

Article

Surface Water Hydrochemistry in the Keriya River System, Southern Tarim Basin, China: Controlling Factors and Irrigation Suitability

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Abstract

Inland rivers in arid regions are important water resources that support ecosystem stability and human activities. This study comparatively investigated the hydrochemical characteristics, controlling factors, and irrigation suitability of six glacier-fed inland rivers along the southern margin of the Tarim Basin using hydrochemical analysis, Gibbs and Piper diagrams, ion-ratio analysis, principal component analysis (PCA), and PHREEQC inverse mass-balance modeling. The six rivers exhibited distinct hydrochemical characteristics despite their common origin in the Kunlun Mountains. Carbonate weathering dominated the Bostan and Nur rivers, while the Kaxi River exhibited relatively stable hydrochemical characteristics mainly associated with rock weathering. In contrast, evaporite dissolution and evaporative concentration exerted stronger influences on the Uruksayi and Buzang rivers, which also showed more pronounced longitudinal variations in major ion concentrations. The Keriya River showed an overall transition from silicate-weathering-dominated conditions in the upper reaches toward stronger evaporite dissolution and evaporative concentration downstream. PHREEQC inverse mass-balance modeling suggested that halite dissolution, gypsum dissolution, dolomite dissolution, calcite precipitation, and cation exchange contributed to the hydrochemical evolution of the Keriya River. Several abrupt variations in ion concentrations were observed along the river courses, suggesting that localized processes, including tributary mixing, groundwater inputs, or potential anthropogenic influences, may contribute to these hydrochemical changes. PCA extracted two principal components explaining 86.0% of the total variance. PC1 (70.5%) represented overall ion enrichment and mineralization, whereas PC2 (15.5%) reflected carbonate-related hydrochemical variations. Irrigation suitability assessment showed that all rivers exhibited low sodium hazards, while salinity was the main factor limiting irrigation suitability in the middle and lower reaches of the Keriya River and in the Uruksayi and Buzang rivers. This study improves the understanding of hydrochemical evolution and water quality assessment of arid inland rivers and provides scientific support for sustainable water resource management and oasis ecosystem protection in the southern Tarim Basin.



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Keywords: hydrochemical characteristics; Keriya River; PHREEQC; principal component analysis; irrigation suitability; Tarim Basin; arid inland rivers

1. Introduction

Hydrochemistry serves as a key indicator of environmental conditions and geochemical processes within river systems. The dissolved ionic composition of river water reflects the integrated effects of rock weathering, mineral dissolution, water–rock interactions, and various environmental factors operating across a drainage basin [1,2]. In arid and semi-arid regions, inland rivers have long been a focal area of hydrochemical research owing to their extreme water scarcity, fragile ecosystems, and intense human disturbance [3]. Such rivers are typically developed within a compound geomorphic setting of mountain–oasis–desert, originating in high-altitude glacierized headwaters and primarily recharged by snowmelt and glacial meltwater, before gradually disappearing into the desert interior after passing through oasis agricultural zones, thereby forming a distinctive hydrological cycle and characteristic pattern of longitudinal hydrochemical variation [4,5]. Limited precipitation, intense evaporation, and geochemical processes such as evaporite dissolution and evaporative concentration constitute the principal natural mechanisms driving hydrochemical evolution in arid inland rivers [6,7]. Against the backdrop of global warming, rising temperatures and intensified evaporation in arid regions, accelerated glacier retreat, and growing anthropogenic water demands have given rise to increasingly severe threats including soil salinization, water quality deterioration, and overexploitation [8,9]. It is therefore of critical importance to investigate the hydrochemical characteristics of these rivers and their controlling factors for sustainable water resource management and ecological conservation in arid regions.

Numerous factors influence river hydrochemistry, including climatic conditions, geological settings, hydrological processes, and basin lithology [10]. Studies conducted in arid and semi-arid river systems worldwide have consistently demonstrated that the major dissolved ions in river water are derived predominantly from natural water–rock interactions, with carbonate weathering, silicate weathering, and evaporite dissolution serving as the principal sources of dissolved solutes. For example, in the Indus River basin of the Ladakh region, India, the rapid dissolution of carbonate rocks and evaporites has been identified as the dominant source of major ions in the mountainous headwaters [11]. Similar hydrochemical characteristics have been reported in the Amu Darya Basin and other arid inland river systems, where river salinity and dissolved ion concentrations increase progressively from upstream to downstream owing to the combined effects of prolonged water–rock interactions and evaporative concentration along river flow paths [12–14]. Likewise, studies in large arid basins such as the Nile have shown that basin lithology plays a dominant role in shaping hydrochemical facies, with carbonate-dominated catchments typically producing Ca–HCO₃-type waters, whereas evaporite-bearing terrains promote the evolution toward Na–Cl- and Na–SO₄-type waters [15,16]. Collectively, these studies indicate that lithology-dependent weathering and progressive evaporative enrichment are the major natural processes governing hydrochemical evolution in arid-region rivers. In China, hydrochemical research has primarily focused on the inland rivers of the arid northwest, including the Tarim, Heihe, Shiyang, Shule, Ili–Balkhash, and Kunlun Mountain regions. These river systems develop within a distinctive mountain–oasis–desert landscape, resulting in pronounced longitudinal gradients in hydrochemical characteristics. Studies of the Shiyang, Heihe, and Shule River basins consistently show that upstream waters are typically dominated by Ca²⁺ and HCO₃[−], reflecting the strong influence of rock weathering, whereas increasing mineralization in downstream reaches is primarily associated with evaporative concentration and evaporite dissolution [17,18]. Within the Ili–Balkhash Basin, carbonate weathering has been identified as the dominant source of dissolved solutes in river waters, while evaporative concentration and evaporite dissolution become increasingly important in downstream reaches and terminal lake environments [19]. Hydrochemical

and isotopic studies of glacial meltwater in the Kunlun Mountains further identified silicate weathering and cation exchange as major geochemical processes controlling dissolved ion composition [20]. Previous investigations in the Tarim Basin also reported relatively high total dissolved solids (TDSs) in river water, with Ca^{2+} , Mg^{2+} , and Na^+ as the dominant cations, and demonstrated that hydrochemical evolution is jointly controlled by water–rock interaction, evaporative concentration, and evaporite dissolution [21,22]. Collectively, these inland river systems constitute the principal freshwater resources sustaining oasis ecosystems and agricultural production across northwestern China, where hydrochemical evolution is closely coupled with mountain–oasis–desert ecological processes.

The Tarim Basin, located in southern Xinjiang Uyghur Autonomous Region of China, is the largest inland basin in the country [23]. In recent years, under the combined influence of global climate change and regional human activities, inland rivers along the southern margin of the Tarim Basin have faced prominent issues including water scarcity, increased water mineralization, and ecosystem degradation. The region receives little precipitation and experiences strong evaporation, so river flows depend mainly on glacier and snowmelt from the Kunlun Mountains, making them highly sensitive to climate change [24]. With rising temperatures and glacier retreat, runoff variability has increased, reducing the stability of water supply [25]. Concurrently, rapid expansion of oasis agriculture has led to increasing water withdrawals, reducing ecological flows to downstream desert areas and terminal oases. The combined pressures on water quantity and quality have become key factors limiting the sustainable development of oases and the maintenance of ecological security in the southern Tarim Basin [26]. Hydrochemical investigations of rivers in the Tarim Basin have shown that total dissolved solids concentrations are substantially higher than the global river average [27,28]. The Keriya River, the largest river in the study area, originates in the Kunlun Mountains and serves as one of the principal water sources for the Yutian Oasis, playing a significant role in maintaining regional ecological stability and supporting socioeconomic development [29]. The Bostan, Uruksayi, Kaxi, Buzang, and Nur Rivers, all located within Cele County, also originate in the Kunlun Mountains and collectively form an important component of the drainage network along the southern margin of the Tarim Basin [30]. Although previous studies have examined the hydrochemistry of rivers in the Tarim Basin, including the Keriya River, these efforts have largely focused on the mainstream of the Tarim River or on specific reaches of individual rivers. Systematic comparative studies of small- to medium-sized endorheic rivers remain notably absent. To address this gap, the present study conducts a comparative hydrochemical investigation of six glacier-fed inland rivers along the southern margin of the Tarim Basin: the Keriya, Bostan, Uruksayi, Kaxi, Buzang, and Nur Rivers. The specific objectives are to: (1) characterize and compare the hydrochemical facies and their spatial distribution patterns across the six rivers; (2) quantify the relative contributions of individual mineral weathering reactions to hydrochemical evolution using PHREEQC inverse mass-balance modeling; and (3) evaluate the irrigation suitability of surface waters. Through a multi-river comparative design, this study investigates the hydrochemical evolution of arid inland rivers by integrating natural geochemical processes, including water–rock interaction, mineral dissolution, and evaporative concentration. In addition, abrupt changes in hydrochemical parameters between adjacent sampling sites are examined to explore whether localized external inputs, such as tributary mixing or anthropogenic activities, may contribute to river chemistry variations. The findings will provide new data on the hydrochemical characteristics of small- to medium-sized endorheic rivers in this region and offer a scientific basis for sustainable water resource management and oasis ecological protection along the southern margin of the Tarim Basin.

