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Original Research

Insights into the Physico-Chemical Parameters of Surface Water and Their Impact on Water Quality and the Pollution

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Abstract

Despite the fact that high-quality water is essential for existence on Earth, it is contaminated by a multitude of natural and human activities. This study compared the physicochemical and biological characteristics of water in the Kabul River with those of various water quality regulatory organizations over the course of six months at five distinct locations, in addition to calculating the water quality index (WQI). Color, turbidity, EC, alkalinity, pH, ammonia, phosphate, total hardness, Mn, Fe, and fecal coliform all exceeded the allowable threshold among the twenty parameters. The principal component analysis (PCA) study identified three primary factors that contribute to the variability in water quality: factor 1 (PC1) explains 46.57% of the variance; factor 2 (PC2) explains 39.27%; and factor 3 (PC3) explains 14.16%. It may contain an assortment of organic matter, metal concentrations, and nutrient content. According to the study, the contamination level in the river increases from upstream (at the city entrance) to downstream (at the city departure) as a result of solid refuse disposal, agricultural and industrial activities, and the discharge of domestic effluents. The assessment indicates that the water upstream of the Kabul River is unfit for potable use but appropriate for agricultural purposes, laundry, and aquatic life. In contrast, the water located midstream and downstream (specifically S3, S4, and S5) is deemed unsuitable for aquatic life.

Keywords: Kabul River, PCA, physical-chemical parameters, pollution, water quality

Introduction

The significance of water quality in urban regions cannot be overstated, given its direct impact on ecological systems, human health, and the purity of potable water [1]. Routine monitoring of water bodies, incorporating an adequate number of parameters, is imperative for mitigating risks and averting disease outbreaks [2]. The Kabul River, which is among the five largest rivers in Afghanistan [3], is crucial for the reconstruction of Afghanistan and the advancement of its socioeconomic condition. Despite having

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an approximate total length of 700 kilometers, Afghanistan is traversed by only 560 kilometers [4]. Although comprising a mere 12% of Afghanistan's land area, it consumes 26% of the country's annual water discharge capacity.

Considering the scarcity of research conducted on the water quality of the Kabul River in Kabul City, the available evidence supports the presence of water contamination. Several studies have been conducted to analyze the water quality of the Kabul River. Recently, Imran et al. gathered 394 water samples from the Kabul River, each located within a vertical distance of one kilometer from the river bank. Out of these samples, 169 (43%) were determined to be harmful for drinking, while 225 (57%) were deemed safe [5]. Z. Ullah et al. performed research to evaluate the current condition of the water quality of the Kabul River, located near Peshawar in Pakistan [6]. In 2009, a total of seven locations were selected for sampling in both the upstream and downstream areas of the River Kabul. The research included the analysis of the physico-chemical and microbiological properties of the samples, along with an investigation into potential sources of pollution. Akhtar et al. conducted research on the examination of water resources and utilization across the Kabul River Basin (KRB). The area of research was divided into several hydrological and administrative entities, such as province-level and sub-basin level [7]. Jawadi et al. conducted research to assess the overall condition of groundwater in the local Kabul Basin. The objective was to identify its appropriateness for both drinking and irrigation uses, both now and in the future [8]. Sediqi and Komori provide a thorough evaluation of the sustainability of the KRB by using the Standardized Runoff Index as a measure of runoff. The research being conducted seeks to acquire a detailed understanding of water sustainability in the basin by using the principles of dependability, resilience, and vulnerability [9]. Khuram et al. discovered a total of 209 distinct species of algae and cyanobacteria at four specific locations along the Kabul River. The river is mostly populated by green algae, diatoms, and charophytes, which indicates the influence of agricultural activities in the area. Based on the River Pollution Index, the river's water exhibits low alkalinity and low salinity and is polluted with fertilizers [10]. According to Ahmed et al., the water quality of the Kabul River has been significantly contaminated due to the fast growth of urban areas and industries [11]. Sub-lethal organic contamination is a result of the release of pollutants and additional waste materials into the river. The discharges from many leather manufacturing units, as well as various other businesses, in tandem with human waste and cattle dung, are causing significant pollution to the river ecosystem at a concerning pace.

According to data from the United States Geological Survey, the levels of nitrate, sodium, dissolved solids, and trace element concentrations (e.g., selenium (Se), strontium (Sr), uranium (U), and zinc (Zn)) surpassed the thresholds set by the World Health Organization (WHO) [12]. Furthermore, an assessment of the surface and subsurface water quality in the Kabul Basin was conducted in 2010. Particularly in the basin's most populous regions, the contamination from bacteria (total coliform) and concentrations of conductance, chloride, nitrate, and boron surpassed international drinking water quality standards, according to the findings [13]. Furthermore, it was documented that the central region of Kabul exhibited a higher degree of pollution in comparison to the sub-basins of Paghman, Shomali, and Logar [14].

Since 2001, water scarcity and rising water demand in Kabul have been caused by the city's population expansion. The limited water resources in Kabul, conversely, have been further strained due to inadequate management and the effects of climate change.

Kabul is confronted with a dual challenge of escalating water demand and a scarcity of water resources due to its expanding population. Furthermore, the water resources are being impacted by climate change, and inadequate management has exacerbated the already limited subterranean water resources in Kabul. The surface and ground water are experiencing a decline in quality and an increase in salinity, hardness, fecal coliform bacteria, nitrate, and heavy metal concentrations, all of which pose a potential health risk to the inhabitants of Kabul [15, 16]. As a result, there is growing apprehension regarding the availability of water in Kabul City in the near future [17].

In addition, Afghanistan is a nation that has struggled to progress in numerous domains and was notably feeble in the realm of research, specifically regarding the water quality of the Kabul River, throughout its forty years of imposed conflicts. A consequence of less progressive efforts is the current information predicament encountered by the local population. Furthermore, due to the relatively new nature of the environment in Afghanistan, information derived from it may be exceptionally current. For instance, water pollution has emerged as a significant concern in Kabul following the events of September 2001, primarily due to resource mismanagement and inadequate urban infrastructure. In this regard, the contamination of the Kabul River is a relatively recent subject, as are the published evaluations and assessments derived from prior data. The classification of the aforementioned concerns also encompasses the character of the Kabul River. The majority of the efforts have been devoted to international organizations whose knowledge is extremely limited to the data available online or deposited. The Kabul River, which supplies water to Kabul City and its environs, is one of Afghanistan's five most significant rivers. It is also utilized for hydroelectric, agriculture, industry, domestic purposes, and livestock.

Pollution of rivers results from a brisk pace of industrialization expansion, improper urbanization practices, careless depletion of natural resources, and agricultural operations [18-20]. Hence, it is imperative to conduct water quality measurements and monitoring in order to ascertain vital physical-chemical and biological attributes [21, 22]. The objective of this study is to examine the sources of pollution and the physicochemical and biological water quality along the Kabul River, which flows through the most densely populated region of the nation.

