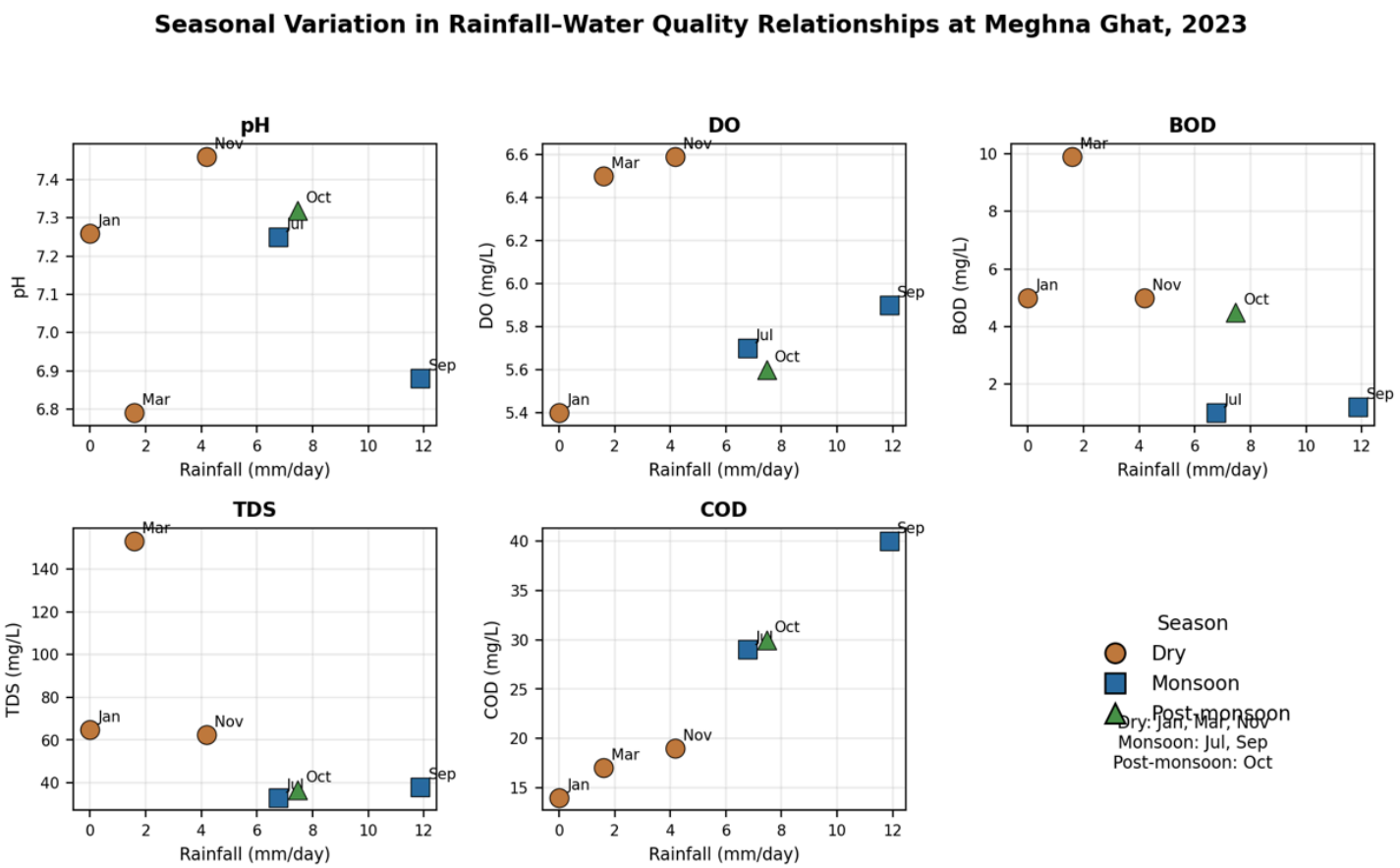


Figure 8

Seasonal scatter plots of rainfall versus pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), total dissolved solids (TDS), and chemical oxygen demand (COD) at Meghna Ghat, 2023, grouped by season (dry: Jan, Mar, Nov; monsoon: Jul, Sep; post-monsoon: Oct).