2. Materials and Methods

2.1. Study Area

The Tarim Basin is a typical inland arid basin in northwestern China, with numerous inland rivers developed in the surrounding mountain ranges, totaling approximately 144 in number. These rivers originate primarily in the peripheral high-mountain zones of the Tianshan, Kunlun, and Pamir ranges, and either converge toward the basin interior or disappear within the oasis–desert zone [8,31]. The study area is situated along the southern margin of the Tarim Basin in Xinjiang, at the northern foot of the Kunlun Mountains, representing a typical mountain–oasis–desert system transitioning from the high-altitude Kunlun Mountain zone to the southern fringe of the Taklamakan Desert. The study area encompasses six inland rivers: the Keriya, Bostan, Buzang, Nur, Kaxi, and Uruksayi Rivers (Figure 1). The terrain is elevated in the south and low in the north, with elevations ranging from 1065 to 6802 m. The climate is warm-temperate inland arid desert. Mean annual precipitation in the Tarim Basin lowlands is less than 50 mm, while potential evapotranspiration exceeds 2000 mm yr^{−1}; precipitation in the mountainous areas increases with elevation and is predominantly stored in solid form [32]. The Keriya River is the largest river in the study area, located within Yutian County of the Hotan Prefecture, Xinjiang, with a total length of approximately 530 km. It originates from glaciers and permanent snowfields above 5500 m in the Kunlun Mountains, and is primarily recharged by snowmelt and glacial meltwater, which accounts for more than 60% of annual runoff, exhibiting pronounced seasonal variability [33]. The upper reaches are composed of two major tributaries, the Kulap River and the Kashtash River; the middle reaches extend from their confluence to the Yutian Oasis; and the lower reaches lie downstream of the Yutian Oasis. The elevations of the upper, middle, and lower reaches are 2600–6100 m, 1400–2600 m, and 1100–1400 m, respectively. The river ultimately disappears into the interior of the Taklamakan Desert, forming the Dariyaboy Oasis at its terminal reach. The Yutian Oasis is the principal agricultural zone and population center within the basin, with agricultural irrigation representing the predominant water use [34]. Bostan, Buzang, Nur, Kaxi, and Uruksayi are all located within Cele County and belong to the same endorheic drainage system on the northern slope of the Kunlun Mountains. They are smaller in scale than the Keriya River and all flow from south to north into the Taklamakan Desert. The regional stratigraphy is underlain by Precambrian metamorphic rocks and Paleozoic granites of the Kunlun orogenic belt, with carbonate rocks developed in the mid-mountain zone. The piedmont alluvial–proluvial plain is dominated by Quaternary alluvial deposits, and evaporite formations including gypsum and rock salt are locally developed in the lowlands [35].

2.2. Sample Collection and Measurement

Field investigations and surface water sampling were conducted in August 2025. A total of 115 surface water samples were collected from six rivers, namely the Keriya River ($n = 37$), Bostan River ($n = 12$), Uruksayi River ($n = 12$), Kaxi River ($n = 12$), Buzang River ($n = 12$), and Nur River ($n = 30$). Sampling sites were established from the upstream mountainous areas to the middle oasis regions and downstream desert reaches, providing representative coverage of the spatial variability in hydrogeological conditions and land-use patterns across the watershed. In situ measurements of pH, electrical conductivity (EC), dissolved oxygen (DO), water temperature (T), total dissolved solids (TDSs), and salinity (SALT) were performed immediately at each sampling site using a multiparameter water quality analyzer (YSI EXO2, YSI Inc., Yellow Springs, OH, USA). Salinity and TDS readings were directly obtained from the instrument, although these values were internally calculated based on measured EC and water temperature according to the manufacturer's

technical specifications. Before sampling, each bottle was rinsed three times with the river water to be sampled, after which the sample was collected directly using the rinsed bottle. The collected samples were immediately sealed, transported in insulated coolers containing ice packs and protected from light, and delivered to the Public Technical Service Center, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences. Upon arrival, the samples were stored at 4 °C and analyzed as soon as possible. Major ion concentrations were determined in the laboratory. Cl^- and SO_4^{2-} were measured by ion chromatography (ICS-5000, Thermo Fisher Scientific, Sunnyvale, CA, USA) according to the laboratory's standard operating procedures. Na^+ , K^+ , Ca^{2+} , and Mg^{2+} were determined by inductively coupled plasma optical emission spectrometry (ICP-OES; Agilent 735, Agilent Technologies, Santa Clara, CA, USA). HCO_3^- was determined by potentiometric titration using an automatic titrator (G20S, METTLER TOLEDO, Greifensee, Switzerland). The method detection limit for all analyzed major ions was 0.01 mg L^{-1} . All analyses were performed at the Public Technical Service Center, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, in accordance with the laboratory's quality control protocols. The charge balance error (CBE) for all water samples was within $\pm 5\%$, indicating acceptable analytical quality for hydrochemical interpretation. The geographic coordinates of all sampling sites are provided in Supplementary Table S1.

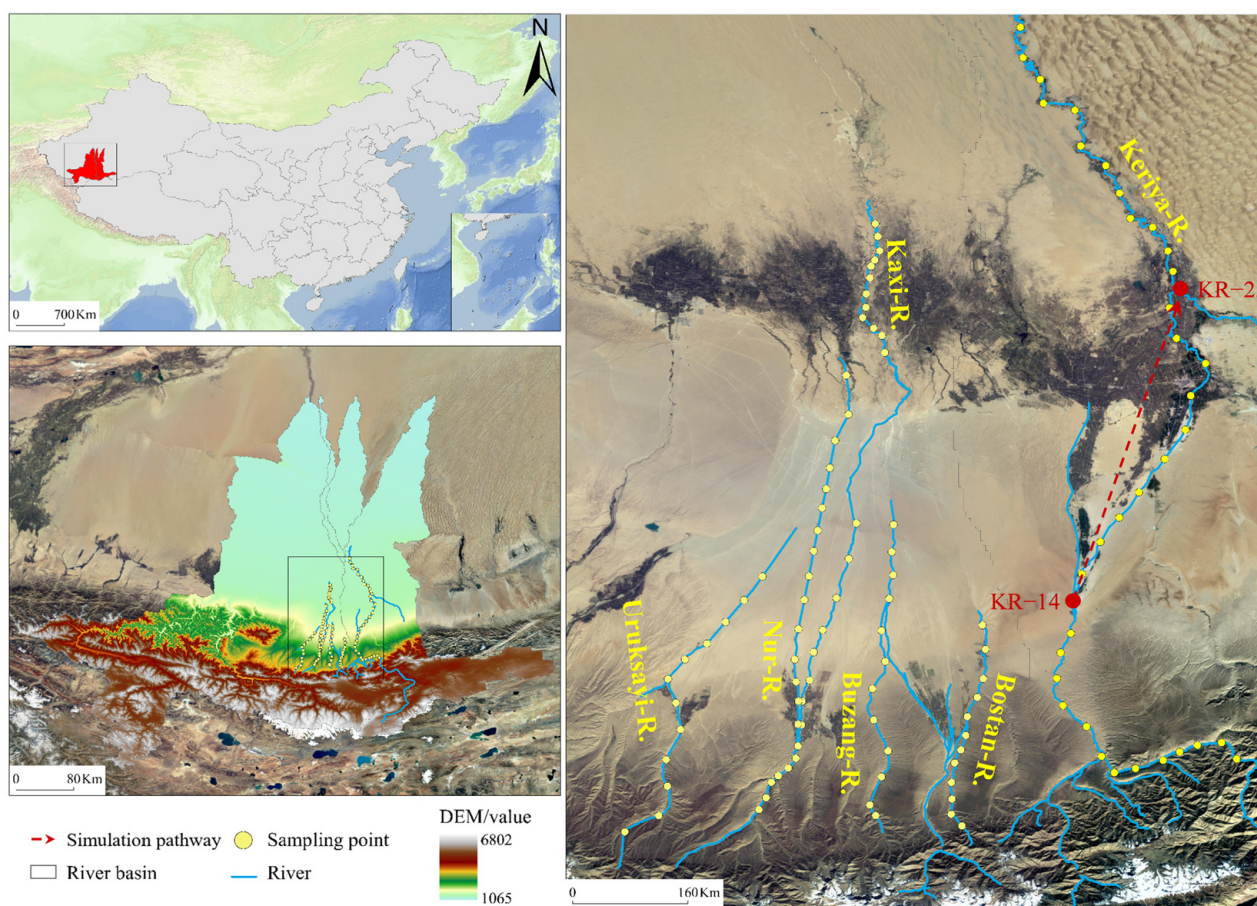


Figure 1. Overview of the Study Area and Map of Sampling Locations.