Materials and Methods

Study Area

As illustrated in Fig. 1, the eastern region of the country, situated at 34º31′ North latitude and 69º10′42′ East longitude, comprises Kabul City and the Kabul River, both of which have been designated as research areas. It is a narrow valley situated at an altitude of 1800 meters above sea level, bounded by the Hindu Kush Mountains [23]. Dry to semi-arid conditions prevail [24]. The Kabul River originates at the base of the Unai and Sang-Lakh mountains, situated to the south of Kabul City [24]. It travels north for approximately 21 kilometers after entering the Kabul province from the south, after traversing the Maidan valley. In Dehmazang, it converges with the Paghman River, which has its source in the eastern foothills of the Paghman Mountains. The Logar River, which empties into the Kabul River in Plecharkhy, flows in an easterly direction. En route, it flows past Kabul City and into Tangi Garu, where it exits the study area and provides irrigation to the easternmost region of Afghanistan [25]. From S1 to S5, the investigation area spans a total of 49.50 kilometers in length. The sampling locations and sites are illustrated in Fig. 1.

Water Sampling

A cumulative of thirty water samples were gathered from five discrete sampling locations across the Kabul River, denoted as S1 to S5, between August 2021 and January 2022. The source of the S1 was Shahtoot Dam. S2 was collected at the terminus of Lalander Canyon from Gulbagh. The source of S3 was Dehmazang. S4 was collected in Polecherkhy, the confluence of the Logar and main rivers. S5 was collected from the Tangi-e Gharu below the city limits of Kabul. Each of the conceptualized data points was compared to the WHO (2011) [26] and the Afghan National Standard Authority (ANSA) standard values.

Analytical Procedures and Water Quality Assessment

The parameters, such as temperature, pH value, dissolved oxygen (DO), total dissolved solids (TDS), and electrical conductivity (EC), were measured on-site by using a Multi-parameter (HI 98194). Physicochemical parameters, including alkalinity, nitrate, sulfate, phosphate, chloride, ammonia, total hardness, Cu, Zn, Mn, Fe, and Al, were determined in accordance with the American Public Health Association (APHA) 20th edition method and a spectrophotometer (Orion Aqua Meter 8000) [27]. For color analysis, the Hach color test instrument (Co-10-100, 0-500) was utilized. The odor and flavor were assessed using ANSA standards methodologies, while the turbidity was determined using a turbidity meter (Orion AQ3010). The detection of total and fecal coliforms in the water samples was conducted utilizing the user manual for

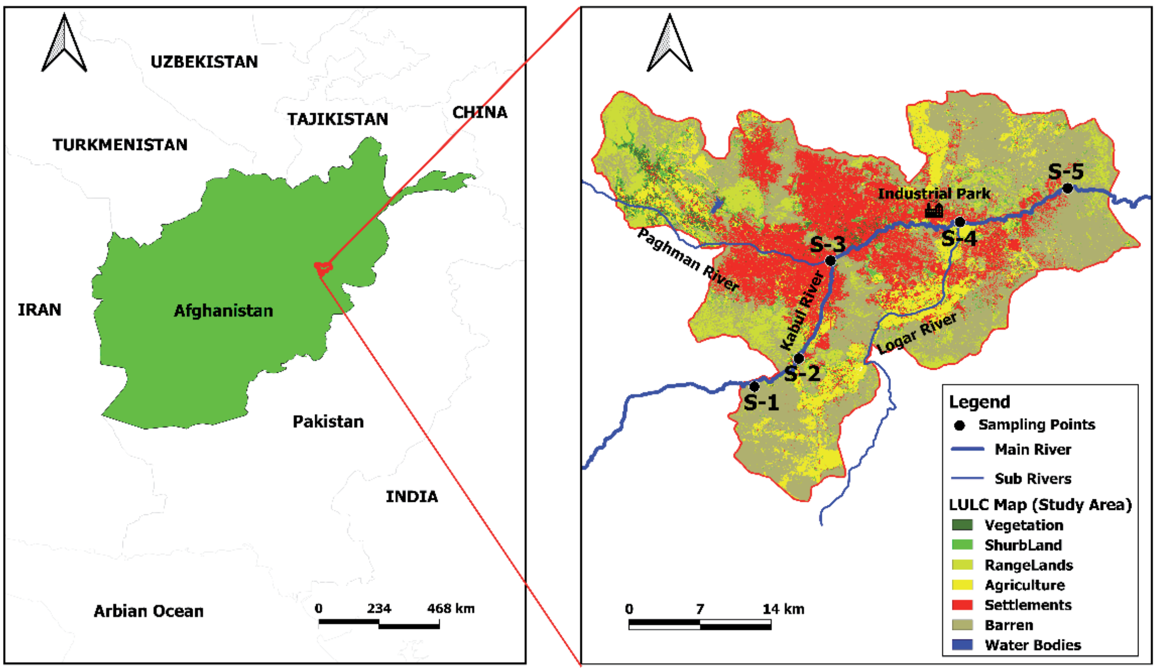

Fig. 1. Description of the sampling points.

the DelAgua portable water test kit, version 5.0 [28]. All of the compounds utilized in this investigation were obtained from Merck (Darmstadt, Germany) and were of analytical grade. Each sample was collected in triplicate, and the corresponding standard deviations are provided with the results. The water quality index was calculated using the following equations (Eqs. 1 and 2) [29]:

$$WQI = \sum QiWi / \sum Wi \quad (1)$$

$$QI = 100[Vi - V0/Si - V0] \quad (2)$$

Where Wi represents the unit weight of the ith parameter; Vi is the estimated concentration of the nth parameter in the analyzed water; V0 is the ideal value of this parameter in pure water; *V*0 = 0 (*except for pH* = 7.0 *and DO* – 14.6 *mg/L*; Si is the recommended standard value of the parameter [30].

Results and Discussion

Physico-Chemical Characteristics of River Water

The physico-chemical parameters and biological analysis serve as initial investigations for determining the characteristics, qualities, and classifications of water. Table 1 presents a synopsis of the values, including the average and standard deviation. Water temperature is one of the most significant physical factors influencing aquatic ecosystems, as aquatic life is directly impacted by abnormally high or low temperatures. Temperature influences several additional water quality parameters that are significant in industrial, residential, environmental, and agricultural contexts [31, 32]. Seasonally, the temperature of the Kabul River varied considerably. The highest recorded temperature (30ºC) occurred in August 2021, and the lowest (1.3ºC) was recorded in December 2021, as indicated in Table 1. Furthermore, the highest temperature recorded between the measurement sites was 30ºC at S4, whereas the lowest temperature was 1.3ºC at S5.

