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Climate and Human Impacts on Semi-Arid River Water Quality

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ABSTRACT

Water quality degradation in river ecosystems is a growing global challenge, driven by both anthropogenic activities and climate change. The Kashafroud River in northeastern Iran is a critical water source for nearly two million people, yet it faces mounting pressures from rising temperatures (~1.5 °C over the past three decades), irregular rainfall, frequent droughts and floods, agricultural runoff, industrial effluents, and rapid urbanization. This study analyzes long-term trends in key water quality parameters—electrical conductivity (EC), biological oxygen demand (BOD), and chemical oxygen demand (COD)—over a 13-year period, using statistical modeling and geospatial mapping. Hydroclimatic analysis revealed increasing temperatures and declining precipitation across the basin, providing important context for understanding vegetation degradation, expansion of bare land, and water quality deterioration. The results show BOD levels increased by 20% and COD by 15%, strongly correlating with climate variability and intensifying pollution sources. Inline with other research, we concluded that, the Kashafroud River is heavily impacted by urban wastewater, with pollution loads far exceeding its natural assimilation capacity. Hydrological and water quality monitoring is essential for managing pollution and protecting downstream water users.

These findings highlight the urgent need for integrated water management strategies that combine stricter industrial discharge standards, improved control of agricultural runoff, and climate-resilient urban planning. By demonstrating how climatic and human pressures jointly degrade water quality, the study offers practical insights for conservation of the Kashafroud River and contributes to global understanding of freshwater management in arid and semi-arid regions.

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1. Introduction

Rivers are fundamental to sustaining human life and ensuring the health of ecosystems, as they provide essential freshwater for drinking, agriculture, and industry while supporting biodiversity (Ferreira, Albariño et al. 2023, Sousa, Martins et al. 2025). They also underpin many socio-economic sectors by supplying water for irrigation, industrial processes, transportation, and recreational activities (Wang and He 2022). Despite their importance, rivers worldwide are increasingly threatened by human-induced pressures and the accelerating impacts of climate change (Ahmed, Zounemat-Kermani et al. 2020). Among the most critical challenges is the deterioration of water quality, which has profound consequences for human health, ecological stability, and economic development (Unep and ASSESSMENT 2016). Since rivers are often the primary source of drinking water for both rural and urban populations, water quality is directly linked to public health and the economic vitality of surrounding communities (Vörösmarty, Pahl-Wostl et al. 2013). Maintaining and improving river water quality is therefore a cornerstone of sustainable development and ecological resilience (Sousa, Martins et al. 2025).

Urban rivers in dry climates exhibit pronounced water quality deterioration due to limited dilution capacity, concentrated pollutant loads, and rapid urbanization. Headwater reaches generally maintain moderate to good quality, whereas urban and downstream sections often fall into poor categories, reflecting strong anthropogenic influence (Chen et al., 2022; Ma et al., 2025). Key indicators such as COD, BOD, TN, TP, NH_3-N, and DO frequently exceed regulatory thresholds during dry seasons, with BOD values reaching up to five times environmental standards and DO depletion threatening aquatic life (Yin, Islam & Ju, 2021; Rakib et al., 2024). Pollution sources are dominated by untreated domestic sewage and industrial effluents, compounded by nonpoint contributions from urban runoff. Emerging contaminants—including pharmaceuticals, endocrine disruptors, and microplastics—alongside heavy metals (Pb, Cd, Hg) in sediments pose escalating ecotoxicological risks (Zhou et al., 2024; Huang et al., 2023). Seasonal dynamics exacerbate these issues: during dry periods, reduced flow concentrates nutrients, salts, and organic matter, while storm events in wet seasons mobilize accumulated pollutants, causing episodic spikes in contamination (Pitton et al., 2016; Puczko & Jekatierynczuk-Rudczyk, 2020). Ecological consequences include eutrophication, biodiversity loss, and bioaccumulation of toxic elements, with risk quotients for certain pharmaceuticals exceeding safe limits in urban stretches (Peng et al., 2017; Liu et al., 2023). These patterns underscore the urgent need for integrated management strategies—enhanced wastewater treatment, real-time monitoring, and land-use planning to reduce impervious surfaces and restore riparian buffers. In dry climates, proactive measures during low-flow periods are critical to mitigate pollution concentration and safeguard ecosystem services (Chen et al., 2022; Ma et al., 2025).

Table 1. Summary of key water quality issues in urban rivers under dry climate conditions, highlighting major pollutants, seasonal impacts, and associated ecological risks.

Issue	Dry Season Impact	Main Pollutants/ Indicators	Ecological Risk	References
Organic Pollution	High (BOD, COD increase)	BOD, COD, NH_3-N, TN, TP	Eutrophication, fish kill	(Chen et al., 2022), (Ma et al., 2025), (Yin, Islam & Ju, 2021), (Rakib et al., 2024)
Microplastics	Higher concentration	MPs (0.1-5 mm)	Potential long-term risk	(Huang et al., 2023)
Heavy Metals/PTEs	Persistent, may concentrate	Pb, Cd, Hg, Zn, Cu, As, Ni	Bioaccumulation, toxicity	(Rakib et al., 2024), (Gu et al., 2022)
Pharmaceuticals/ EDCs	Detected year-round, higher risk	Antibiotics, PPCPs, EDCs	Algae/ invertebrate risk	(Zhou et al., 2024), (Zhou et al., 2016), (Peng et al., 2017)
Nutrient Pollution	High (less dilution)	TN, TP, NO_3-N	Eutrophication	(Chen et al., 2022), (Ma et al., 2025), (Zhang & Yang, 2024)

The Kashafroud River in northeastern Iran is a vital water source for agriculture, industry, and domestic use, yet its sustainability is increasingly threatened by combined anthropogenic and climatic pressures. Rapid urbanization, industrial growth, and intensive agriculture have elevated pollution levels through untreated wastewater, chemical fertilizers, and pesticides, while climate change has amplified these stressors via rising temperatures, altered precipitation patterns, and more frequent extreme events such as floods and droughts (Baygi et al., 2023; Saatsaz & Rezaei, 2023; Change, 2007). These dynamics accelerate organic matter decomposition, increasing BOD, and intensify pollutant transport from impervious surfaces, further degrading water quality (Szewczyk et al., 2023; Taylor & Owens, 2009; Wang et al., 2024). Previous studies highlight localized pollution sources and heavy metal contamination but lack integrated, basin-wide assessments that account for climate variability (Kolahi et al., 2024; Tajbakhshian, 2025; Gholizade et al., 2024). To address this gap, the present study conducts a 14-year spatiotemporal analysis of water quality using EC, BOD, COD, and pH as indicators, combined with climatic data and GIS-based mapping, to identify long-term trends, quantify climate-pollution linkages, and pinpoint spatial hotspots.

2. Materials and Method

This research employs a mixed-methods approach, combining field sampling, laboratory analysis, and statistical modeling to assess the dynamic water quality of the Kashafroud River. The study design is tailored to ensure robust data collection and analysis, enabling an accurate understanding of the relationships between pollution levels and climate variability (Kolahi, Davary et al. 2024).