2.3. Piper and Gibbs Models

To characterize the hydrochemical properties and elucidate the principal geochemical processes controlling water composition, Piper trilinear diagrams and Gibbs diagrams were employed. The Piper diagram provides a systematic method to classify water types and examine the relative proportions of major cations (Ca^{2+} , Mg^{2+} , $\text{Na}^+ + \text{K}^+$) and anions

(HCO_3^- , SO_4^{2-} , Cl^-), expressed in milliequivalents per liter, allowing for the identification of hydrochemical facies and the inference of water–rock interaction mechanisms [36].

Gibbs diagrams were applied to determine the dominant factors influencing water chemistry, including atmospheric precipitation, lithological control, and evaporation–concentration processes. These diagrams plot the ratios $\text{Na}^+ / (\text{Na}^+ + \text{Ca}^{2+})$ or $\text{Cl}^- / (\text{Cl}^- + \text{HCO}_3^-)$ against total dissolved solids (TDSs), facilitating the identification of the primary geochemical controls on ionic composition [37].

2.4. PHREEQC Model

PHREEQC, developed by the U.S. Geological Survey (USGS), is a geochemical modeling package widely used to simulate hydrogeochemical processes under equilibrium and kinetic conditions [38]. Based on thermodynamic principles and the law of mass action, PHREEQC can be used to predict aqueous speciation, mineral saturation indices, reaction pathways, and mass transfer between aqueous and solid phases [39]. Based on the hydrochemical variations along the course of the Keriya River, one representative simulation path was selected for inverse mass-balance modeling. The inverse model was established according to the principle of mass conservation, using the measured hydrochemical compositions at the initial and terminal points of the selected simulation path as model constraints. Differences in water chemistry between the two sampling points were used to infer the hydrogeochemical reactions occurring along the path, including mineral dissolution–precipitation, gas exchange, and other geochemical processes, and to quantify the mass transfer associated with each reacting phase. The model inputs included the measured concentrations of the major cations (Na^+ , K^+ , Ca^{2+} , and Mg^{2+}), major anions (Cl^- , SO_4^{2-} , and HCO_3^-), and pH. According to the mineralogical characteristics of the Quaternary sediments and the regional geological setting, calcite, dolomite, gypsum, halite, sylvite, and $\text{CO}_2(\text{g})$ were defined as potential reactive phases in the inverse model. All simulations were performed using the phreeqc.dat thermodynamic database distributed with PHREEQC, and the inverse modeling results were accepted only when the prescribed mass-balance constraints were satisfied.

2.5. Data Analysis Methods

ArcGIS 10.7 was used to generate the sampling site map of the study area. Excel was employed to calculate the mean values and coefficients of variation of the water quality parameters. Origin 2026 was used to construct ion ratio plots and analyze the correlations among hydrochemical variables at significance levels of 0.05, 0.01, and 0.001. Principal component analysis (PCA) was subsequently performed using SPSS 27.0 on the standardized hydrochemical dataset from the Keriya River and the other five neighboring rivers.

PCA is an effective multivariate statistical method for reducing data dimensionality while retaining the maximum variance contained in the original dataset. In this study, PCA with varimax rotation was applied to identify the major factors controlling river water chemistry and to evaluate the influence of human activities on hydrochemical characteristics. The suitability of the dataset for PCA was assessed using the Kaiser–Meyer–Olkin (KMO) test and Bartlett’s test of sphericity. Principal components (PCs) with eigenvalues greater than 1 were retained for interpretation [40]. Following the classification proposed by Wang, factor loadings were categorized as strong (≥ 0.75), moderate (0.50–0.75), and weak (0.30–0.50) based on their absolute values [41].

3. Results

3.1. Major Ionic Components

Hydrochemical statistics show that the pH values of all river samples range from 7.42 to 8.46, with a mean value of 8.04, indicating weakly alkaline conditions typical of arid inland surface waters (Table 1). Differences in major ion compositions among the studied rivers and their longitudinal variations are shown in Figure 2. The overall longitudinal tendencies of major ion concentrations were further evaluated using trend-line fitting, and the corresponding regression equations are provided in Supplementary Table S2. In the Keriya River, TDS ranges from 479 to 1572 mg L⁻¹, with a mean value of 1079 mg L⁻¹, indicating relatively high mineralization. The dominant cations and anions follow the orders Na⁺ > Ca²⁺ > Mg²⁺ > K⁺ and Cl⁻ > SO₄²⁻ > HCO₃⁻, respectively. The relatively high variability of Na⁺, Cl⁻, and K⁺ indicates pronounced spatial heterogeneity of these ions along the river course. Major ion concentrations remain relatively stable from KR-1 to KR-18, increase sharply at KR-19, and show further adjustment near KR-26, where Na⁺, Cl⁻, and SO₄²⁻ increase while HCO₃⁻ decreases. Trend-line fitting indicates an overall increasing tendency for most major ions, with Cl⁻ and Na⁺ showing the largest positive slopes (13.39 and 12.28, respectively), followed by SO₄²⁻ (slope = 5.78). These ions exhibited pronounced longitudinal increases along the river course. In the Bostan River, TDS ranges from 353 to 682 mg L⁻¹, with a mean value of 443 mg L⁻¹. The dominant cations and anions are Ca²⁺ > Na⁺ > Mg²⁺ > K⁺ and HCO₃⁻ > SO₄²⁻ > Cl⁻, respectively. The generally low variability of major ions indicates relatively limited differences among sampling sites. Ca²⁺ and SO₄²⁻ concentrations are relatively high from BS-1 to BS-3, decrease markedly at BS-4, remain relatively stable from BS-4 to BS-9, and increase again from BS-10 to BS-12, showing staged hydrochemical variations along the river course. Trend-line fitting indicates contrasting longitudinal tendencies among major ions, with Cl⁻ showing an increasing tendency (slope = 3.53), whereas SO₄²⁻ exhibits the strongest decreasing trend (slope = -6.11). In the Uruksayi River, TDS ranges from 1300 to 1400 mg L⁻¹, with a mean value of 1343 mg L⁻¹, representing the highest mineralization among the six rivers. The dominant ions follow the orders Na⁺ > Ca²⁺ > Mg²⁺ > K⁺ and SO₄²⁻ > Cl⁻ > HCO₃⁻. Although TDS shows limited variability, Cl⁻ and Na⁺ exhibit substantial spatial variations among sampling sites. Major ion concentrations remain stable from UK-1 to UK-10, increase sharply at UK-11, and decrease markedly at UK-12, suggesting localized variations in hydrochemical conditions rather than continuous downstream enrichment. Trend-line fitting reveals an overall increasing trend for major ions, with SO₄²⁻, Cl⁻, and Na⁺ showing the most pronounced increases (slopes = 30.62, 25.91, and 19.32, respectively), indicating their dominant role in controlling longitudinal hydrochemical evolution. In the Kaxi River, TDS ranges from 1230 to 1320 mg L⁻¹, with a mean value of 1293 mg L⁻¹. The dominant ions are Na⁺ > Ca²⁺ > Mg²⁺ > K⁺ and HCO₃⁻ > SO₄²⁻ > Cl⁻, respectively. The relatively low variability of major ions indicates uniform ionic compositions among sampling sites. Hydrochemical conditions remain stable along most of the river, except for a synchronous decrease in major ions near KX-9. Trend-line fitting further reveals an overall decreasing tendency of major ions, with HCO₃⁻ showing the most pronounced decline (slope = -1.01), whereas other ions display relatively weak decreasing trends. In the Buzang River, TDS ranges from 420 to 1310 mg L⁻¹, with a mean value of 1083 mg L⁻¹. The dominant ions follow the orders Na⁺ > Ca²⁺ > Mg²⁺ > K⁺ and SO₄²⁻ > Cl⁻ > HCO₃⁻. Many major ions concentrations generally increase along the river course, although this trend does not continue at BZ-12, where a distinct deviation occurs. Trend-line fitting reveals heterogeneous longitudinal variations among major ions, with SO₄²⁻ showing an increasing trend (slope = 5.34), whereas HCO₃⁻ exhibits a pronounced decreasing trend (slope = -15.71). In the Nur River, TDS ranges from 36 to 1620 mg L⁻¹, with a

mean value of 729 mg L^{-1} , showing the largest variability in mineralization among the six rivers. The dominant ions are $\text{Ca}^{2+} > \text{Na}^+ > \text{Mg}^{2+} > \text{K}^+$ and $\text{HCO}_3^- > \text{SO}_4^{2-} > \text{Cl}^-$, respectively. HCO_3^- remains relatively stable, whereas other major ions exhibit stronger spatial variability. The concentrations of major ions are relatively high from NR-1 to NR-6 and decrease markedly after NR-6, particularly those of Na^+ , Cl^- , and SO_4^{2-} . Trend-line fitting confirms an overall decreasing tendency, with SO_4^{2-} , Na^+ , and Cl^- showing pronounced negative trends (slopes = -3.06 , -1.42 , and -1.14 , respectively).