The presence of color in water has the potential to disrupt the photosynthesis of aquatic vegetation and has an effect on the entire aquatic food chain by influencing light penetration. Furthermore, such changes could potentially impact the reproductive patterns and behavior of aquatic organisms, thereby causing direct ecological consequences [33]. The admissible value of color, as determined by the Afghanistan National Standard Administration, is within ≤15 TCU (True color unit). Color values in different sampling locations for this investigation ranged from 0 to 71 TCU, with a peak of 71 TCU recorded at S3 and a minimum of 0 TCU observed at S1. Nevertheless, the months of August and September exhibited the least amount of color, whereas October registered the most. With the exception

Table 1. Summary statistics of physico-chemical parameters in water samples collected from the Kabul River. This table presents the overall range and averages with standard deviations of the parameters. Values after ± show standard deviations of the mean values (n = 3).

Parameters	Units	S1		S2		S3		S4		S5		
		Range	Mean±SD	Range	Mean±SD	Range	Mean±SD	Range	Mean±SD	Range	Mean±SD	LOD
Temperature	°C	2.5 – 22	9±2	4 – 23	11±2	2 – 30	11±2	3 – 30	12±2	2 – 28	11±3	-
Color	TCU	0 – 2.0	0.7±0.01	2 – 5	3.0±0.02	57 – 71	67±6	49 – 62	58±4	35 – 41	39±5	-
pH	-	8.2 – 8.3	8±1	7 – 8	8±1	7 – 8	8±1	7.8 – 7.9	8±1	7.7 – 8.7	8±1	-
DO	mg/L	3.2 – 3.7	3.6±0.2	2 – 3	2.7±0.2	0.01 – 0.1	0.1±0.01	0.01 – 0.1	0.08±0.01	0.01 – 0.1	0.1±0.01	0.01
Turbidity	NTU	6 – 24	13±4	7 – 34	18±4	35 – 51	47±7	34 – 53	47±5	12 – 56	43±6	0.1
TDS	mg/L	266 – 328	299±32	347 – 781	553±35	389 – 950	690±26	616 – 981	807±36	739 – 1176	936±65	0.1
EC	µS/cm	521 – 655	597±33	693 – 1563	1128±44	778 – 1901	1400±43	878 – 1890	1536±23	995 – 1851	1618±24	100
Alkalinity	mg/L	362 – 395	372±23	332 – 382	368±34	339 – 410	366±24	325 – 421	364±21	244– 430	327±21	120
Nitrates	mg/L	12 – 26	16±3	3 – 60	17±3	1 – 15	7±2	11 – 20	14±2	23 – 26	24±2	1.0
Sulphates	mg/L	15 – 16	16±2	19 – 48	36±3	32 – 60	50±4	81 – 90	88±8	122 – 218	180±10	1.0

Phosphates	mg/L	1 – 3	1.6±0.2	0.02 – 4.6	1.3±0.01	0.35 – 6	4.4±0.8	1 – 4	3.0±0.3	2 – 3	2.4±0.3	0.1
Chlorides	mg/L	0.01 – 0.02	0.003±0.0E5	0 – 152	89±12	0.01 – 102	62±6.23	0.01 – 121	76±12.5	0.01 – 195	122±10	0.01
Ammonia	mg/L	1 – 10	2±0.2	0.05 – 8	2±0.01	0.6 – 43	17±1.25	2 – 49	19±1.5	3 – 39	13±2	0.01
Total Hardness	mg/L	311 – 406	363±24	402 – 546	487±27	398 – 461	436±25	413 – 496	460±21	434 – 550	503±16	50
Water quality index	-	12 – 333	97±21	13 – 271	81±21	100 – 1218	605±31	117 – 378	617±15	131 – 365	250±13	-

of S1 and S2, the color values surpassed the threshold established by ANSA. The color value was considerably enhanced from upstream to downstream, especially in S3 and S4, which are located in the most populated areas. River water that is becoming increasingly colored may be primarily caused by the presence of dissolved substances, untreated municipal drainage, agricultural discharge, or industrial effluents.

Turbidity refers to the degree of haziness or cloudiness in water, which is caused by a multitude of small particulates that are generally not perceptible to the naked eye [34]. Water turbidity should not surpass 5 nephelometric turbidity units (NTU), as stated by WHO (2011). The turbidity levels observed in our research varied between 5.99 and 56.1 NTU, with the lowest value documented at S1 and the highest at S5. The minimum recorded turbidity level was 5.99 NTU in September 2022, whereas the maximum value of 56.1 NTU was documented in January 2022. Turbidity levels in all samples collected at different stations and months exceeded the standards set by both the WHO and the national government for potable water. The increase may be attributable to solid waste disposal, domestic drainage, especially in the midpoint and downstream, and industrial effluent, which further impacts S4 and S5.

WHO (2011) specifies that the optimal pH range for potable water is between 6.5 and 8.5. The pH values of water samples examined in our research varied between 7.53 and 8.71. S5 exhibited the maximum pH value, whereas S2 displayed the lowest (Table 1). August, nevertheless, witnessed the lowest and highest pH levels recorded. The mildly alkaline pH level of 8.71 observed at S5 indicates the possibility of effluent contamination originating from agricultural and industrial sources in close proximity to the location. The elevated pH level may be ascribed to pollution stemming from anthropogenic activities, such as the discharge of municipal solid waste into rivers and effluents, or pollution caused by limestone deposits [35].

The electrical conductivity (EC) of water serves as an indicator of both the salinity and dissolved ion concentration of the water [34]. It pertains to the capacity of the water to conduct electrical current. The water sample exhibited a range of EC values, with S3 recording the maximum value of 1901 µS/cm and S1 the lowest at 521 µS/cm. Nevertheless, notable variations in EC values were observed across stations and months. August recorded the highest EC value of 1901 µS/cm, while January 2022 recorded the lowest of 521 µS/cm (Table 1). With the exception of S1, the majority of the EC values exceeded the national standards, which is recommended to be not exceeding 1250 µS/cm. A possible explanation for the rise in EC values from upstream to downstream along the river is the amalgamation of agricultural runoff, industrial effluent, and domestic drainage. In addition, ions and minerals that are liberated by natural rock degradation may contribute to an increase in the EC of the area under study [36].

Trace quantities of both inorganic (natural) salts and dissolved organic substances comprise total dissolved solids (TDS) in water [35]. Water samples contained total dissolved solids ranging from 266 to 1176 mg/L. At S1, the minimum value was determined, and at S5, the maximum value was observed. Table 1 presents the identical minimum value of 266 mg/L documented in January 2022 and the maximum value of 1176 mg/L documented in September 2022. While the concentrations of total dissolved solids increased from upstream S1 to downstream S5, only two samples (S5 in September and October) exceeded the TDS limits of 1000 mg/L as set by ANSA.