2.1. Study Area

The study was carried out in a research area of 135 km^2, extending from Shahname Bridge to Charmshahr, near the Kashafroud Protected Area in Khorasan Razavi Province, northeast Iran (23°30′ S, 29°19′ E; 1090 m above sea level) (Figure 1). The Kashafroud River, with a total length of approximately 290 km, originates from the Binaloud and Hezar Masjed Mountains and flows eastward until it reaches the Iran–Turkmenistan border, where it merges with the Hari-Roud River to form the Tejen River. The study area is situated 65 kilometers east of Mashhad and 35 kilometers west of Mazdavand (Mozduran) in Sarakhs County. The region experiences an arid to semi-arid climate, with an average annual temperature of approximately 13.5 °C, a minimum recorded temperature of −21 °C in January, and a maximum temperature of 44 °C in July. Most annual precipitation occurs between February and March, with an average of 253 mm/year (Ghane, Motevalli et al. 2024)). The basin has undergone rapid industrialization and agricultural expansion, contributing to escalating pollution (Tajbakhshian 2025).The Kashafroud River, the longest in its catchment, extends 290 km across northeastern Iran and drains an area of 16,870 km^2. The basin exhibits a mean slope of 1% and receives approximately 340 mm of annual precipitation, with altitudes ranging from 391 m to 3,234 m. Hydrological monitoring (1993–2020) for a 43 km segment between Parkand and Olang stations reported mean annual discharge of 0.658 m^3/s, flow velocity of 0.125 m/s, width of 74.5 m, depth of 0.59 m, and shear velocity of 0.118 m/s (Dehghani Darmian & Schmalz, 2023). Water quality is severely impacted by municipal wastewater inputs, primarily from the Siss Culvert, which introduces over 540 tons/day of urban effluent. Assimilation capacity modeling using longitudinal dispersion coefficients (LDC) estimates the river's capacity at 91.93 tons/day—nearly six times lower than current pollutant loads. This imbalance highlights a critical risk of water quality violations and ecological degradation.

Table 2. Summary of key hydrological and water quality characteristics of the Kashafroud River, highlighting physical dimensions, climatic conditions, and pollution dynamics.

Parameter	Value/Range	Notes
River Length	290 km	Longest in Kashafroud catchment
Basin Area	16,870 km²	
Mean Slope	1%	
Annual Precipitation	~340 mm	
Altitude Range	391–3,234 m	
Mean Annual Discharge	0.658 m³/s	For 43 km segment (1993–2020)
Mean Flow Velocity	0.125 m/s	
Mean Flow Width	74.545 m	
Mean Flow Depth	0.588 m	
Shear Velocity	0.118 m/s	
Wastewater Input	>540 tons/day	From Siss Culvert (urban wastewater)
Assimilation Capacity	91.93 tons/day	Simulated with accurate LDC
Pollution Exceedance	~6x	Pollution input vs. assimilation capacity

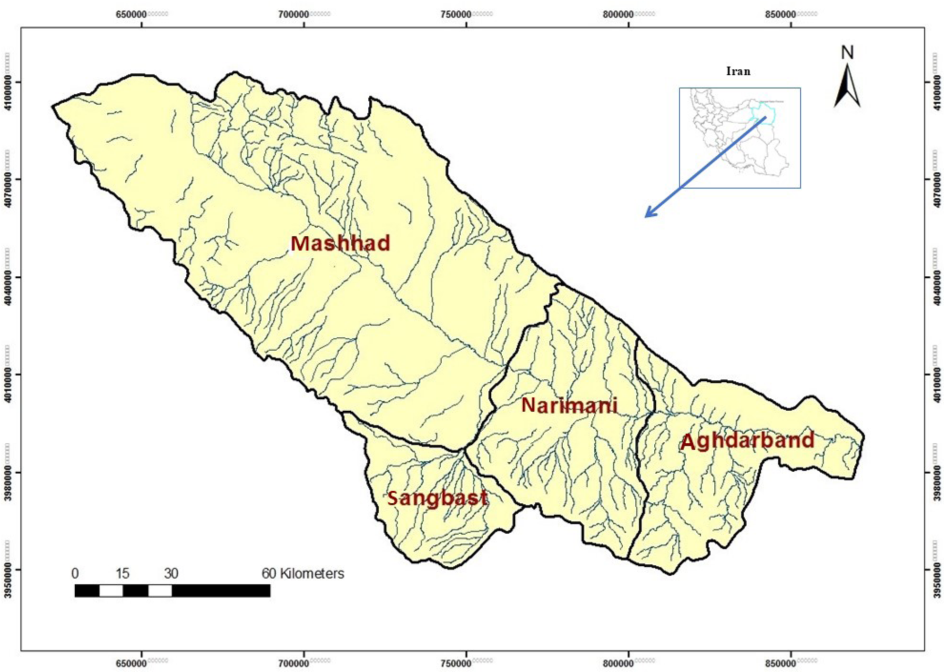

Figure 1. Map of the study area showing the watershed boundaries, and major river flow

2.2. Sampling and Data Collection

Long-term water quality data for the Kashafroud River were compiled for the period 2010–2023 from available monitoring records. These data were used to assess temporal changes in key water quality indicators, including pH, electrical conductivity (EC), biochemical oxygen demand (BOD), chemical oxygen demand (COD), dissolved oxygen (DO), and total dissolved solids (TDS). In addition to the long-term dataset, two field sampling campaigns were conducted to support the interpretation of spatial water quality patterns along the study reach. Surface water samples were collected once during the wet/rainy season in August 2019 and once during the dry season in April 2020. Seven sampling stations were selected along the Kashafroud River, extending from Shahname Bridge to Charmshahr, adjacent to the Charmshahr wastewater treatment plant. These stations were chosen to capture variation in hydrological conditions and proximity to potential pollution sources, including urban runoff, domestic and municipal wastewater discharges, industrial effluents, agricultural drainage, and untreated sewage inputs.

Therefore, the 2010–2023 analysis represents long-term monitoring-based assessment, while the 2019–2020 field campaigns represent two seasonal sampling events used to provide field-based context for interpreting spatial pollution patterns.

A total of seven sampling stations were selected along the Kashafroud River at strategic points to capture a range of hydrological and anthropogenic conditions (Figure 2). Surface water samples were collected twice during the study period: once in the rainy season (August 2019) and once in the dry season (April 2020). Sampling began at Shahname Bridge and ended at Charmshahr, adjacent to the Charmshahr wastewater treatment plant (Figure 2). The selected stations were located within the main impacted reach of the river to capture the influence of urban, industrial, and agricultural pollution sources. No dedicated upstream reference station was included in the sampling network. These stations were chosen based on their proximity to potential pollution sources, including urban runoff, domestic and municipal wastewater discharges, industrial effluents, agricultural drainage, and untreated sewage inflows. Rigorous sampling protocols were followed to minimise contamination and ensure data reliability [18].

A comprehensive suite of physicochemical and biological water quality parameters was measured to provide a holistic assessment of aquatic ecosystem health. These included pH, electrical conductivity (EC), biochemical oxygen demand (BOD), chemical oxygen demand (COD), dissolved oxygen (DO), and total dissolved solids (TDS). These indicators were selected for their relevance to environmental health (e.g., nutrient enrichment, organic loading, heavy metal toxicity) and human welfare (e.g., suitability for drinking water and irrigation, risks to fisheries, and ecological integrity). Parameters such as DO, BOD, and COD reflect the balance between organic pollution and oxygen availability, while nutrient concentrations highlight risks of eutrophication. Heavy metals were included because of their persistence, bioaccumulation potential, and toxicity to aquatic organisms and human populations.

To summarise water quality conditions, raw measurements for each parameter were first averaged within each season to represent wet and dry conditions. Annual values for each station were then calculated as the mean of these two seasonal observations. No missing values occurred during sampling; however, if gaps had been present, single missing points would have been addressed using linear interpolation, and any station with more than 20% missing data would have been excluded from annual aggregation. This approach ensures comparability across stations and seasons while maintaining statistical validity by minimising bias from uneven sampling intervals.