Table 1. Statistics on the chemical composition of rivers in the study area.

Type	Statistical Value	pH	TDS	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	Cl^-	SO_4^{2-}
Keriya River	Min	7.63	479	55.1	38.8	96.7	8.0	184.1	118.0	173.2
	Max	8.40	1572	97.3	72.6	421.5	23.7	338.0	481.4	355.7
	Mean	8.17	1079.5	66.2	57.1	256.8	15.9	256.2	305.1	270.5
	CV (%)	2	31	17	24	58	43	24	53	27
Bostan River	Min	7.42	353	83.4	22.4	45.6	6.6	148.4	43.4	111.5
	Max	8.43	682	114.2	34.4	88.3	9.9	205.5	85.5	308.0
	Mean	7.76	443	94.1	27.2	54.5	7.4	186.1	62.8	177.0
	CV (%)	3	20	12	18	21	12	11	21	45
Uruksayi River	Min	7.74	1300	53.1	18.5	46.5	4.4	127.8	41.9	101.5
	Max	8.35	1400	175.7	117.7	469.5	22.8	169.1	601.3	753.8
	Mean	8.12	1343.3	82.5	37.5	124.0	7.7	147.3	149.9	242.6
	CV (%)	2	2	38	69	90	63	8	98	70
Kaxi River	Min	7.74	1230	50.5	19.5	66.4	8.9	118.5	84.4	100.6
	Max	8.31	1320	69.2	25.5	92.1	11.3	159.9	118.0	135.3
	Mean	7.97	1293.3	63.2	23.9	76.8	10.1	150.3	99.4	123.3
	CV (%)	2	2	7	6	7	7	7	7	6
Buzang River	Min	8.01	420	150.9	99.5	254.1	19.7	133.1	384.4	531.3
	Max	8.43	1310	192.9	118.5	297.2	23.8	304.4	456.9	609.2
	Mean	8.26	1082.5	177.5	108.0	268.7	21.8	224.0	416.8	562.2
	CV (%)	1	35	7	5	5	6	26	5	4
Nur River	Min	7.63	36	52.5	15.2	39.1	5.8	125.7	42.2	89.0
	Max	8.46	1620	79.4	26.6	106.3	11.0	145.4	118.3	216.2
	Mean	7.98	729.1	59.7	17.5	51.1	6.9	135.1	53.8	113.6
	CV(%)	2	76	12	20	38	26	4	37	36

3.2. Characterization of Major Ion Components

The Piper trilinear diagram was used to characterize the hydrochemical facies and spatial variations of the six rivers (Figure 3). Hydrochemical facies were classified according to the milliequivalent percentages (meq%) of major ions, with ions contributing $\geq 25\%$ of the total cations or anions regarded as dominant components [42]. In the cation triangle, samples from the upper reaches of the Keriya River were dominated by $\text{Ca}^{2+} + \text{Mg}^{2+}$, which accounted for 61% of total cations, whereas $\text{Na}^+ + \text{K}^+$ accounted for 40%. Along the river course, the relative contribution of $\text{Na}^+ + \text{K}^+$ increased, exceeding that of $\text{Ca}^{2+} + \text{Mg}^{2+}$ in the middle and lower reaches and reaching a maximum of 68%. This pattern indicates an overall shift in cation composition along the river, although localized variations were also observed. The Bostan River exhibited the highest proportion of alkaline earth cations among the six rivers, with $\text{Ca}^{2+} + \text{Mg}^{2+}$ accounting for 73% of total cations. Its samples were tightly clustered near the Ca^{2+} apex, indicating a strong dominance of alkaline earth cations. Similarly, the Nur River was dominated by $\text{Ca}^{2+} + \text{Mg}^{2+}$, which accounted for 66% of total cations. In contrast, several samples from the Uruksayi River were distributed closer to the

$\text{Na}^+ + \text{K}^+$ apex, indicating greater variability in alkali cation proportions. Samples from the Kaxi and Buzang rivers were distributed between the Ca^{2+} and $\text{Na}^+ + \text{K}^+$ end-members, reflecting relatively balanced contributions of alkaline earth and alkali cations. In the anion triangle, most samples were distributed toward the SO_4^{2-} apex, indicating that SO_4^{2-} was the dominant anion in most rivers. In the upper reaches of the Keriya River, SO_4^{2-} accounted for 37% of total anions, followed by Cl^- and HCO_3^- , which contributed 35% and 28%, respectively. Toward the downstream reaches, the proportion of Cl^- increased to 52%, accompanied by a decrease in the relative contribution of HCO_3^- . Consequently, sample distribution shifted toward the Cl^- apex, indicating an increased contribution of Cl^- to downstream hydrochemical compositions. Samples from the Urukseyi and Buzang rivers were mainly distributed between the Cl^- and SO_4^{2-} end-members, whereas samples from the Bostan and Nur rivers were concentrated between the SO_4^{2-} and HCO_3^- end-members. The Kaxi River exhibited a relatively balanced distribution among the three major anions, with no single anion showing clear dominance. In the central diamond field of the Piper diagram, samples from the upper reaches of the Keriya River showed a slight predominance of alkaline earth cations, while strong-acid anions exceeded weak-acid anions, corresponding to the Ca-SO_4 hydrochemical facies. From the upper to the lower reaches, the hydrochemical facies gradually shifted toward the Na-Cl-SO_4 type, accompanied by an increasing contribution of Na^+ and Cl^- . This transition became more pronounced in the middle and lower reaches, where alkali cations and chloride increasingly dominated the ionic composition. Although the overall downstream evolution showed a consistent shift in hydrochemical facies, localized variations were also observed along the river course. The Bostan and Nur rivers were classified as $\text{Ca-SO}_4\cdot\text{HCO}_3$ -type waters, whereas the Urukseyi and Buzang rivers were classified as $\text{Ca-Na-SO}_4\cdot\text{Cl}$ -type waters. The Kaxi River exhibited a $\text{Na}\cdot\text{Ca-Cl}\cdot\text{SO}_4\cdot\text{HCO}_3$ hydrochemical facies, reflecting the relatively balanced proportions of major cations and anions.

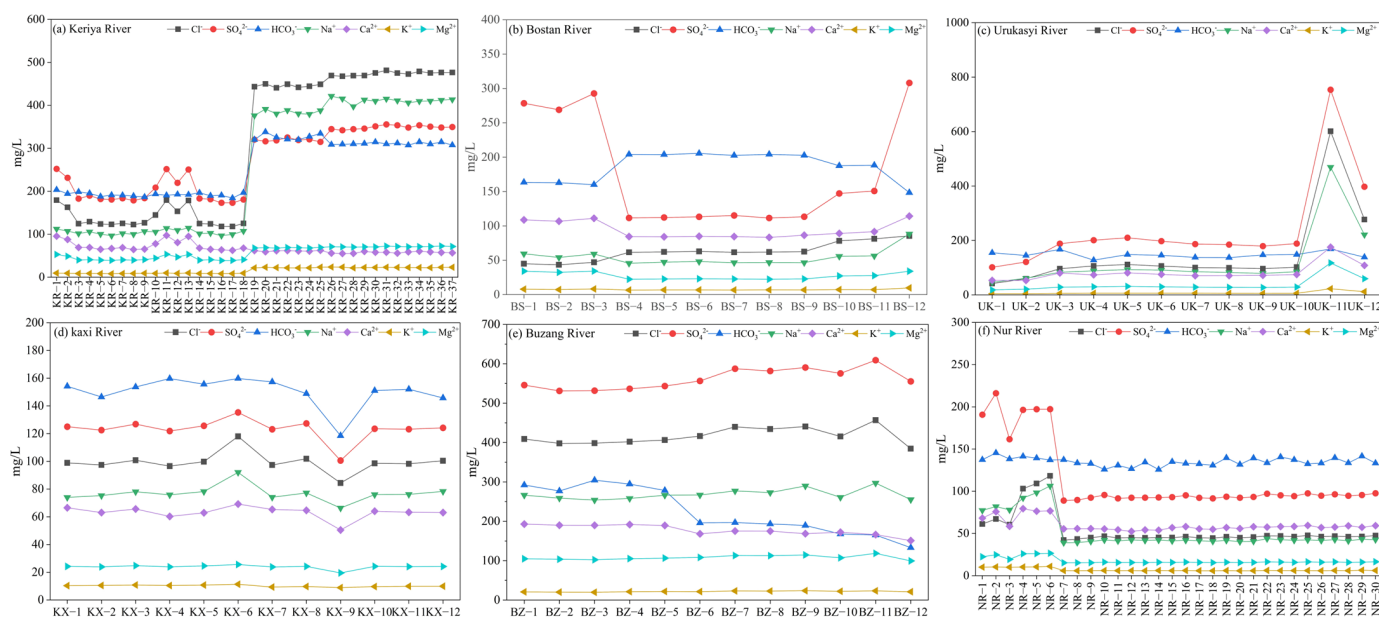


Figure 2. Spatial variation trends of major ion concentrations along sampling points of six rivers.