The alkalinity of water quantifies its resistance to variations in pH. The alkali concentration in the water is denoted by bicarbonates, carbonates, or hydroxides. Scaling occurs on fixtures and in the water distribution system, imparts a carbonated flavor to the water, and dries out the epidermis [34]. The alkalinity levels of the water samples in the present investigation ranged from 243.7 to 429.5 mg/L. However, it is worth noting that the highest and lowest values were established at S5. On the contrary, the lowest recorded alkalinity value of 243.7 mg/L occurred in September, while the highest value of 429.5 mg/L was obtained in December (see Table 1). The recommended range for alkalinity in potable water is 20–200 mg/L, as stated by the WHO. In our research, every sample exceeded the recommended threshold. On the riverbanks, the high concentration may have resulted from the mingling of industrial effluent, municipal sewage, or laundry detergent.

Dissolved oxygen (DO) is an essential component of water quality monitoring and analysis investigations. Fish with insufficient levels of DO perish and develop at a slower rate. Moreover, eutrophication ensues, a detrimental process that contaminates water unfit for human consumption [37]. Dissolved oxygen concentrations in water samples exhibited a range of 0.01 to 3.70 mg/L, with S1 containing the highest concentration of 3.70 mg/L and S3-S5 the lowest (0.01 mg/L). Discernible minimum values (S3–S5) and maximum DO concentrations were observed at S1 during the month of August. It was determined that the DO concentration in the Kabul River fell below the critical threshold for the aquatic ecosystem. A low concentration of DO signifies elevated levels of pollution, specifically in the midpoint and downstream regions of the Kabul River. These levels are a result of bacterial and human activities.

Nutrients and Ionic Pollution in the Area

The concentrations of ionic pollutants were also measured and analyzed as part of this research. Elevated levels of nitrate (NO_3^-) have been identified as a potential hazard to public health, especially in countries with high NO_3^- concentrations in their water supplies [38]. While NO_3^- levels in surface and subterranean waters are generally insignificant, they have the potential to increase due to ammonia oxidation induced by NO_3^- leaching from agricultural effluent, percolating water, or human or animal waste contamination (WHO 2004). The NO_3^- concentration exhibited a seasonal variation, with the lowest recorded value (0.38 mg/L) found in S3, whereas the highest value (59.5 mg/L) was observed in S2. Aside from a single sample from S2 in January 2022, the NO_3^- content of the remaining samples was below the recommended limits. Particularly in S2, the elevated nitrate concentration could denote the utilization of chemical and animal waste manure for agricultural purposes and as effluent from villages.

Sulfate is an ion that occurs naturally in surface water. Sulfate enters water through the process of natural weathering from gypsum and associated minerals [39]. A sulfate limit of 250 mg/L has been set by the WHO for potable water. The sulfate concentrations observed in this study were significantly lower than the values established by the WHO (2008) [40]. The concentrations of sulfate varied from 15.12 to 217.8 mg/L, with the minimum value documented at S1 and the maximum value observed at S5. The minimum recorded value (15.12 mg/L) occurred in January 2022, whereas the maximum recorded value (217.8 mg/L) occurred in August 2022 (Table 1). The rise in sulfate concentrations further downstream may be ascribed to a multitude of factors, including chemical reactions, industrial operations, and manufacturing that discharge compounds containing sulfate into the water.

The WHO (2011) specifies that the maximum allowable phosphate (PO_4^-) concentration in potable water is 0.1 mg/L. The water samples contained phosphate concentrations ranging from a minimum of 0.021 mg/L at S2 to a maximum of 5.50 mg/L at S3. Table 1 presents the recorded values, with the highest value of 5.50 mg/L occurring in January 2022 and the lowest value of 0.021 mg/L occurring in November. August water samples, with the exception of S2, all exceeded the standard limits. The majority of the inhabitants in the Kabul River region employ triple superphosphates for agricultural purposes. Thus, the presence of phosphates in water may be attributed to human activity. An identical finding was reported by Howladar et al. [34] regarding surface water pollution in Bangladesh as a consequence of agricultural activities.

Chloride is present in the majority of materials in diverse configurations. The potential sources of its presence in natural water are the dissolution of wastewater disposal, contamination, and salt deposits [41]. The minimal chloride concentration in the Kabul River was documented as zero mg/L in sections S1 through S5 in December 2021 and January 2022. Conversely, the highest chloride concentration was measured at 195 mg/L in section S5 in September. It was determined that every water sample fell below the established standard limit (250 mg/L). Table 1 demonstrates that S1 was present in modest concentrations in the samples for the majority of the periods.

The total hardness of water can be influenced by both anthropogenic and natural processes. Anthropogenic sources include industrial discharges and domestic effluent, while natural sources involve the accumulation of minerals through geological interactions with rocks and sediment. On the other hand, the levels of calcium and magnesium compounds have a significant impact on the hardness of water [42]. The recommended threshold for total hardness in potable water is 500 mg/L (WHO, 2011). The total hardness of the water samples examined in our research ranged from 311 to 550 mg/L, with the maximum concentration from S5, whereas the lowest value was from S1 (Table 1). From August to October, the preponderance of water samples, excluding S2 and S5, remained within the established standard limit. In S2, the hardness concentration may be the result of agricultural and household sewage, whereas in S5, it could be the result of industrial and domestic sewage mixing or soil erosion.

The variability of ammonia (NH_3) concentrations in surface water is attributable to both natural processes and human activities. Natural sources include the emission of NH_3 by phytoplankton and aquatic vegetation and the decomposition of organic matter. NH_3 in surface water can be attributed to anthropogenic sources, which consist of industrial discharges, animal waste runoff, and agricultural activities. An excess of NH_3 can induce toxicity and impede respiration in aquatic organisms, among other negative consequences. Further, heightened levels of NH_3 can be a factor in the process of eutrophication, which results in diminished oxygen levels in aquatic environments and accelerated algal proliferation. In water samples, the concentration of NH_3 ranged from 0.049 to 48.6 mg/L, with the highest concentration recorded at S4 and the lowest concentration at S1 (Table 1). Likewise, the minimum NH_3 concentration (0.049 mg/L) was recorded in January 2022, whereas the highest concentration (48.6 mg/L) was detected in December. Around 1.5 mg/L is the threshold odor concentration of NH_3 in water. According to the WHO (2011), a taste threshold limit of 35 mg/L has been suggested. The preponderance of the five samples in this investigation exceeded the limits of 1.5–35.0 mg/L. The rise in parameters observed in the midstream and downstream sections (S3, S4, and S5) was ascribed to the discharge of untreated effluent originating from agricultural and domestic operations in the river's vicinity.