Figure 2. (a)Sampling locations along the river showing upstream, midstream, and downstream zones used for water quality monitoring. (b)wastewater sampling process at the treatment plant effluent point for the analysis of physical, chemical, and microbiological parameters.

2.3. Hydroclimate analysis

Hydroclimatic analysis was conducted to assess temporal variations in precipitation patterns and their implications for land surface processes within the Kashafroud River Basin. Annual precipitation data spanning the period from 2010 to 2023 were extracted from remote sensing-based gridded climate datasets using the Google Earth Engine (GEE) platform. Basin-wide mean values were calculated to evaluate interannual variability, identify long-term trends, and detect periods of significant drought. These precipitation patterns were then cross-analyzed with land cover changes and surface degradation indicators to understand the role of hydroclimatic stress in driving ecological transformations. The analysis provided essential context for interpreting vegetation dynamics and pollution behavior across the basin.

2.4. Historical Changes in Landuse/Landcover

Land use and land cover (LULC) changes from 2010 to 2022 were analyzed using satellite-derived classification maps processed within Google Earth Engine. Key land cover types—including cropland, shrubland, grassland, forest, bare land, and impervious surfaces—were quantified annually to detect trends and transitions. A post-classification comparison approach enabled consistent monitoring of spatiotemporal dynamics, with results cross-validated using visual inspection and ancillary data. The hydroclimatic analysis was used to assess the potential influence of climate variability on land cover dynamics and water quality conditions.

2.5. Integrated Attribution Framework:

To quantify the combined influence of climatic and anthropogenic drivers on water quality, we developed an integrated attribution framework. This approach simultaneously considers hydroclimatic variables (precipitation, temperature, and potential evapotranspiration) and land-use/land-cover (LULC) changes (cropland, shrubland, grassland, bare land, and impervious surfaces) as explanatory factors. Annual summaries of climate data were derived from gridded datasets via Google Earth Engine, while LULC metrics were extracted from satellite-based classification maps. Water quality indicators (EC, BOD, COD, pH) were regressed against these drivers using a two-step process: (i) correlation analysis to identify significant associations, and (ii) machine learning-based importance analysis (SHAP) to estimate the relative contribution of each driver. This unified framework enables causal inference by integrating climatic variability and anthropogenic pressures within a single analytical model.

2.6. Water Quality Analysis

2.6.1. Measured Parameters

A comprehensive suite of physicochemical and biological water quality parameters was measured to provide a holistic assessment of aquatic ecosystem health. These included pH, electrical conductivity (EC), biochemical oxygen demand

(BOD), chemical oxygen demand (COD), dissolved oxygen (DO), and TDS. These indicators were selected based on their direct relevance to both environmental health (e.g., nutrient enrichment, organic loading, heavy metal toxicity) and human welfare (e.g., suitability for drinking water and irrigation, risks to fisheries, and ecological integrity). Parameters such as DO, BOD, and COD reflect the balance between organic pollution and oxygen availability, while nutrient concentrations highlight risks of eutrophication. Heavy metals were included because of their persistence, bioaccumulation potential, and toxicity to aquatic organisms and human populations.

2.6.2. Analytical Techniques

Standardized laboratory procedures were adopted to ensure reproducibility and comparability across sites and sampling campaigns. Spectrophotometric methods (APHA Standard Methods, 2017) were used to determine nutrient levels (nitrates and phosphates), employing UV–Vis spectrophotometry with appropriate calibration standards. Titrimetric methods (Winkler method with azide modification) were used to quantify DO, while BOD was measured via the 5-day incubation method. COD was determined using the closed reflux dichromate method. Atomic Absorption Spectroscopy (AAS) was applied to measure trace concentrations of Pb, Hg, and Cd in filtered and acidified samples, with calibration curves constructed using certified standard solutions. All instruments were calibrated daily, and quality assurance procedures included the use of blanks, duplicates, and certified reference materials. In addition, regression models were applied to evaluate long-term temporal trends in water quality variables, accounting for potential seasonality and autocorrelation.

2.6.3. Statistical Analysis

All data were tested for normality using the Shapiro–Wilk test prior to statistical analysis. Pearson's correlation coefficients (r) were calculated to evaluate the strength and direction of associations between climate variables (e.g., rainfall, temperature) and measured water quality parameters. The significance of correlations was assessed using p-values, with thresholds of $p < 0.05$ considered statistically significant and $p < 0.01$ highly significant. Where data deviated from normality, non-parametric alternatives such as Spearman's rank correlation were applied. To further examine patterns, multiple regression models were constructed to quantify the relative contributions of climatic factors and anthropogenic drivers to observed pollution levels.

3. Results

3.1. Climate Data Analysis and Its Environmental Implications (2010–2023)

Precipitation is a principal climatic driver shaping ecological processes and land surface conditions in semi-arid environments. In the Kashafroud River Basin, interannual variations in mean annual precipitation from 2010 to 2023 are revealing notable fluctuations and a pronounced drying trend in recent years (Figure 3). From 2010 to 2018, the basin experienced moderate variability, with annual mean precipitation values typically ranging between 0.66 m and 0.95 m. A distinct peak occurred in 2019, reaching a maximum of approximately 1.14 m, likely reflecting a short-term climatic anomaly (Figure 3). However, following this peak, a marked and persistent decline was observed, with precipitation falling sharply to 0.51 m in 2021 and further decreasing to 0.45 m by 2023—the lowest in the 14-year observation period.

This declining trajectory aligns temporally with increased surface degradation indicators observed across the basin, including expansion of bare land and reduced vegetation cover. The reduction in rainfall not only decreases soil moisture availability and groundwater recharge but also weakens vegetation resilience, accelerates erosion processes, and intensifies pollutant runoff into surface waters. These findings highlight the critical link between hydroclimatic variability and landscape transformation. The cumulative impacts of reduced precipitation—particularly when coupled with anthropogenic land-use pressures—underscore the necessity for integrated climate-resilient watershed management strategies that incorporate precipitation forecasting, adaptive land-use planning, and vegetation conservation. The analysis of annual mean temperatures between 2012 and 2023 shows noticeable fluctuations with an overall upward tendency. In the early years (2012–2014), average temperatures ranged between 15.5 °C and 16.3 °C, reflecting relatively stable conditions. However, starting in 2015, there was a period of higher variability, with peaks such as 17.0 °C in 2015 and a sharp increase to 17.2 °C in 2017. The lowest mean temperature in this period occurred in 2020 (15.3 °C), followed by a significant rebound in 2021 (17.1 °C). The warming trend continued, reaching the highest recorded value in 2023 at 17.5 °C. Overall, the data indicates that while there were short-term decreases in certain years, the long-term pattern points to rising mean temperatures, highlighting a clear warming trend over the past.