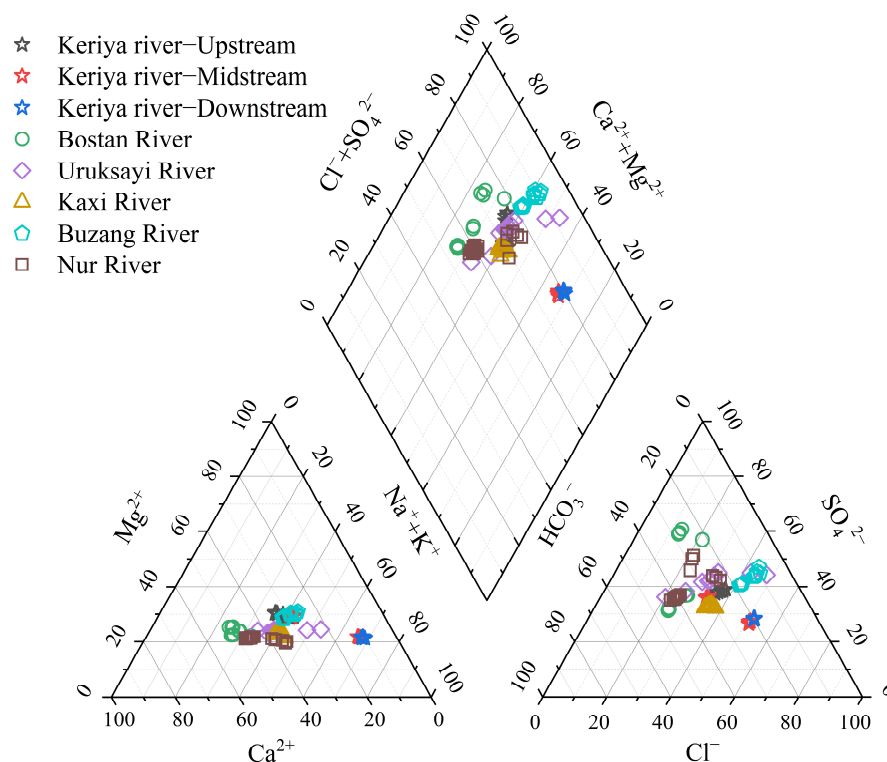


Figure 3. Piper diagram of major ions in the Keriya River and its adjacent watersheds.

3.3. Interrelationships Among Major Ions in Surface Water Chemistry

Correlation analysis was used to examine the relationships among major ions and their associations with river-water mineralization (Figure 4). Strong positive correlations generally indicate similar spatial variation patterns among ions and may reflect common hydrochemical controls, whereas weak or negative correlations suggest different geochemical behaviours [43]. For the Keriya River, TDS was very significantly and positively correlated with EC ($p < 0.001$), indicating the close relationship between the instrument-derived mineralization parameter (TDS) and EC variation. TDS was also significantly positively correlated with Cl^- , SO_4^{2-} , Na^+ , K^+ , and Mg^{2+} ($p < 0.01$), suggesting that these ions were closely associated with variations in the overall dissolved-solute content, although the correlation strength differed among ions. Cl^- was very significantly positively correlated with SO_4^{2-} , Na^+ , K^+ , and Mg^{2+} ($p < 0.001$), and Na^+ was also very significantly positively correlated with K^+ and Mg^{2+} ($p < 0.001$), indicating highly consistent variation among these ions. In contrast, Ca^{2+} was very significantly negatively correlated with Cl^- , SO_4^{2-} , Na^+ , and Mg^{2+} ($p < 0.001$), showing a pattern different from that of the main salinity-related ions. HCO_3^- was very significantly positively correlated with Na^+ , K^+ , and Mg^{2+} ($p < 0.001$), suggesting some consistency in their overall variation. Together with the Piper diagram results, the increasing proportion of Cl^- in the Keriya River indicates an overall hydrochemical shift from HCO_3^- dominance toward Cl^- enrichment. For the other five rivers, TDS was very significantly positively correlated with EC, Cl^- , SO_4^{2-} , Na^+ , and Mg^{2+} ($p < 0.001$), indicating that variations in mineralization and electrical conductivity were mainly controlled by these ions. Overall, most major ions showed positive correlations (Figure 4b), suggesting broadly similar variation trends among ions in these rivers. In particular, SO_4^{2-} was very significantly positively correlated with Cl^- and Na^+ ($p < 0.001$), reflecting similar variation characteristics. Unlike in the Keriya River, Ca^{2+} in the other five rivers was very significantly positively correlated with SO_4^{2-} , HCO_3^- , Na^+ , and Mg^{2+} ($p < 0.001$), indicating that Ca^{2+} generally varied in parallel with the other major

ions. The contrasting Ca^{2+} correlation patterns between the Keriya River and the other five rivers reveal differences in the overall hydrochemical evolution characteristics of the river systems.

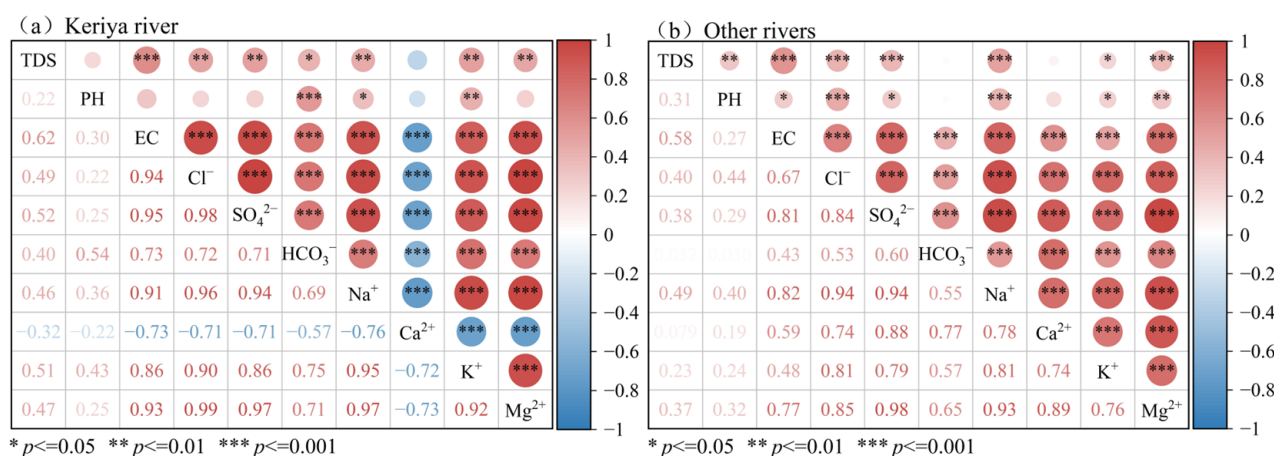


Figure 4. Spearman's correlation coefficients for major ions and other parameters in the Keriya River and its adjacent watersheds.

3.4. Major Sources of Ions and Their Influencing Factors

Gibbs diagrams are commonly used to evaluate the relative influences of rock weathering, atmospheric precipitation, and evaporative concentration on river hydrochemistry. In this study, Gibbs bivariate diagrams were constructed using $\lg(\text{TDS})$ as the vertical axis and the molar ratios of $\text{Na}^+ / (\text{Na}^+ + \text{Ca}^{2+})$ and $\text{Cl}^- / (\text{Cl}^- + \text{HCO}_3^-)$ as the horizontal axes (Figure 5) in order to identify the major controls on river hydrochemistry in the study area. The river water samples had TDS values ranging from 36 to 1620 mg L^{-1} , $\text{Na}^+ / (\text{Na}^+ + \text{Ca}^{2+})$ ratios ranging from 0.34 to 0.88, and $\text{Cl}^- / (\text{Cl}^- + \text{HCO}_3^-)$ ratios ranging from 0.21 to 0.78. Overall, most samples were distributed between the rock-weathering dominance field and the evaporative-concentration influence field, indicating that river hydrochemistry in the study area is jointly affected by rock weathering and evaporative concentration. The Keriya River samples showed a shift from rock-weathering dominance toward stronger evaporative concentration. In the upper reaches, the mean $\text{Na}^+ / (\text{Na}^+ + \text{Ca}^{2+})$ and $\text{Cl}^- / (\text{Cl}^- + \text{HCO}_3^-)$ ratios were 0.58 and 0.42, respectively, and the mean TDS was 1021.7 mg L^{-1} . Most samples from this section fell within the rock-weathering dominance field, suggesting that the upper river water was mainly influenced by ion inputs related to rock weathering. Toward the middle and lower reaches, the $\text{Na}^+ / (\text{Na}^+ + \text{Ca}^{2+})$ and $\text{Cl}^- / (\text{Cl}^- + \text{HCO}_3^-)$ ratios increased to 0.77 and 0.51, and further to 0.88 and 0.60, respectively, while the mean TDS increased to 1230.3 mg L^{-1} . These changes indicate that the influence of evaporative concentration on river hydrochemistry became stronger toward the downstream reaches. The Bostan and Nur river samples were generally located close to the rock-weathering dominance field, with some samples approaching the precipitation dominance field. Their relatively low $\text{Na}^+ / (\text{Na}^+ + \text{Ca}^{2+})$ and $\text{Cl}^- / (\text{Cl}^- + \text{HCO}_3^-)$ ratios indicate that their hydrochemical compositions are mainly controlled by rock weathering and may also be influenced by recharge from low-mineralization water sources, whereas evaporative concentration is relatively weak. The Kaxi River samples were mainly distributed within the rock-weathering dominance field, with mean $\text{Na}^+ / (\text{Na}^+ + \text{Ca}^{2+})$ and $\text{Cl}^- / (\text{Cl}^- + \text{HCO}_3^-)$ ratios of 0.55 and 0.40, respectively. This indicates that rock weathering is the primary controlling factor, although evaporative concentration also has some influence. The Uruksayi River showed an overall distribution pattern similar to that of the Kaxi River, but some samples had higher $\text{Cl}^- / (\text{Cl}^- + \text{HCO}_3^-)$ and $\text{Na}^+ / (\text{Na}^+ + \text{Ca}^{2+})$