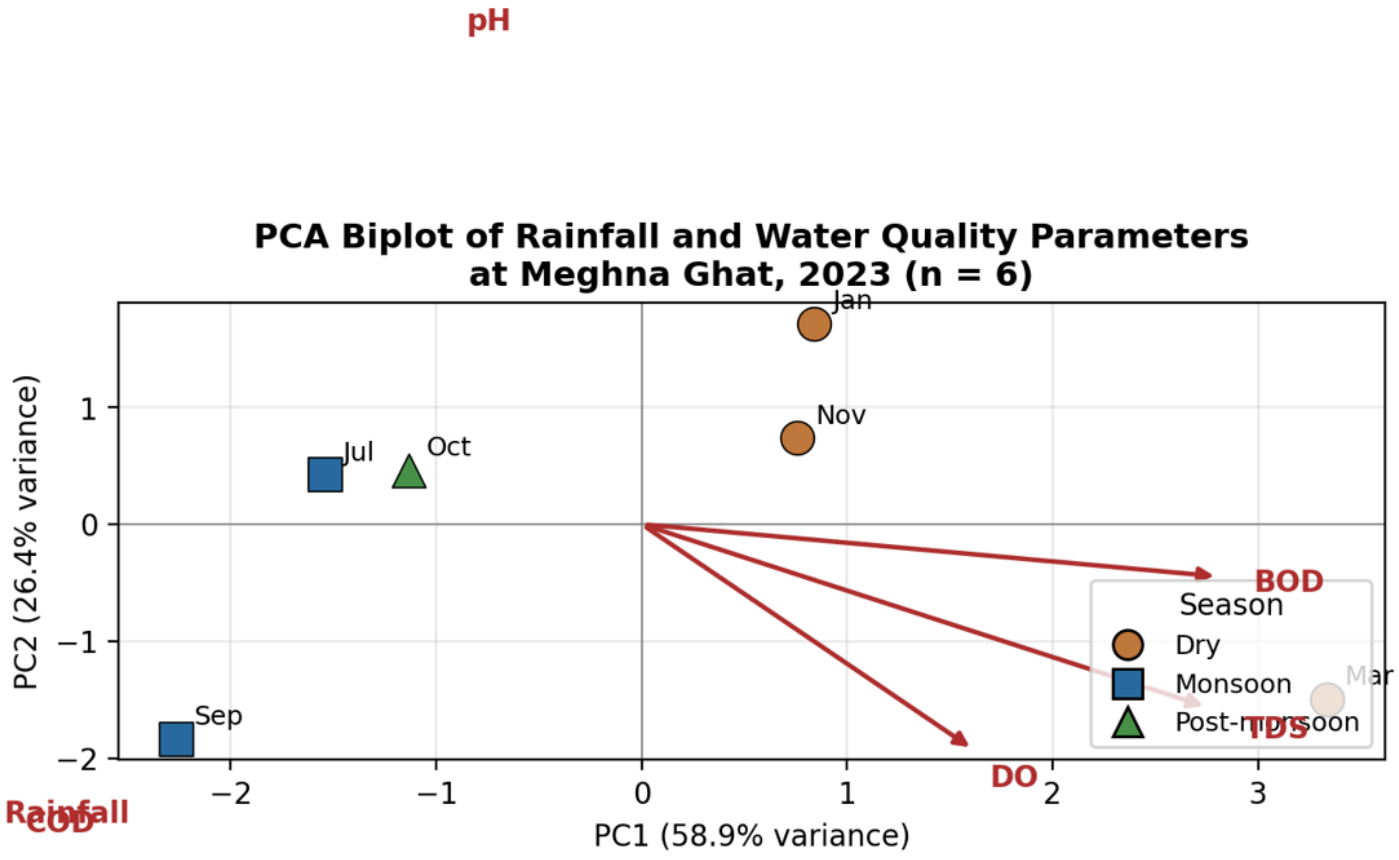


Figure 9

Principal component analysis (PCA) biplot of rainfall and water quality parameters at Meghna Ghat, 2023 (n = 6). Points show the six monthly observations (colored by season); arrows show variable loadings on the first two principal components (58.9% and 26.4% of variance, respectively).