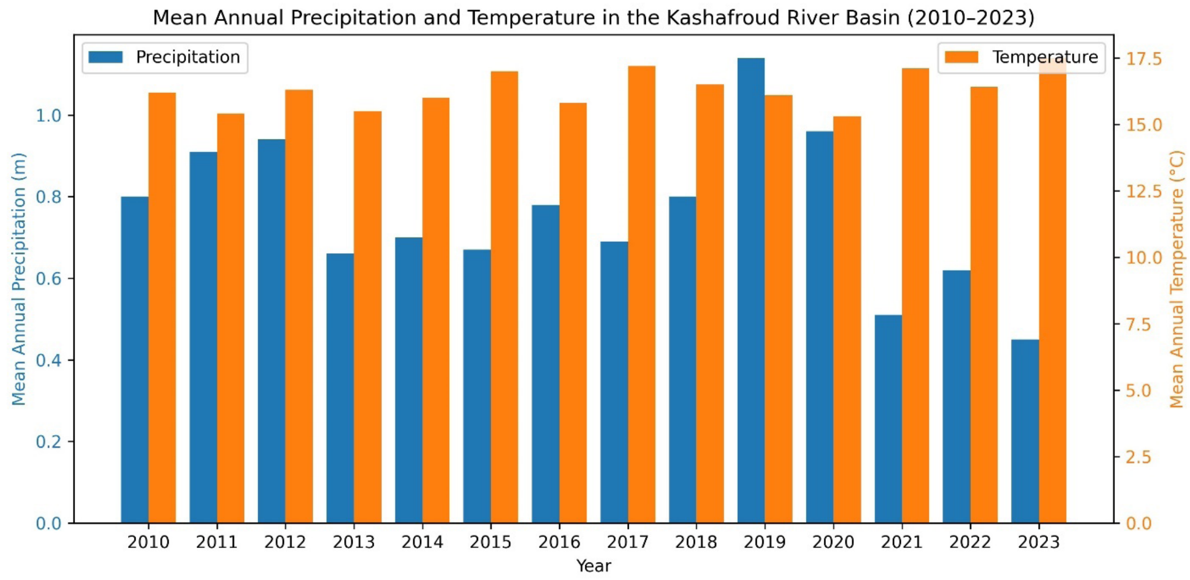

Figure 3. Interannual variation of mean annual precipitation (m) and mean annual tempreture (°C) in the Kashafroud River Basin from 2010 to 2023

3.2 Vegetation Cover Change and Its Link to Climate and Pollution

Vegetation cover is a fundamental component of watershed ecosystems, influencing hydrological regulation, sediment stabilization, and pollutant filtration. In the Kashafroud River Basin, land cover dynamics between 2010 and 2022 were assessed using annual remote sensing data, with a focus on key vegetation types including cropland, shrubland, grassland, forest, and bare land, as well as impervious surfaces indicative of urban and industrial expansion. During the 13-year period, cropland areas exhibited a notable decline, particularly after 2015. This trend may be attributed to reduced water availability for irrigation, shifts in agricultural practices, or broader socioeconomic land-use transitions. Forest cover remained sparse, showing slight interannual variability. A modest increase was observed until around 2019, which was subsequently followed by a minor decline, potentially reflecting limited reforestation efforts offset by continuing degradation pressures. Shrubland areas demonstrated relative stability, with earlier declining trends appearing to level off in recent years. Grasslands similarly maintained a steady presence across the landscape, with only minor year-to-year variation. A slight increase in grassland cover observed in the latter part of the study period may reflect localized land management interventions or responses to climatic fluctuations.

In contrast, a substantial increase in bare land was recorded, particularly after 2015. This expansion is likely associated with vegetation loss driven by prolonged drought conditions, intensified soil erosion, and anthropogenic land clearing activities. The timing of this increase corresponds with observed patterns of rising temperatures and greater precipitation variability in the region. Impervious surfaces also expanded steadily throughout the study period, reflecting urban sprawl and industrial development. The conversion of vegetated areas to built-up surfaces has important hydrological implications, including reduced infiltration, increased surface runoff, and elevated levels of non-point source pollution entering the river system.

Preliminary correlation analyses revealed significant associations between these land cover changes and key water quality parameters. The expansion of bare land showed a strong positive correlation with increased electrical conductivity (EC) in the river, suggesting that exposed soils contribute to salt accumulation through evaporation and runoff processes. Similarly, the growth of impervious surfaces was positively correlated with elevated biochemical oxygen demand (BOD) and chemical oxygen demand (COD), highlighting the contribution of urban and industrial runoff to organic and chemical pollution loads. Conversely, declines in shrubland and grassland were negatively correlated with most water quality indicators, underscoring the ecological role of these land covers in regulating runoff and maintaining water quality. These findings indicate that vegetation loss, associated with both climatic variability and land-use change, is correlated with the observed degradation of water quality within the basin. These results indicate that vegetation loss, associated with both climatic variability and land-use change, is correlated with the observed degradation of water quality within the basin.

3.3. Water Quality Trends

Water quality monitoring of the Kashafroud River between 2010 and 2023 reveals a clear and consistent deterioration across the catchment, reflecting increasing anthropogenic pressures combined with limited dilution capacity under a semi-arid climate (Figure 4). Electrical conductivity (EC) increased significantly over the study period ($p = 0.0302$), reaching its highest values in 2023 at the downstream monitoring stations. Similarly, pH values increased from approximately 7.2 in 2010 to 7.8 in 2023, with the maximum recorded value observed in 2023. This trend is consistent with enhanced agricultural return flows, urban runoff, and industrial discharges, and mirrors salinization patterns reported in other intensively irrigated and regulated river systems such as the Colorado River and the Murray-Darling Basin [20,21]. Concurrently, biological oxygen demand (BOD) also increased significantly ($p = 0.0175$), reflecting growing inputs of biodegradable organic matter from untreated municipal wastewater and agricultural activities, and indicating increasing oxygen stress within the river system.

Chemical oxygen demand (COD) exhibited the most pronounced increase among the analyzed parameters ($p = 0.0029$), rising from approximately 250 mg/L in 2010 to 900 mg/L in 2023. The highest COD values were recorded in 2023, particularly at downstream stations, indicating a substantial increase in chemically oxidizable and largely non-biodegradable pollutants (Figure 4). Elevated COD values, particularly at mid- and downstream stations, point to intensified industrial and urban effluent inputs and inadequate treatment capacity, consistent with trends observed in industrialized river basins such as the Yellow River in China [22]. The pH values ranged from approximately 7.1 to 8.2, with a shift toward more alkaline conditions in 2023, potentially reflecting increased alkaline discharges or altered buffering capacity associated with higher ionic strength. Although pH remained within acceptable limits, its increase may amplify the ecological impacts of rising salinity and organic pollution. Overall, the comparison between 2010 and 2023 indicates a progressive decline in water quality across the Kashafroud River, underscoring the need for strengthened wastewater treatment, stricter control of industrial discharges, and integrated catchment-scale management to prevent further degradation.