Trace Metal Concentrations in the Area

The concentrations of Cu, Zn, Mn, Fe, and Al in water samples collected from the Kabul River are illustrated in Fig. 2. The concentration of Al in the water sample was between 0.005 and 0.065 mg/L, with S5 having the maximum concentration of Al (0.065 mg/L) in October, and the lowest recorded value for S1 (0.005 mg/L) in August (Fig. 2a). Each water sample was found to be below the national standard limits, which were recommended to be 0.2 mg/L. The concentration of Cu varied from 0.093 to 0.98 mg/L. The minimum concentration value (0.093 mg/L) was observed at S2 in August 2022, whereas the maximum concentration value (0.98 mg/L) was recorded for S5 in December 2021 and January 2022 (Fig. 2b). Despite having the maximum concentration of all the sampling points, S5 does not surpass the allowable limit. In a similar fashion, the Zn concentration in the sample water varied between 0 and 0.046 mg/L. The highest recorded values were in S5, while the lowest were in S1 and S2. December recorded the highest concentration value of 0.046 mg/L, while August through November yielded the lowest concentration value of 0 mg/L in samples S1 and S2 (Fig. 2c). The zinc content was determined to be below the allowable threshold.

Fe is compulsory for the transportation of oxygen throughout the blood and is therefore vital to the human body. On the other hand, an overabundance of Fe in water may result in discoloration, turning laundry, dishes, and plumbing fixtures like basins yellow, red, or brown [34]. The range of Fe concentrations in the water sample was 0.03 to 3.73 mg/L. S3 yielded the minimum and maximum values. September 2022 recorded the maximum Fe concentration (3.73 mg/L), while January 2022 recorded the lowest (0.03 mg/L) (Fig. 2d). In aggregate, 27% of the samples exhibited Fe concentrations that surpassed the limits set by local and international standards. Soil erosion, atmospheric deposition of Fe-containing particulates onto urban surfaces in S3, and the mingling of urban discharge resulting from the corrosion of Fe pipelines may all contribute to the presence of iron in the Kabul River. In addition, industrial effluent may have contributed to the Fe concentration in S4. Moreover, the introduction of trace metals into aquatic environments may transpire naturally as a result of the erosion of soil particles, pebbles, and minerals by moving water [43].

In the water samples, the Mn concentration ranged between 0 and 0.86 mg/L. The maximum value was acquired from S3, while the minimum values were documented at S2 and S3. In contrast, the lowest recorded value of 0 mg/L occurred between August and September 2022, while the highest value of 0.86 mg/L was detected in January 2022 (Fig. 2e). It was found that 23% of the 30 samples exceeded the WHO-recommended limits of 0.4 mg/L and 0.30 mg/L, respectively. The Mn concentration in the Kabul River is susceptible to both natural and anthropogenic influences. This occurs naturally, as when flowing water erodes boulders, minerals, and soil particles. Orris and Bliss assert that Kabul is a metropolis abundant in various minerals and constructive raw materials, including chalcocite, malachite, pyrite, bornite, chalcopyrite, covellite, hematite, magnetite, chrysocolla, azurite, sand, clay, marble, limestones, dolomites, and quartzites [44]. Human activities, including the agricultural application

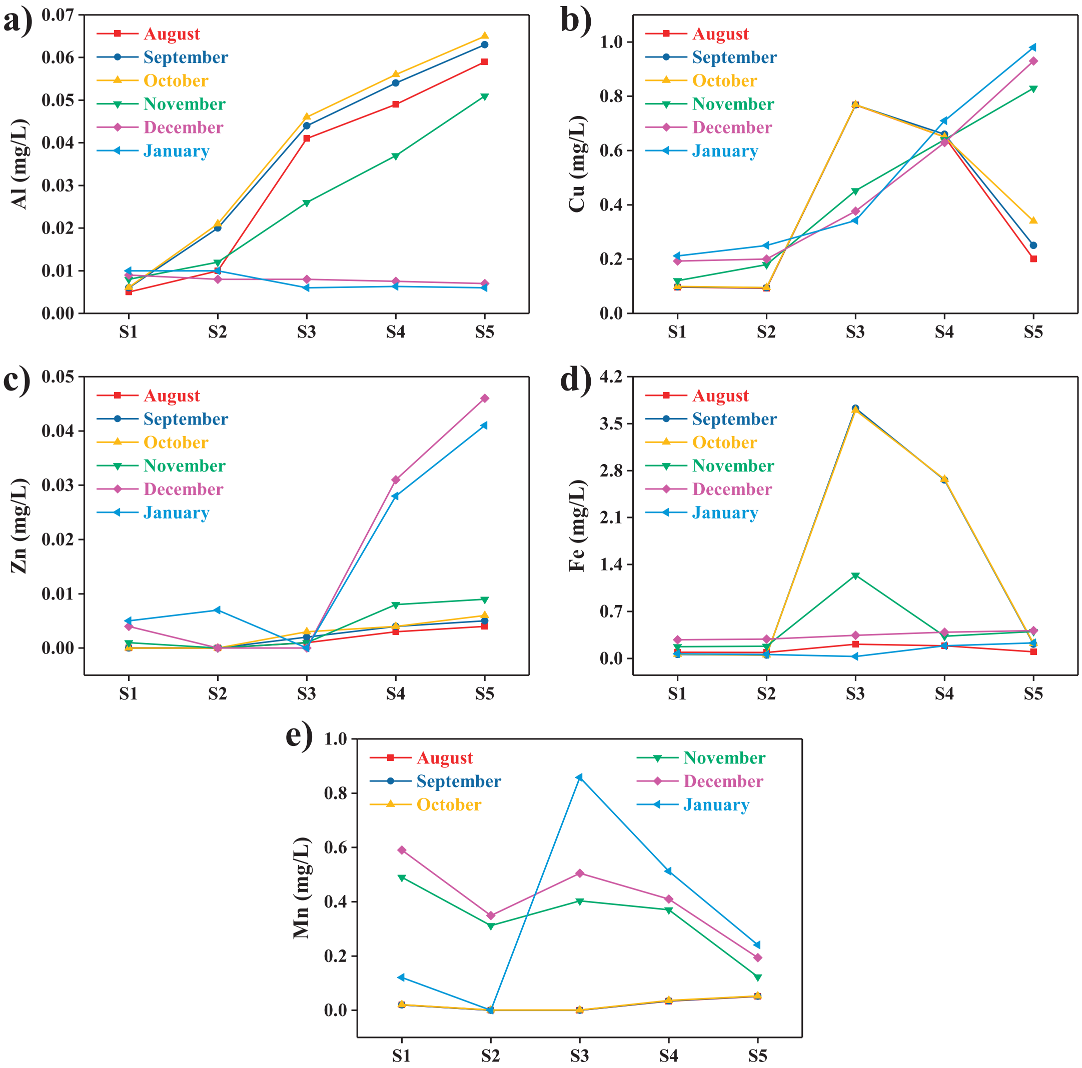

Fig. 2. The concentrations of trace metals in the Kabul River at sampling locations: a) aluminum, b) copper, c) zinc, d) iron, and e) manganese.

of manganese-containing pesticides and fertilizers, can cause the release of Mn. An additional factor that contributes to the contamination of river water is the combination of industrial and domestic effluent.