ratios, suggesting stronger evaporative concentration in parts of the river. The Buzang River had a mean $\text{Cl}^-/(\text{Cl}^- + \text{HCO}_3^-)$ ratio of 0.66 indicating a relatively pronounced influence of evaporative concentration. Overall, the hydrochemical composition of the six rivers is controlled by the combined effects of rock weathering and evaporative concentration, with different dominant processes among individual rivers. The middle and lower reaches of the Keriya River, together with the Uruksayi and Buzang rivers, show stronger evaporative-concentration characteristics, whereas the Bostan, Nur, and Kaxi rivers are more strongly characterized by rock-weathering control. These regional hydrochemical patterns may also be locally modified by variations in hydrological conditions along individual river reaches.

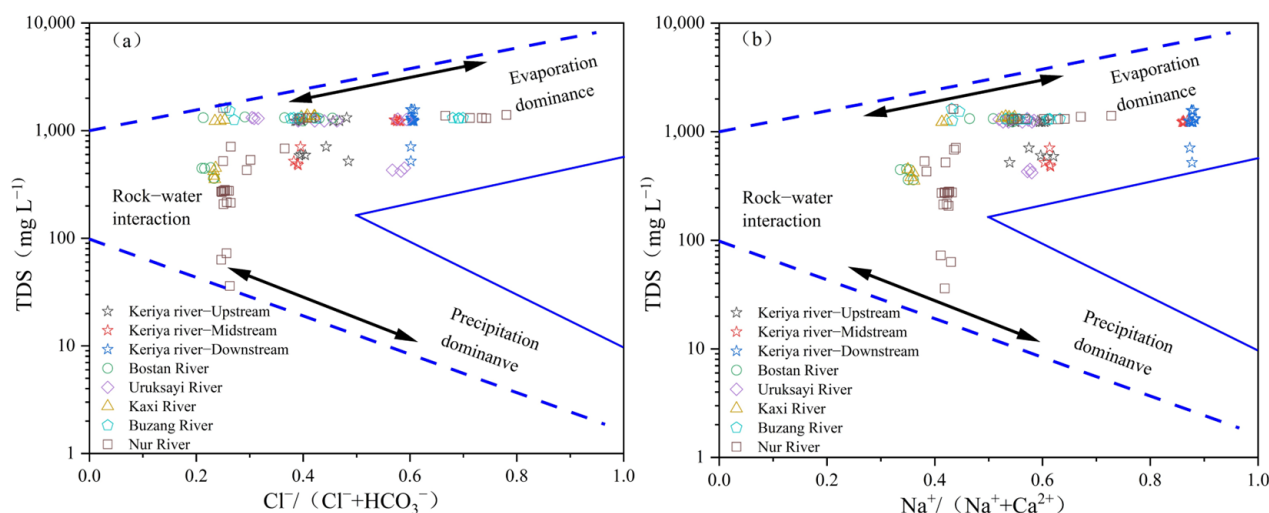


Figure 5. Gibbs Plots of Chemical Parameters for the Keriya River and Its Adjacent Watersheds: (a) TDS versus $\text{Na}^+ / (\text{Na}^+ + \text{Ca}^{2+})$; (b) TDS versus $\text{Cl}^- / (\text{Cl}^- + \text{HCO}_3^-)$.

Different rock-weathering processes release characteristic ions and thereby influence river hydrochemistry [2]. In the southern Tarim piedmont, silicate metamorphic rocks are mainly distributed in mountainous reaches, carbonate strata occur in piedmont zones, and gypsum- and halite-bearing sediments are present in downstream plains [35]. Major ion ratios were used to identify dissolved-ion sources. In general, Na^+ and K^+ are derived from silicate weathering and evaporite dissolution; Ca^{2+} and Mg^{2+} from carbonate weathering, evaporite dissolution, and silicate weathering; SO_4^{2-} and Cl^- mainly from evaporite dissolution; and HCO_3^- mainly from carbonate weathering [44]. The $\text{Ca}^{2+}/\text{Na}^+$ versus $\text{Mg}^{2+}/\text{Na}^+$ and $\text{Ca}^{2+}/\text{Na}^+$ versus $\text{HCO}_3^-/\text{Na}^+$ diagrams (Figure 6a,b) show that most samples plot between the silicate and carbonate end-members, indicating mixed silicate and carbonate weathering. Samples from the upper Keriya River are closer to the silicate end-member, whereas those from the middle and lower reaches shift toward the evaporite end-member, indicating a stronger contribution from evaporite dissolution. The Bostan and Nur rivers plot close to the carbonate end-member, suggesting dominant carbonate weathering. Samples from the Kaxi, Uruksayi, and Buzang rivers occupy intermediate positions between the carbonate and evaporite end-members, indicating combined effects of carbonate weathering and evaporite dissolution. The Cl^-/Na^+ diagram (Figure 6c) shows that most samples plot close to the 1:1 line, indicating that Na^+ and Cl^- are mainly derived from halite dissolution. Samples from the middle and lower Keriya River plot below the 1:1 line, suggesting additional Na^+ sources besides halite dissolution. In the $\text{SO}_4^{2-}/\text{Ca}^{2+}$ diagram (Figure 6d), most samples plot above the 1:1 line, indicating multiple sulfate sources, including gypsum dissolution. The higher $\text{SO}_4^{2-}/\text{Ca}^{2+}$ ratios in the middle and lower Keriya River suggest enhanced gypsum dissolution, while carbonate precipitation may partly account for the relative depletion of Ca^{2+} . In the $\text{SO}_4^{2-}/\text{Cl}^-$ diagram

(Figure 6e), most samples also plot above the 1:1 line, consistent with the widespread occurrence of gypsum-bearing strata. Some samples from the lower Keriya River plot below the line, indicating a relatively greater contribution from halite dissolution. The $(\text{SO}_4^{2-} + \text{HCO}_3^-)/(\text{Ca}^{2+} + \text{Mg}^{2+})$ diagram (Figure 6f) shows that upper Keriya River samples plot close to the 1:1 line, whereas middle and lower reach samples shift above the line, suggesting relative enrichment of alkali cations in the middle and lower reaches. Buzang River samples plot below the 1:1 line, indicating relative enrichment of $\text{Ca}^{2+} + \text{Mg}^{2+}$. As shown by the Ca^{2+} -EC and SO_4^{2-} -EC relationships in Supplementary Figure S1, the relatively high $\text{Ca}^{2+} + \text{Mg}^{2+}$ concentrations are more likely related to carbonate weathering, such as dolomite dissolution, rather than gypsum saturation. In the $\text{HCO}_3^-/\text{Ca}^{2+}$ diagram (Figure 6g), upper Keriya River samples plot below the $y = x$ line, consistent with calcite precipitation, whereas middle and lower reach samples fall between the $y = x$ and $y = 2x$ lines, suggesting mixed calcite and dolomite dissolution. Buzang River samples also plot below the $y = x$ line, indicating evaporative concentration accompanied by calcite precipitation. A strong negative relationship between $(\text{Ca}^{2+} + \text{Mg}^{2+} - \text{HCO}_3^- - \text{SO}_4^{2-})$ and $(\text{Na}^+ + \text{K}^+ - \text{Cl}^-)$, with $R^2 = 0.782$ and a slope of -0.913 (Figure 6h), indicates cation exchange. In this process, Ca^{2+} and Mg^{2+} are adsorbed onto exchange sites, while Na^+ and K^+ are released into the water. Compared with the upper reaches, the middle and lower Keriya River samples show larger deviations, suggesting that cation exchange is more evident in the more mineralized sections. Overall, ion-ratio analyses show distinct hydrochemical controls among the six rivers. Carbonate weathering dominates the Bostan and Nur rivers, whereas evaporite dissolution contributes more strongly to the Uruksayi and Buzang rivers. The Keriya River shows a clear hydrochemical contrast between the upper and middle-lower reaches, reflecting the combined effects of silicate weathering, evaporite dissolution, evaporative concentration, carbonate precipitation, and cation exchange. In particular, the abrupt increases in Na^+ , Cl^- , and SO_4^{2-} in parts of the middle and lower reaches suggest that, in addition to natural factors, river hydrochemistry may also be influenced by human activities and various other external inputs.