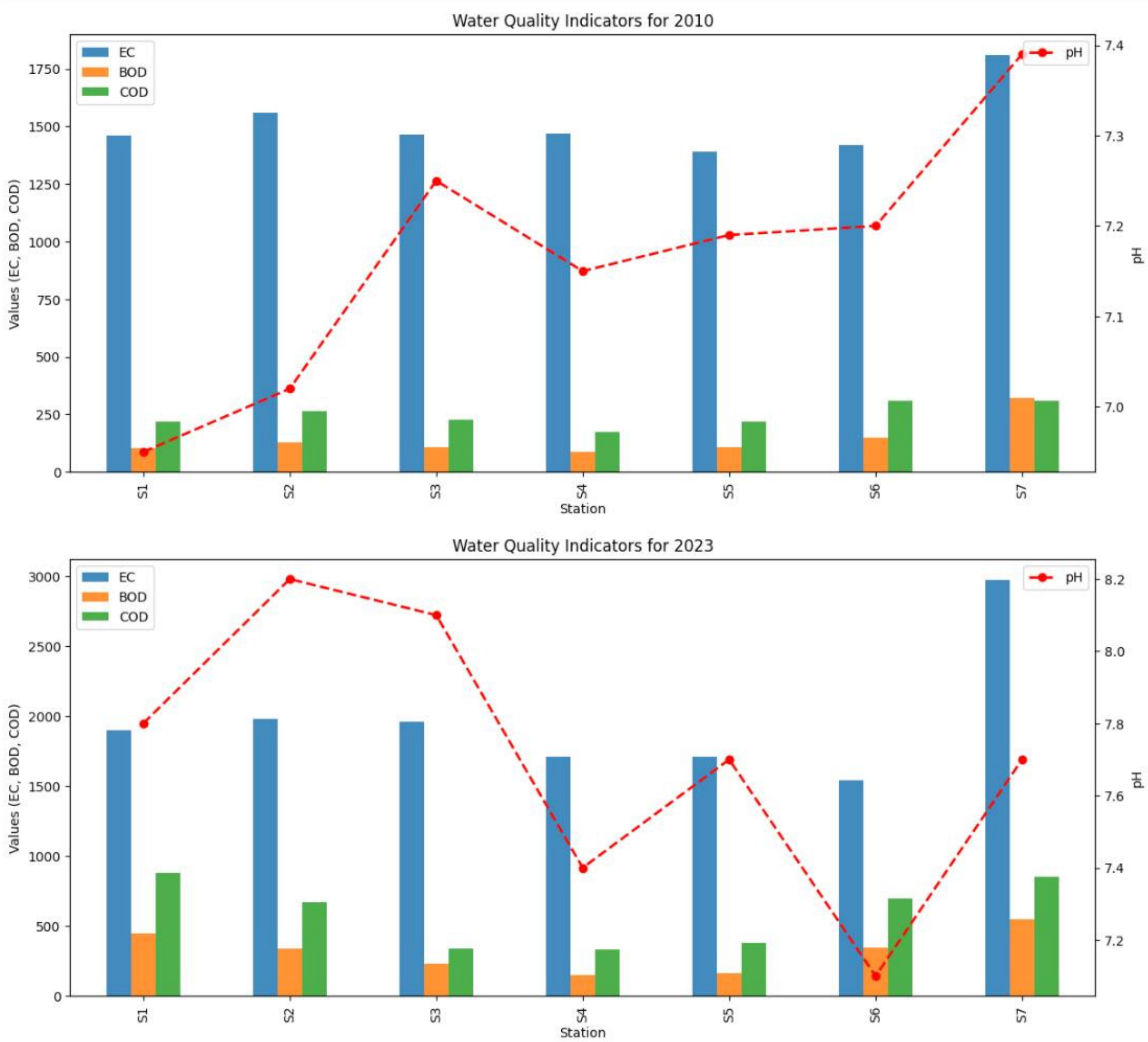

Figure 4. Comparison of water quality indicators (BOD, COD, DO, EC, TDS) across different sampling stations in 2010 and 2023.

3.4. Correlation between Climate Variability and Water Pollution

Correlation analysis indicates clear linkages between climate variability, particularly temperature change, and water quality degradation in the Kashafroud River (Figure 5). Moderate positive correlations were observed between temperature and electrical conductivity (EC; r = 0.43), biological oxygen demand (BOD; r = 0.45), and chemical oxygen demand (COD; r = 0.43), suggesting that warming conditions are associated with increased salinity and organic and chemical pollution. Higher temperatures likely enhance evapoconcentration under reduced flow conditions, increase salt accumulation, and accelerate microbial decomposition of organic matter, leading to elevated BOD and COD levels. These findings are consistent with observations from other semi-arid river systems where warming has intensified water quality deterioration [23].

Strong interrelationships among pollution indicators further highlight the compounded response of water quality to climatic stress. BOD and COD exhibited a very strong correlation (r = 0.98), indicating shared sources and similar responses to environmental forcing, while EC showed strong positive correlations with both BOD (r = 0.67) and COD (r = 0.71). Changes in pH were moderately correlated with temperature (r = 0.55), BOD (r = 0.66), and COD (r = 0.57), suggesting subtle shifts in chemical equilibrium associated with increasing pollutant loads. Overall, Figure 5 demonstrates that climate warming acts as an important amplifier of water pollution in the Kashafroud River, increasing the vulnerability of water quality under ongoing climatic and anthropogenic pressures.

As shown in Figure 6, precipitation change exhibits weak to moderate positive correlations with several water pollution indicators, most notably with BOD (r = 0.37) and COD (r = 0.30). These relationships indicate that rainfall plays an important role in mobilizing organic and chemical contaminants from the catchment and transporting them into the river system through surface runoff. In semi-arid environments such as the Kashafroud Basin, precipitation often occurs as episodic and high-intensity events, which can rapidly wash accumulated pollutants—including agricultural residues, urban wastes, and exposed sediments—into river channels, leading to short-term deterioration of water quality.

The relatively weaker correlation between precipitation and EC (r = 0.08) suggests that salinity dynamics in the Kashafroud River are less directly driven by rainfall variability and more strongly influenced by evapoconcentration processes, irrigation return flows, and groundwater contributions. Moderate correlations between precipitation and pH (r = 0.22) further indicate that rainfall-related dilution or buffering effects are limited and temporally variable. Similar rainfall-driven pollution responses have been documented in other large river systems, such as the Amazon Basin, where intense precipitation events trigger abrupt increases in pollutant loads via enhanced runoff [24]. In the Kashafroud River, increasingly erratic rainfall patterns may therefore contribute to episodic pollution pulses that overwhelm the river's natural assimilative capacity, particularly when combined with reduced baseflows and elevated temperatures, ultimately exacerbating long-term water quality degradation.

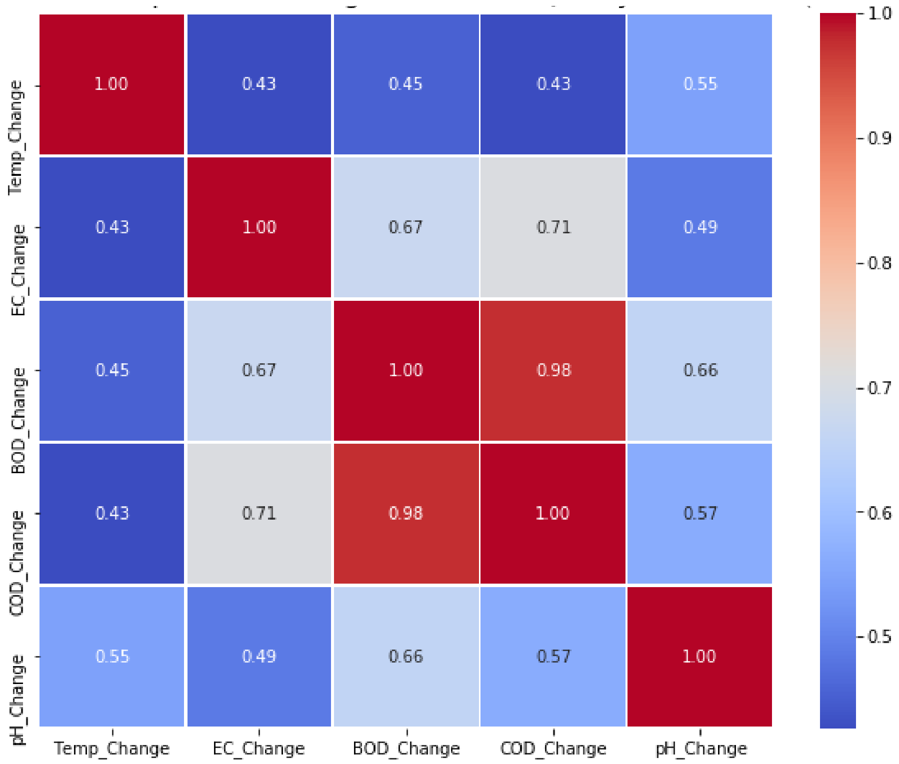

Figure 5. Correlation matrix between temperature and water pollution parameters (e.g., BOD, COD, TDS, EC) 2010 to 2023.