Fecal Contamination

Upon examination of the water samples obtained from the Kabul River, it was determined that the fecal coliform levels ranged from 60 to 502 colony-forming units (CFU) per 100 mg/L (Fig. 3). The minimum level of fecal contamination was documented in January 2022, whereas the maximum level was detected in October 2021. In terms of sampling locations, S3, S4, and S5 contained the highest concentrations of contamination, with 502 CFU/100 mg/L detected at each site. S1 exhibited the lowest level of fecal contamination (60 CFU) in comparison to the remaining samples. In accordance with the ANSA and WHO standards for potable water quality, no microorganisms may be detected in 100-mL water samples. From August to January 2022, all water samples from S1 to S5 in this study exceeded the permissible limit of local and WHO potable water quality guidelines (Table 1).

Fecal contamination in the river results from the direct or indirect discharge of untreated agricultural effluent, industrial effluent, domestic sewage, and animal excrement into the river [45]. Zhang et al. documented comparable findings, namely that illicit waste disposal has resulted in the contamination of Chinese rivers with fecal matter [46]. In addition, surface and groundwater samples obtained from urban regions in Kabul revealed the presence of 12% total coliform and 4.7% fecal coliform, respectively. One of the principal factors contributing to this contamination is inadequate sewage infrastructure [47].

Water Quality Index (WQI) of the Area

The determination of the WQI involved the analysis of concentrations extracted from water samples. Water

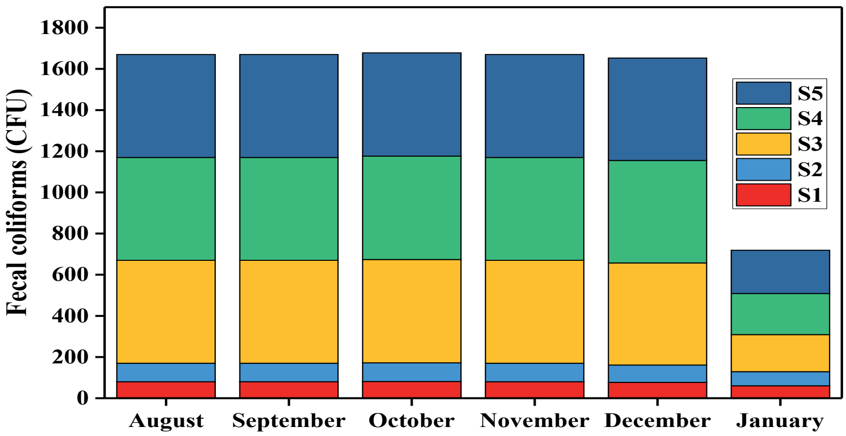

Fig. 3. The presence of fecal coliform colonies in the Kabul River at sampling locations.

with a WQI value below 50 is deemed to be of acceptable quality and is hence advised for consumption. Values between 51 and 100 on the WQI are categorized as poor to very poor and are not recommended for consumption, whereas values exceeding 100 are considered exceedingly hazardous. Fig. 4 illustrates the WQI values of samples from sampling points S1 through S5 that were collected for this investigation between August 2021 and January 2022. The samples obtained from S1 and S2 exhibited consistently low WQI values (13–21) in August-October, whereas November and December had WQI values of 100 or higher. In general, the WQI values exhibited a range of 12 to 1378. The minimum WQI value of 12 was documented in September and October at S1, whereas the maximum WQI value of 1378 was observed in December at S4. A discernible upward trajectory was observed in the WQI, specifically during the transition from S1 to S5 and in the last quarter of 2021 (November and December) and January 2022. This pattern indicates that the quality of the water will deteriorate in the autumn. October and September exhibited generally lower values than the remaining months.

According to the results of this analysis, a mere 27% of the gathered samples were identified as having a WQI value below the threshold of 50. The present investigation found that the presence of fecal coliforms, altered physicochemical properties, and increased metal concentrations in the collected water samples mitigated WQI changes [32, 48]. Our study's WQI results indicated that the water quality of the Kabul River was unsuitable for human consumption, as indicated by the selected values of one or more water quality parameters considered for the WQI conclusion (Table 2).

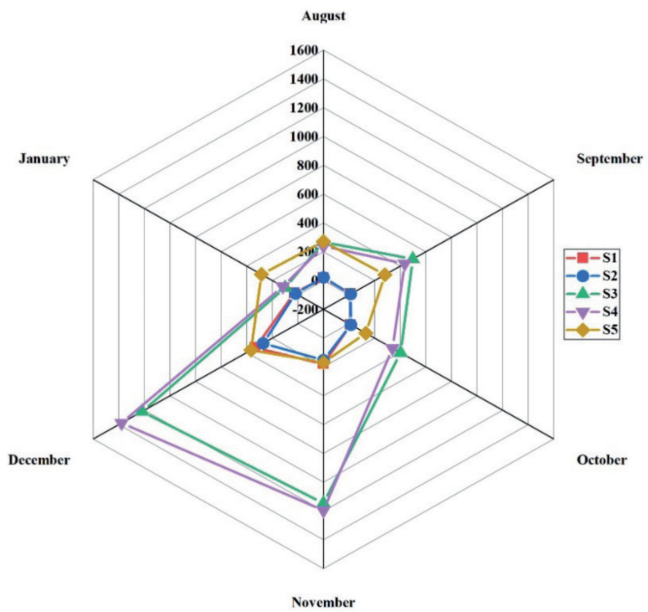

Fig. 4. Water quality index of the collected samples and sites at the Kabul River. Error bars show the standard deviation of three replicates.

Table 2. Water quality index (WQI) and status of water quality.

WQI range	Descriptions
0-25	Excellent
26-50	Good
51-75	Poor
76-100	Very poor
>100	Unfit for drinking

Source: Ansari et al. [35].