3.5. PHREEQC Inverse Mass-Balance Modeling of the Keriya River

The saturation indices (SIs) of the major minerals along the KR-14→KR-25 flow path are presented in Table 2. Calcite and dolomite exhibited positive saturation indices throughout the simulation, indicating supersaturation with respect to these carbonate minerals and a tendency for precipitation. The SI of calcite increased from 0.50 to 0.69, while that of dolomite increased from 0.90 to 1.69, suggesting an increasing tendency for carbonate precipitation along the flow path. In contrast, gypsum, halite, sylvite, and $\text{CO}_2(\text{g})$ remained undersaturated throughout the simulation, indicating their potential for continued dissolution. The SI of gypsum changed only slightly, whereas that of halite and sylvite increased but remained below saturation. The PHREEQC inverse mass-balance modeling results are summarized in Table 3. Along the KR-14→KR-25 flow path, halite, gypsum, and dolomite dissolved, whereas calcite precipitated. Halite exhibited the greatest dissolution among all modeled minerals, indicating that it was the principal source of Na^+ and Cl^- . Correspondingly, Na^+ increased from 101.3 to 387.9 mg L^{-1} , while Cl^- increased from 124.7 to 448.9 mg L^{-1} . The SO_4^{2-} concentration increased from 183.1 to 314.9 mg L^{-1} , consistent with gypsum dissolution, and Mg^{2+} increased from 39.8 to 69.3 mg L^{-1} , reflecting the contribution of dolomite dissolution. The exchange phase showed positive NaX values and negative CaX_2 values. At the same time, Ca^{2+} decreased from 67.9 to 62.5 mg L^{-1} despite continued dissolution of gypsum and dolomite. This decrease indicates that part of the dissolved Ca^{2+} was removed through calcite precipitation and cation exchange. PHREEQC inverse modeling further indicates that Na^+ was released from exchange sites into the

aqueous phase, whereas Ca^{2+} was adsorbed onto exchange sites, confirming that forward cation exchange occurred along the KR-14→KR-25 flow path of the Keriya River.

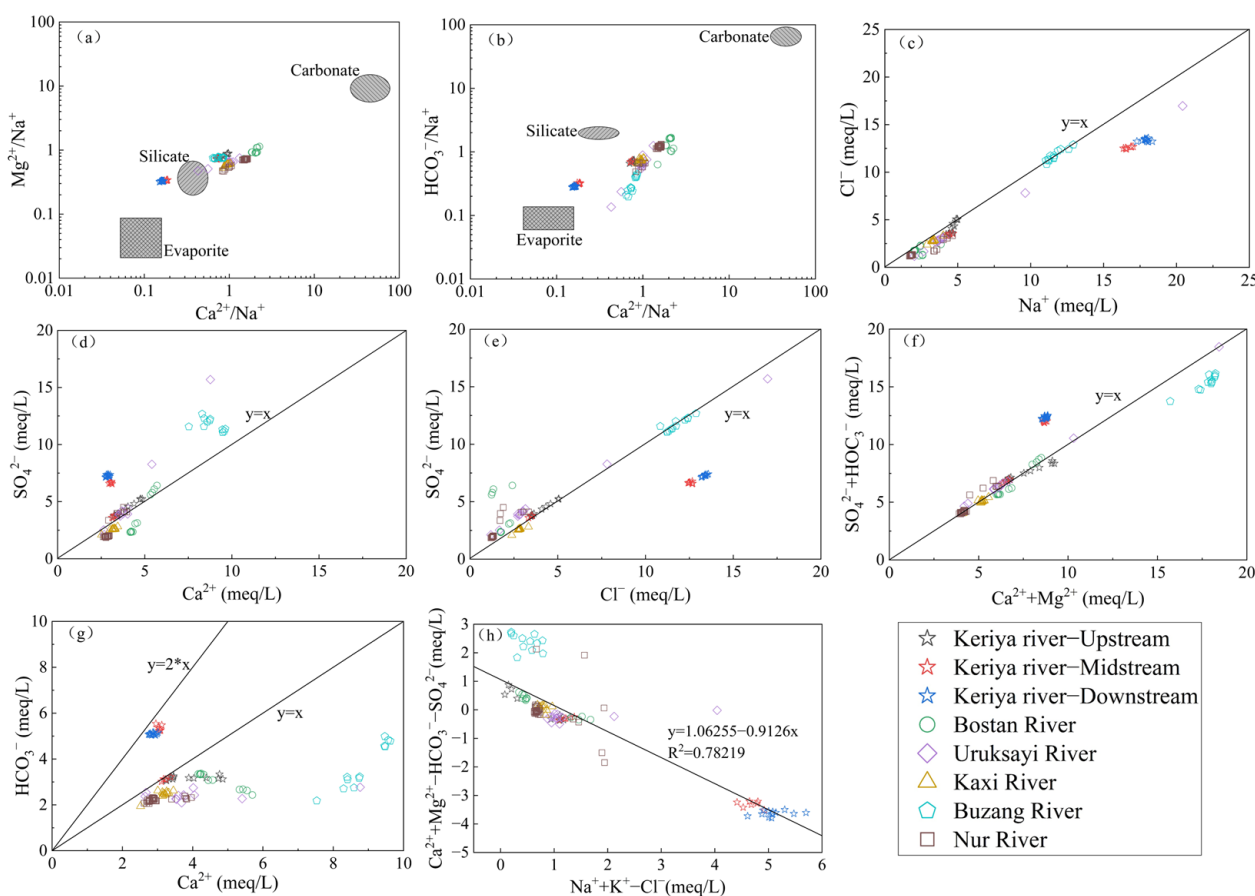


Figure 6. Mixed-phase diagrams of (a) $\text{Ca}^{2+}/\text{Na}^{+}$ and $\text{Mg}^{2+}/\text{Na}^{+}$, (b) $\text{Ca}^{2+}/\text{Na}^{+}$ and $\text{HCO}_3^{-}/\text{Na}^{+}$, (c) Na^{+} and Cl^{-} , (d) Ca^{2+} and SO_4^{2-} , (e) Cl^{-} and SO_4^{2-} , (f) $\text{Ca}^{2+} + \text{Mg}^{2+}$ and $\text{SO}_4^{2-} + \text{HCO}_3^{-}$, (g) Ca^{2+} and HCO_3^{-} , (h) $\text{Na}^{+} + \text{K}^{+} - \text{Cl}^{-}$ and $\text{Ca}^{2+} + \text{Mg}^{2+} - \text{HCO}_3^{-} - \text{SO}_4^{2-}$.

Table 2. Saturation indices of major minerals along the KR-14→KR-25 simulation path.

Sample	Calcite	Dolomite	Gypsum	Halite	Sylvite	CO_2 (g)
KR-14	0.5	0.9	−1.41	−6.44	−7.02	−2.83
KR-25	0.69	1.69	−1.41	−5.33	−6.1	−2.76

Table 3. Results of PHREEQC inverse mass-balance modeling.