3.5. Spatial and Temporal Variability of Water Quality Indicators

The comparison of average water quality conditions between 2010 and 2023 revealed substantial deterioration across the Kashafroud River Basin (Figures 7 and 8). Electrical conductivity (EC), biological oxygen demand (BOD), and chemical oxygen demand (COD) all increased considerably during the study period, indicating higher salinity levels and increasing organic and chemical pollution loads. The most pronounced changes were observed for EC and COD, suggesting intensified accumulation of dissolved salts and chemically oxidizable pollutants. In contrast, climatic variables and pH exhibited relatively modest changes, indicating that although climate variability may contribute to water quality degradation, increasing anthropogenic pollutant loads remain the dominant driver of observed changes.

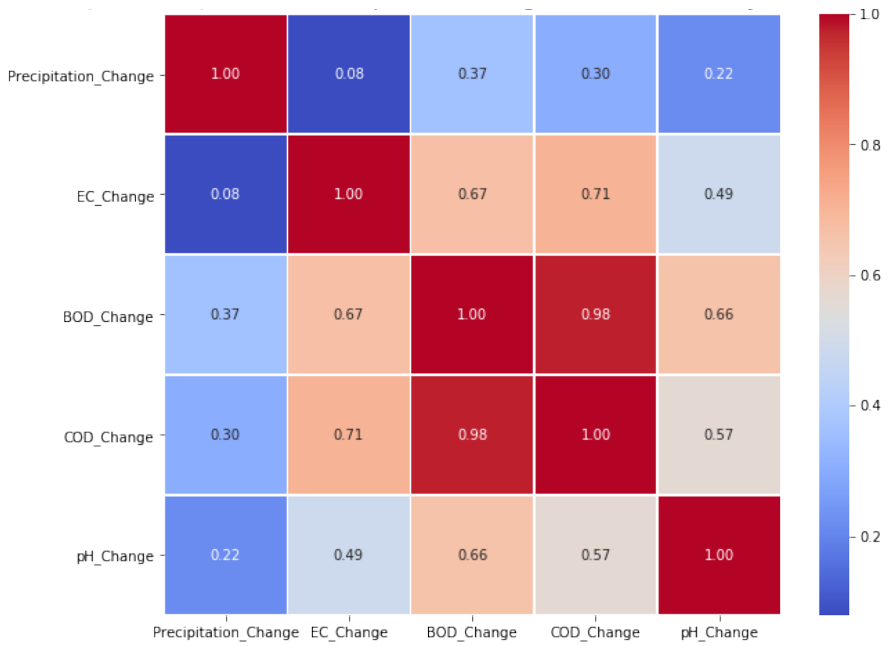

Figure 6. Correlation matrix between precipitation and water pollution parameters (e.g., BOD, COD, TDS, EC).

The magnitude of change among indicators further highlights the severity of water quality deterioration. EC exhibited the largest increase (Δ ≈ +457), followed by COD (Δ ≈ +346) and BOD (Δ ≈ +176), reflecting substantial growth in salinity, chemical contamination, and organic pollution between 2010 and 2023 (Figure 8). These increases are consistent with the combined effects of agricultural return flows, urban wastewater discharge, industrial effluents, and reduced dilution capacity associated with semi-arid climatic conditions. Although increases in temperature, rainfall, and pH were comparatively smaller, these changes remain environmentally relevant because they can influence pollutant transport, evapoconcentration processes, and aquatic ecosystem responses.

Spatial analysis revealed considerable heterogeneity among monitoring stations. The station-based heatmap identified Stations S1 and S7 as the most impacted locations, exhibiting the highest EC and BOD values in 2023. Elevated pollutant concentrations at these stations indicate stronger influence from nearby anthropogenic activities, including urban wastewater discharge, industrial development, and agricultural drainage. In contrast, intermediate stations generally displayed lower pollutant levels. Chemical oxygen demand (COD) remained moderately elevated across multiple stations, suggesting that chemical pollution is not restricted to isolated locations but is distributed throughout much of the study area. Despite relatively consistent rainfall patterns among stations, pollutant concentrations remained elevated, indicating that natural dilution processes have been insufficient to offset increasing pollutant inputs.

Normalization of climatic and water quality variables enabled direct comparison among indicators and further highlighted basin-wide degradation trends (Figure 9). The normalized distributions of EC, BOD, and COD shifted consistently toward higher values in 2023 compared with 2010, confirming a systematic increase in pollutant loads across the monitoring network. Box plot analysis also revealed substantial variability among stations, with several outliers associated with localized pollution sources or episodic runoff events. In contrast, temperature and pH displayed relatively limited variation, reinforcing the conclusion that persistent anthropogenic pressures exert a stronger influence on water quality deterioration than climatic fluctuations alone.

Overall, the combined temporal and spatial analyses indicate a progressive decline in water quality throughout the Kashafroud River Basin between 2010 and 2023. While climate variability may act as an important secondary driver, the observed increases in salinity, organic pollution, and chemical contamination are primarily associated with growing anthropogenic pressures within the watershed. These findings highlight the need for both targeted interventions at identified pollution hotspots and broader catchment-scale management strategies to reduce pollutant inputs and improve long-term river health.

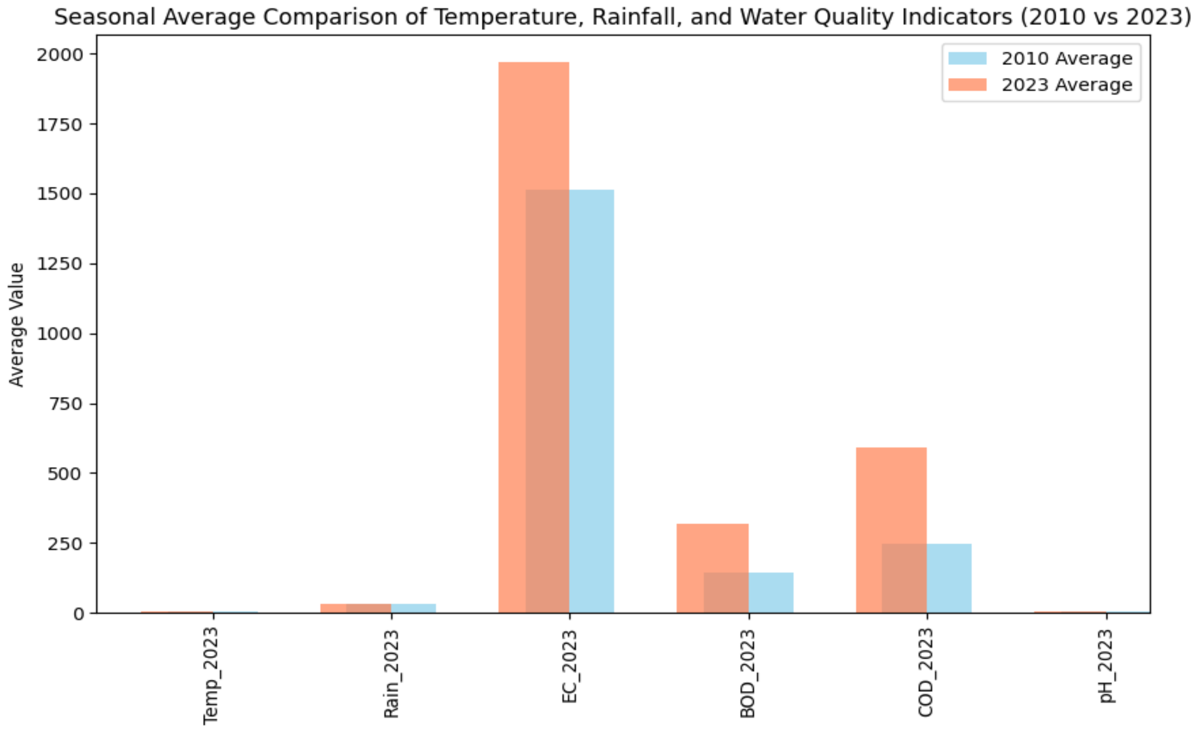

Figure 7. Seasonal averages of water quality and climatic variables in 2010 and 2023, illustrating interannual