Correlation Coefficient Among Water Quality Parameters

The correlation coefficient quantifies the degree of association between variables; its sign is between -1 and 1, with -1 denoting a robust negative correlation, 1 representing a robust positive correlation, and 0 representing no correlation. Certain observations may be derived from the examination of the correlation matrix: Temperature exhibits a positive correlation with chloride, total hardness, EC, and Al, but a negative correlation with manganese only. The correlation between color and phosphate, copper, fecal coliforms, turbidity, and phosphate is strong, while the correlation is moderate with TDS, EC, Fe, and Al (Fig. 5). Ammonia and dissolved oxygen exhibit a moderately negative correlation. Turbidity is negatively correlated with pH and exhibits a significant, strong positive correlation with copper, phosphate, Zn, and fecal coliform bacteria. It is moderately positively correlated with phosphate and Zn. A robust positive correlation was observed between TDS and sulfate, chloride, total hardness, and Al. A moderate correlation was observed between TDS and fecal coliforms, hue, and EC. Electrical conductivity is moderately correlated with variables including temperature, color, total dissolved solids (TDS), chloride, total hardness, aluminum (Al), and fecal coliform. Sulfate exhibits a moderate positive correlation with chloride, total hardness, Al, and fecal coliform, but a strong positive correlation with TDS. There exists a robust positive correlation between color and phosphate, as well as a moderate correlation with turbidity, Cu, and fecal coliform. A moderate positive correlation exists between chloride and temperature, EC, and sulfate, while a strong positive correlation is observed between chloride and total hardness, Al, and TDS.

Principal Component Analysis

PCA is a technique utilized to discern patterns within datasets and visually represent them in a manner that emphasizes both their commonalities and distinctions. Pattern recognition through PCA is an effective method for identifying patterns in high-dimensional data, even in situations where graphical representations are not feasible for data analysis. The data's pattern effectively reduces the data's dimensions with minimal data loss. PCA is a valuable instrument for assessing the ecological dimensions of pollutants in environmental systems when analyzing water quality. PCs were established using the criterion that stipulated the inclusion of factors that accounted for variance in excess of one eigenvalue.

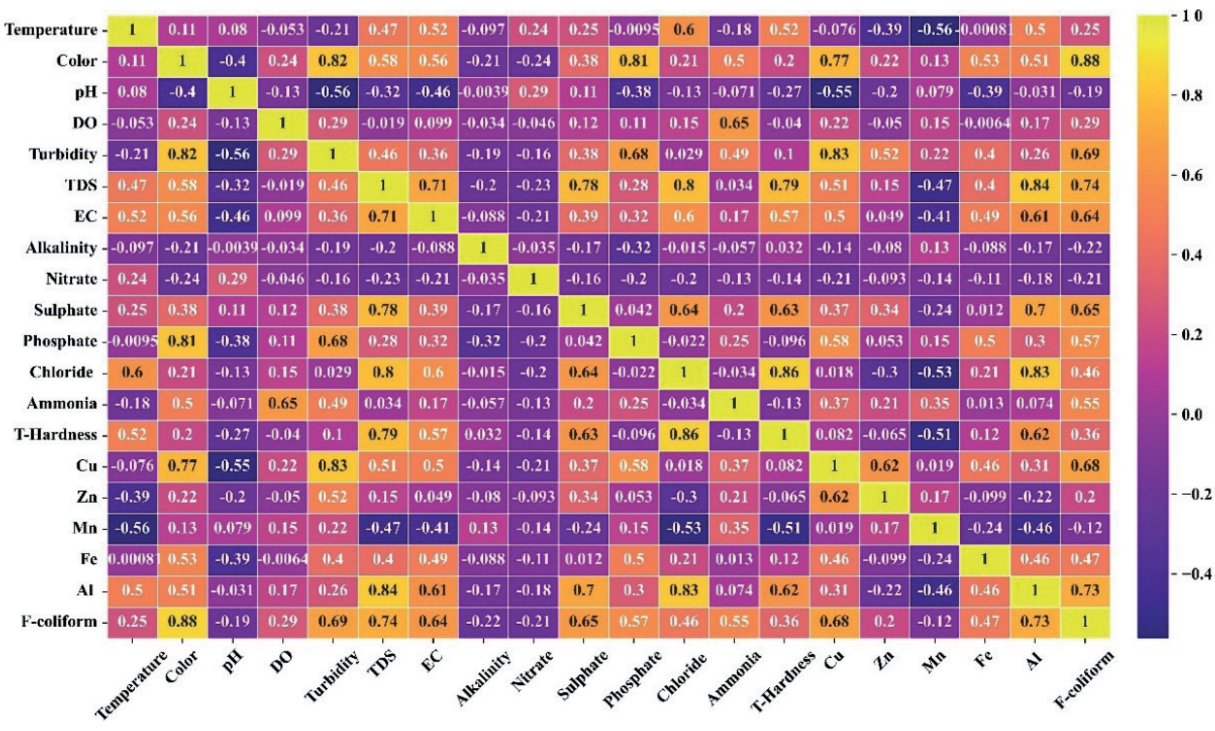

Fig. 5. Correlation coefficients among water quality parameters.

The justification for this is that in the domain of standardized test scores, no single variable should account for more variance than any component. To identify the water pollution sources and water quality in the vicinity of the Kabul River, principal component analysis was performed on twenty variables from five surface water samples in order to determine the most significant parameters in the assessment of water quality. The significance of a factor is quantified by its eigenvalue; factors possessing the highest eigenvalues are deemed to be the most significant. Eigenvalues that are equal to or exceed 1.0 are deemed to be statistically significant [34, 49, 50]. Nevertheless, while individual eigenvalues are all below 1.0, their collective significance is frequently assessed in terms of their contribution to the cumulative explained variance.

Thus, the categorization of principal components into "strong," "moderate," and "weak" is determined by the absolute loading values: greater than 0.75, between 0.75 and 0.50, and less than 0.50 and 0.30, respectively. Table 3 presents a summary of the principal component analysis (PCA), encompassing the factor loadings, eigenvalues of each PC, total variance, and cumulative variance. The PCA was computed using Python software with unrotated loadings for 20 parameters. The table features a bold number to indicate which variable is the most dominant and most strongly correlated with the others.

Table 3. Factor loading and accumulated variance of water quality parameters in the Kabul River.