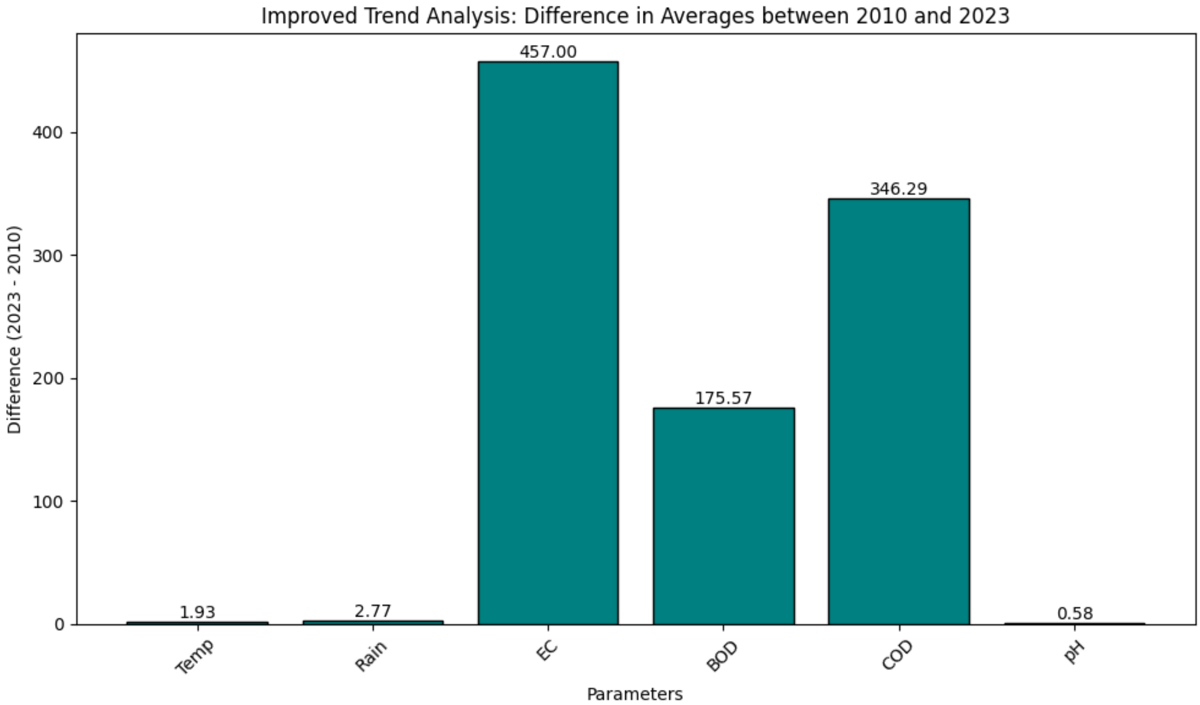

Figure 8. Trend analysis of key water quality indicators (BOD, COD, DO, EC, TDS) between 2010 and 2023 across the study area.

3.6. Analysis of Normalized Data

Normalization of climatic and water quality variables enabled consistent comparison across indicators, revealing clear temporal and spatial patterns in the Kashafroud River (Figure 9). The box plots show substantial variability among monitoring stations, with pronounced dispersion and outliers—particularly in rainfall and pollutant-related variables—likely reflecting episodic events such as intense runoff or localized discharges. Despite this variability, the normalized distributions of EC, BOD, and COD shift systematically toward higher values in 2023 compared to 2010, indicating a basin-wide increase in pollutant loads rather than short-term or seasonal effects. In contrast, temperature and pH exhibit relatively modest changes, suggesting that while climatic variability contributes to fluctuations, persistent anthropogenic pressures dominate the observed deterioration in water quality.

3.7. Cluster-Based Classification of Monitoring Stations Using Water Quality Indicators in 2023

Cluster analysis based on electrical conductivity (EC) and biological oxygen demand (BOD) for 2023 reveals pronounced spatial heterogeneity in water quality across the monitoring network. The stations are grouped into three distinct clusters reflecting varying degrees of pollution. Cluster 0 (stations s3-s6) is characterized by comparatively lower EC (≈1550–1950 µS/cm) and lower BOD levels (≈150–350 mg/L), indicating relatively better water quality and reduced salinity and organic loading. In contrast, Cluster 2 (stations s1 and s2) exhibits moderately elevated EC (≈1900–2000 µS/cm) and higher BOD (≈340–450 mg/L), suggesting moderate to poor water quality likely influenced by sustained pollutant inputs. Cluster 1, represented solely by station s7, shows the highest EC (≈2900 µS/cm) and BOD (≈550 mg/L) values, clearly identifying it as a pollution hotspot with severe water quality degradation, potentially linked to concentrated industrial effluents, sewage discharge, or intensified land-use pressures. Overall, this clustering highlights distinct spatial pollution patterns within the river system and provides a practical framework for targeted management, with immediate remediation required at s7, enhanced monitoring and mitigation for Cluster 2 stations, and Cluster 0 serving as a relative reference for less-impacted conditions.