Parameters	Factor 1	Factor 2	Factor 3
Temperature	0.026	**-0.655**	-0.298
Color	**0.777**	-0.213	**0.500**
pH	-0.580	0.034	-0.061
DO	0.085	-0.013	0.357
Turbidity	**0.662**	-0.009	**0.675**
TDS	0.378	**-0.855**	0.242
EC	**0.535**	**-0.613**	0.064
Alkalinity	-0.170	0.089	-0.100
Nitrate	-0.192	0.082	-0.187
Sulphate	-0.122	**-0.743**	**0.640**
phosphate	**0.770**	0.043	0.221
Chloride	0.047	**-0.943**	-0.036
Ammonia	0.176	0.088	**0.6263**
T-Hardness	0.041	**-0.837**	-0.003
Cu	**0.678**	-0.082	**0.556**
Zn	0.090	0.164	**0.548**
Mn	-0.050	**0.611**	0.378
Fe	**0.708**	-0.186	-0.099
Al	0.306	**-0.832**	0.122
F-coliform	**0.540**	**-0.503**	**0.561**
Eigenvalues	0.204	0.172	0.062
% Variance	46.57%	39.27%	14.16%

The most influential factor, denoted as PC 1, possesses an eigenvalue of 0.204 and accounts for 46.57% of the overall variance. Subsequently, Factor 2 (PC 2), which possesses an eigenvalue of 0.172, makes a substantial contribution by elucidating 39.27% of the overall variance. Factor 3 (PC 3), which possesses an eigenvalue of 0.062, contributes to the collective comprehension by elucidating 14.16% of the overall variance (Fig. 6). The cumulative percentage variance of 100% signifies that the entirety of the variability in the water quality parameters is accounted for by these three factors when considered collectively. Although the magnitudes of the individual Eigenvalues were negligible, the combined impact of these variables offers a holistic understanding of the dataset's underlying structure. F-coliform (0.540), color (0.777), turbidity (0.662), phosphate (0.770), Cu (0.678), and Fe (0.708) all exhibit positive loading. The observed correlation seems to be with parameters that are associated with F-coliform, metals (Cu, Fe, and Al), phosphate, and turbidity. It could reflect elements pertaining to the aesthetics of water and contaminants. Significant quantities of heavy metals, including Al, Cu, Fe, and Zn, are generated within the printing-dyeing and metal-smelting sectors. Additionally, turbidity, color, and phosphate are prevalent in this effluent. Furthermore, agricultural fertilizer use may contribute to elevated levels of phosphate and fecal coliform bacteria. Domestic wastewater may exert an additional influence on the aforementioned variables. Consequently, FA1 was identified as the pollutant source resulting from human activity in this particular context.

Factor 2 (PC 2) is significantly and negatively influenced by chloride, TDS, T-hardness, and Al, while sulfate, temperature, and F-coliform are moderately influential. With Mn, it exhibits a moderately positive correlation. In contrast, factor 2 (PC 2) accounts for 39.28% of the overall variance. A grouping of parameters associated with total dissolved solids (TDS), electrical conductivity (EC), hardness (T-Hardness), and specific ions (Nitrate, Mn, and Zn) is denoted by Factor 2. It may indicate the concentration of ions and minerals. Physical and chemical parameters, including total dissolved solids (TDS), effective carbon (EC), nitrate, and heavy metals (Mn and Zn), can potentially be introduced into a solution through the mixing of untreated effluent from agricultural and industrial sources, as well as the disposal of organic and inorganic waste. Furthermore, it is possible that natural phenomena, including the erosion of soil, boulders, and minerals, are to blame for these concentrations. Within the framework of FA2, anthropogenic activities are recognized as prevalent sources of contamination (Fig. 6).

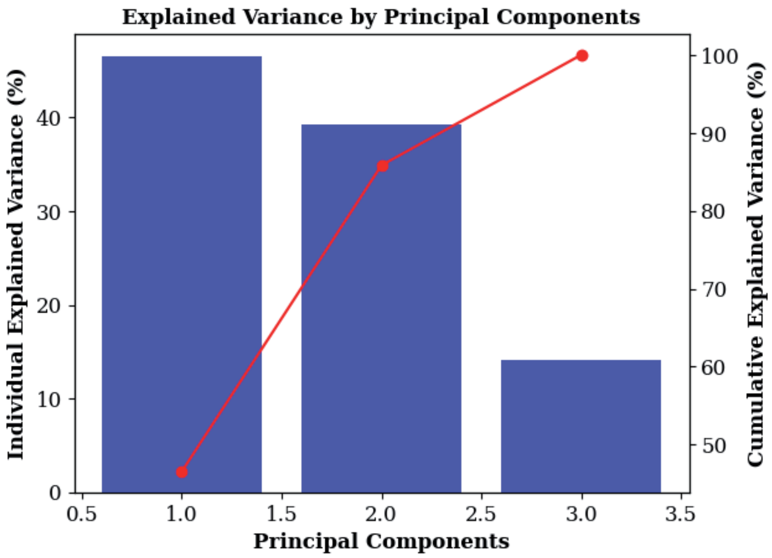

Fig. 6. Scree plot of the percent variability explained by each principal component.

Turbidity, sulfate, ammonia, Cu, F-coliform, Zn, and color explain 14.16% of the total variance in Factor 3 (PC3), which is moderately and positively dominated by these characteristics. Nevertheless, this indicates the presence of a multitude of metals, color, turbidity, DO, phosphate, sulfate, and phosphate ions. Nutrient, organic matter, and metal concentrations may be present in this mixture. The primary sources of water contamination in the Kabul River are, consequently, industrial activity and municipal effluent (14.16%), with agriculture being the subsequent contributor. Moreover, pollution can potentially originate from natural sources as well.

Conclusions

The examination of the physicochemical and biological attributes of the water in the Kabul River indicated that a significant proportion of the water qualities utilized in the computation of the WQI surpassed the acceptable thresholds established by ANSA, Asia, and WHO. While certain parameters, including nitrate, sulfate, chloride, copper (Cu), zinc (Zn), and aluminum (Al), were detected to be within the acceptable range, the concentration of fecal coliforms in every sample collected was found to be excessive.

Furthermore, significant variations in water quality were observed among the samples and across months, as determined by the WQI assessment. In contrast, while the water quality upstream (S1 and S2) was favorable in August, September, and October, it deteriorated in November and December before improving in January 2022. Samples 3, 4, and 5 maintained consistently high index values throughout the duration of the study, which indicated a deterioration in water quality.

The principal component analysis (PCA) study identified three primary factors that contribute to the variability in water quality: factor 1 (PC1) explains 46.57% of the variance; factor 2 (PC2) explains 39.28% of the variance; and factor 3 (PC3) explains 14.16% of the variance. These results indicate that anthropogenic activities are causing the Kabul River to become contaminated with agricultural runoff, industrial wastewater, and domestic wastewater.

In conclusion, the water samples located midstream and downstream of the Kabul River (S3, S4, and S5) are significantly more polluted and unfit for consumption, whereas the water upstream of the river is suitable for aquatic life, irrigation, and cleansing purposes. The results underscore the critical nature of implementing strategies to mitigate contamination sources and enhance water quality in the Kabul River in order to guarantee the availability of potable water that is both hygienic and uncontaminated.

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Conflict of Interest

The authors declare no conflict of interest.

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