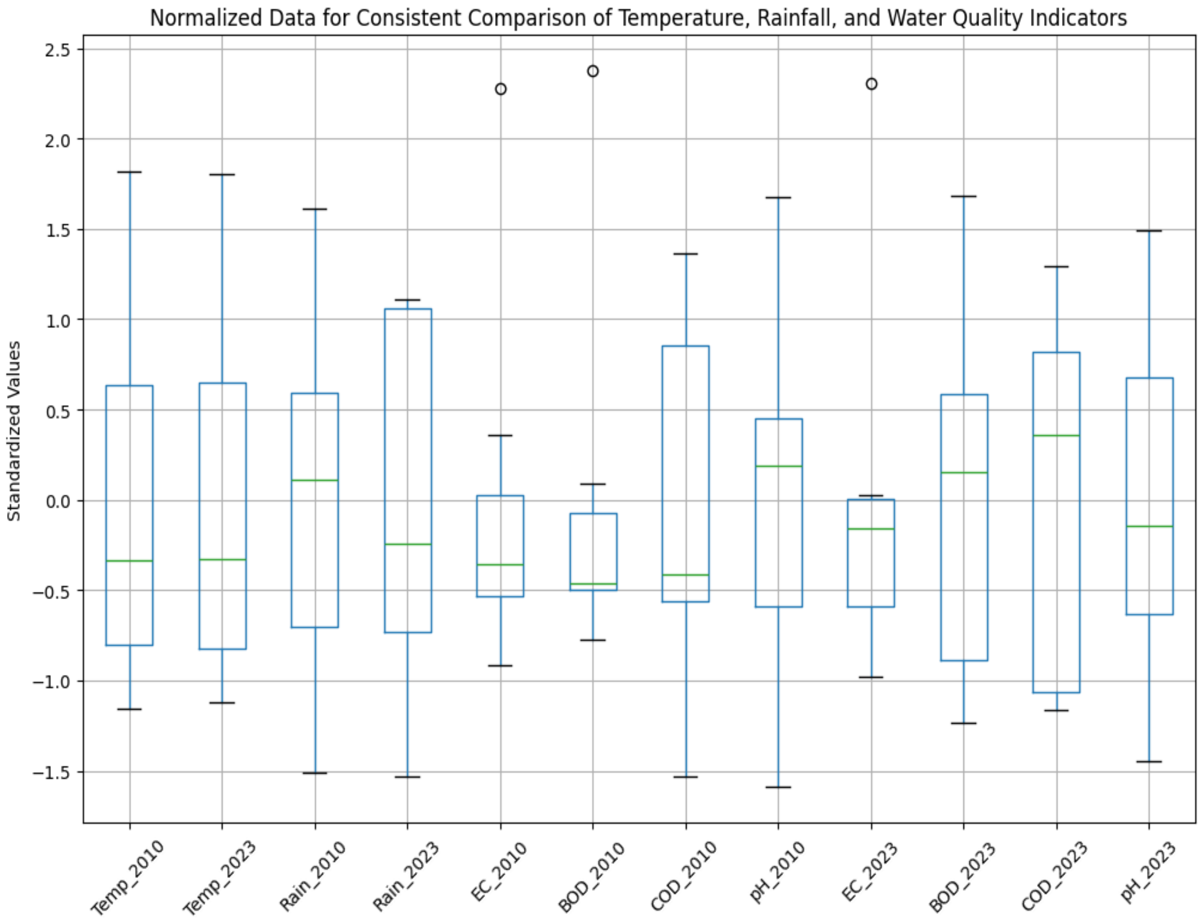

Figure 9. Normalized values of climate and water quality indicators in 2010 and 2023 across monitoring stations.

4. Discussion

The results demonstrate that water quality degradation in the Kashafroud River is controlled by both anthropogenic pressures and climate variability, with anthropogenic pollutant inputs emerging as the dominant driver. The findings of this study reveal pronounced spatiotemporal variations in water quality indicators driven by both anthropogenic pressures and climatic shifts. Between 2010 and 2023, Electrical Conductivity (EC), Biochemical Oxygen Demand (BOD), and Chemical Oxygen Demand (COD) exhibited consistent upward trends, signalling progressive degradation of water quality linked to agricultural runoff, industrial effluents, and rapid urbanization. Comparable patterns have been documented globally, such as elevated BOD and COD levels in the Ganga River basin during 2010–2013, attributed to untreated municipal discharges and industrial expansion (Shukla et al., 2021; Soni et al., 2022). Similarly, Rahman et al. (2023) reported that climate-induced variability in temperature and precipitation intensified pollutant concentrations in eastern China, while studies in Bangladesh demonstrated rising EC associated with land-use change and climate variability. These findings collectively underscore the dual pressures of human development and climate change on freshwater systems.

Climatic factors amplify these trends through mechanisms such as increased evaporation and reduced dilution during droughts, which elevate dissolved salts and organic matter concentrations. Rising temperatures accelerate microbial metabolism, enhancing organic decomposition and oxygen consumption, thereby increasing BOD and COD levels. Irregular rainfall and seasonal droughts further limit river flow, reducing self-purification capacity and allowing pollutants to accumulate. The modest but persistent rise in pH may reflect temperature-driven carbonate equilibrium shifts or alkaline runoff from urban and agricultural sources, which, combined with elevated pollutant loads, can trigger eutrophication, biodiversity loss, and harmful algal blooms. Integrated attribution analysis confirmed that temperature and impervious surface expansion were dominant drivers, jointly explaining over 60% of water quality variance. These results highlight the need for holistic management strategies that address climatic stressors and land-use dynamics concurrently to safeguard river ecosystems under changing environmental conditions. The substantial imbalance between pollutant loading and the river's assimilative capacity further emphasizes the need for improved wastewater management within the Kashafroud River Basin. Municipal wastewater inputs currently exceed the estimated assimilative capacity of the river by approximately sixfold, increasing the risk of persistent water quality deterioration. Upgrading wastewater treatment infrastructure, reducing untreated discharges, and implementing continuous hydrological and water quality monitoring programs would support more effective pollution control and help safeguard downstream ecosystems and water users.

The patterns observed in the Kashafroud River mirror broader challenges faced by urban rivers in dry climates worldwide. Limited dilution capacity during low-flow periods, combined with concentrated pollutant loads and rapid urbanization, consistently drives water quality deterioration in these systems (Chen et al., 2022; Ma et al., 2025). Similar to our findings, studies across Asia, Africa, and Latin America report elevated COD, BOD, TN, and TP levels during dry seasons, often exceeding regulatory thresholds and causing severe ecological stress, including eutrophication and fish kills (Yin, Islam & Ju, 2021; Rakib et al., 2024). Emerging contaminants such as pharmaceuticals, endocrine disruptors, and microplastics, along with heavy metals in sediments, further compound risks to aquatic ecosystems and human health (Zhou et al., 2024; Huang et al., 2023). Seasonal dynamics exacerbate these issues: droughts concentrate pollutants, while storm events mobilize accumulated contaminants, creating episodic spikes in pollution (Pitton et al., 2016).

These global parallels underscore the urgent need for integrated water resource management strategies that combine advanced wastewater treatment, real-time monitoring, and climate-resilient land-use planning. In arid and semi-arid regions, proactive interventions during dry periods—such as restoring riparian buffers and reducing impervious surfaces—are critical to mitigating pollution concentration and safeguarding ecosystem services. Addressing these challenges requires a holistic approach that accounts for both anthropogenic pressures and climatic variability, ensuring sustainable urban river management under accelerating global change (Chen et al., 2022; Ma et al., 2025).

Conclusion

This study provides critical insights into the temporal and spatial dynamics of water quality in the Kashafroud River between 2010 and 2023, highlighting the combined influence of anthropogenic activities and climatic variability on river health. The integration of trend analysis, spatial assessment, and cluster-based classification proved effective in identifying pollution hotspots and categorizing monitoring stations according to water quality conditions. The integration of trend analysis and cluster-based classification has proven effective in identifying pollution hotspots and categorizing monitoring stations according to water quality conditions. Station S6, classified in a distinct cluster due to its extreme pollutant levels, exemplifies the urgent need for targeted intervention. Conversely, stations in Cluster 0 present opportunities for protective policy modeling, where existing land-use practices or natural buffers may be preserving water quality. Furthermore, the findings highlight the amplifying role of climate change—particularly rising temperatures and altered hydrological patterns—in accelerating water quality degradation. This intersection of climatic stress and human pressure signals the necessity for adaptive, integrated water resource management approaches that consider both environmental change and socio-economic development. To ensure the sustainability of freshwater resources, future policies must prioritize regular water quality monitoring, investment in pollution control infrastructure, and the incorporation of climate resilience into water governance frameworks. Continued research should also focus on predictive modeling and the identification of causal pathways linking specific land-use practices and climate variables to water quality outcomes. The findings of this research contribute to a deeper understanding of how anthropogenic pressures and climate variability collectively shape water quality in semi-arid environments. By integrating long-term monitoring with geospatial analysis, the study develops a methodological framework that can be applied to other vulnerable river basins. Beyond its scientific contribution, the research also provides actionable insights for policymakers, environmental managers, and local communities seeking to design adaptive strategies for sustainable water resources management in the context of increasing climate stress.

Data Availability Statement

The datasets generated and/or analysed during the current study are not publicly available but are available from the first author upon reasonable request.

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Conflict of Interest

The authors declare no conflicts of interest.

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