Mineral	Calcite	Dolomite	Gypsum	Halite	CO_2 (g)	NaX	CaX_2	KX
Pathway from KR-14 to KR-25 Concentration (mg L^{-1})	-1.38×10^{-3}	1.27×10^{-3}	1.71×10^{-3}	9.78×10^{-3}	1.10×10^{-3}	3.51×10^{-3}	-1.94×10^{-3}	3.57×10^{-4}

3.6. Principal Component Analysis of the Main Ions

Principal component analysis (PCA) was conducted using eight hydrochemical variables: K^{+} , Na^{+} , Ca^{2+} , Mg^{2+} , Cl^{-} , SO_4^{2-} , HCO_3^{-} , and total dissolved solids (TDSs). The suitability of the dataset for PCA was confirmed by the Kaiser–Meyer–Olkin (KMO) test and Bartlett’s test of sphericity [45,46]. Based on the eigenvalue > 1 criterion, two principal components were extracted, explaining 86.0% of the total variance (Table 4). PC1 explained 70.5% of the total variance and showed strong positive loadings for K^{+} , Na^{+} , Ca^{2+} , and Cl^{-} ,

together with moderate positive loadings for SO_4^{2-} and Mg^{2+} . Therefore, PC1 mainly represents dissolved ion enrichment and overall mineralization. These ions can be supplied by multiple natural processes, including silicate weathering, carbonate weathering, evaporite dissolution, and sulfate mineral dissolution. This interpretation is consistent with the ion-ratio results and the PHREEQC inverse modeling of the representative KR-14→KR-25 flow path, which identified mineral dissolution, carbonate precipitation, and cation exchange as important natural controls on hydrochemical evolution in the Keriya River basin. Spatially, higher PC1 scores occurred mainly in parts of the middle and lower reaches of the Keriya River and in the Buzang River, indicating stronger solute enrichment in these sections. However, the marked increases in Na^+ , Cl^- , and SO_4^{2-} in the middle oasis reach of the Keriya River suggest that external inputs, including possible human activities, may also contribute to local hydrochemical changes. PC2 explained 15.5% of the total variance and was characterized by high positive loadings for HCO_3^- , Mg^{2+} , and SO_4^{2-} . This component mainly reflects carbonate- and sulfate-related hydrochemical variability. The Bostan River showed the highest PC2 scores, consistent with stronger carbonate weathering and higher relative contributions of HCO_3^- , Ca^{2+} , and Mg^{2+} . In contrast, the middle and lower reaches of the Keriya River had relatively low PC2 scores, indicating a lower relative contribution of HCO_3^- under more mineralized conditions. Overall, PCA indicates clear spatial heterogeneity in river hydrochemistry across the study area (Figure 7). PC1 reflects overall solute enrichment, whereas PC2 represents carbonate- and sulfate-related variability. Combined with the Gibbs diagrams, ion-ratio analysis, and PHREEQC modeling, these results suggest that river hydrochemistry is controlled by multiple interacting processes. Natural processes provide the basic geochemical framework, while local hydrological conditions and external inputs may further modify ion composition in specific reaches, particularly in the middle oasis reach of the Keriya River.

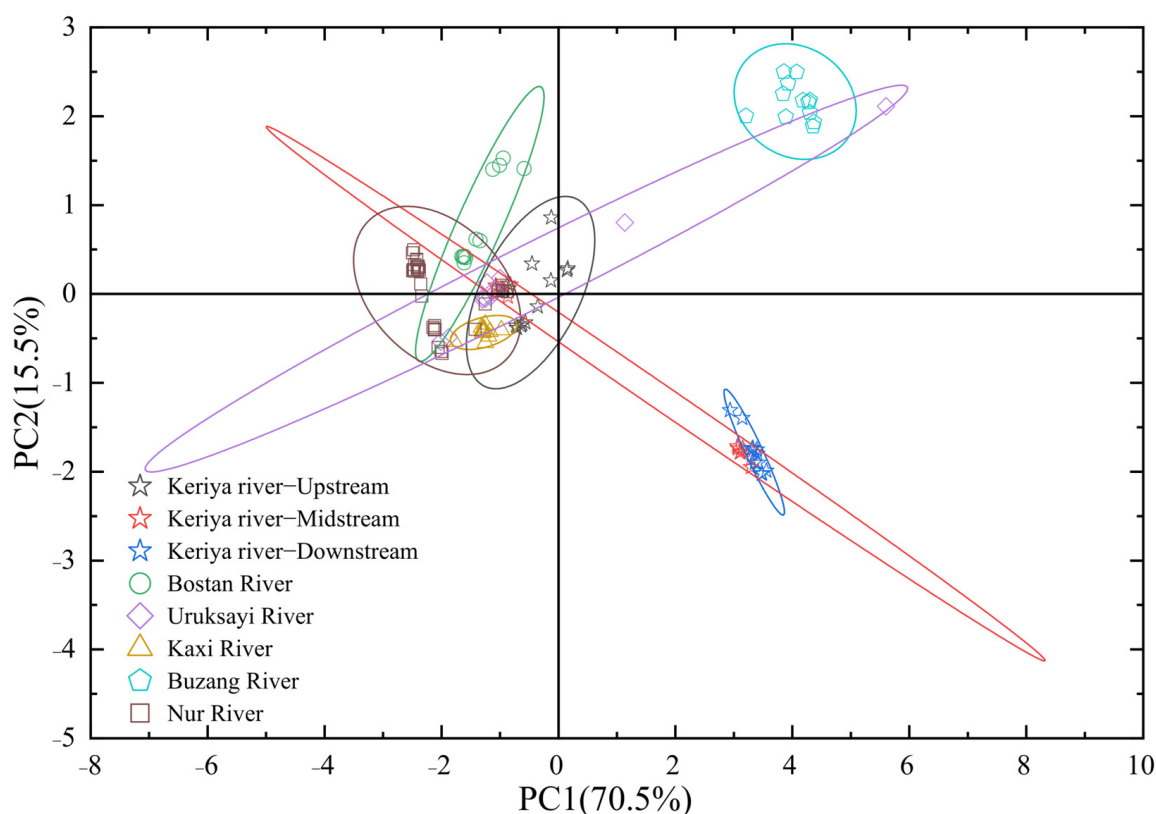


Figure 7. Score plot of PC1 and PC2.

Table 4. Principal component analysis of major ions in surface water from rivers in the study area.

Variable	PC1	PC2	Communalities
K ⁺	0.92	0.35	0.97
Na ⁺	0.87	0.17	0.78
Ca ²⁺	0.86	0.50	0.98
Cl [−]	0.84	0.50	0.96
TDS	0.51	−0.02	0.26
HCO ₃ [−]	−0.06	0.98	0.96
Mg ²⁺	0.50	0.85	0.98
SO ₄ ^{2−}	0.60	0.79	0.98
Eigenvalues	5.64	1.24	
Variance (%)	70.5	15.5	
Cumulative (%)	70.5	86.0	

3.7. Water Quality for Agriculture Irrigation

The suitability of agricultural irrigation water resources depends primarily on the concentrations of sodium and total salinity in the water. Elevated sodium content and high salinity levels in irrigation water can alter soil structure, rendering it dense and less permeable [47]. In this study, the sodium adsorption ratio (SAR) and sodium percentage (%Na) were employed to evaluate irrigation water quality, and their calculation methods are presented as follows:

$$SAR = \frac{K^+ + Na^+}{\sqrt{\frac{Mg^{2+} + Ca^{2+}}{2}}}$$

$$\%Na = \frac{K^+ + Na^+}{Ca^{2+} + Mg^{2+} + K^+ + Na^+}$$

According to the U.S. Salinity Laboratory (USSL) classification, irrigation water can be divided into 16 classes based on salinity hazard (C1–C4) and sodium hazard (S1–S4) [48]. The USSL diagram (Figure 8) shows that all samples fall within the S1 field, indicating a low sodium hazard for the river water. The upstream and some midstream samples from the Keriya River are mainly classified as S1–C3, suggesting relatively high salinity. Downstream, several midstream and downstream samples approach or enter the S1–C4 field, indicating excessive salinity and a gradual decline in irrigation suitability along the flow path. The Nur River samples fall within the S1–C1 and S1–C2 classes, representing relatively ideal irrigation water. The Kaxi and Bostan rivers are mainly classified as S1–C3, indicating suitability only under certain agricultural conditions, whereas the Buzang and Uruksayi rivers fall within S1–C4 and are therefore strongly limited by high salinity.

The sodium percentage (%Na) is an important indicator of the potential sodium hazard posed by irrigation water. Irrigation water with elevated Na⁺ concentrations can displace Ca²⁺ and Mg²⁺ from soil exchange sites, resulting in increased sodium adsorption by clay minerals. This process degrades soil structure, reduces soil permeability, and ultimately inhibits crop growth and decreases agricultural productivity [49]. To further evaluate the suitability of river water for irrigation, a Wilcox diagram (Figure 9) was constructed by plotting sodium percentage (%Na) against electrical conductivity (EC) [50]. Most samples from the upper and middle reaches of the Keriya River fall within the Good to Permissible category. Along the downstream flow path, irrigation water quality gradually shifts toward the Doubtful to Suitable category. Nevertheless, none of the samples fall into the Unsuitable category, indicating that the irrigation suitability of the Keriya River is primarily limited by increasing salinity rather than by sodium hazard. Overall, the Keriya River remains a suitable source of irrigation water. The upper reaches exhibit the highest irrigation water

quality, whereas suitability gradually decreases toward the middle and lower reaches because of the progressive increase in water mineralization. Most samples from the Nur River are classified as Excellent to Good, indicating excellent irrigation suitability. Samples from the Kaxi River and the Bostan River are predominantly distributed within the Good to Permissible category, whereas those from the Buzang River and the Uruksayi River fall mainly within the Doubtful to Suitable category. Overall, river waters in the study area are characterized by a generally low sodium hazard, although the degree of salinity hazard varies considerably among rivers. The Nur River provides the most suitable irrigation water, whereas irrigation use of the Buzang River and the Uruksayi River is most strongly constrained by elevated salinity.

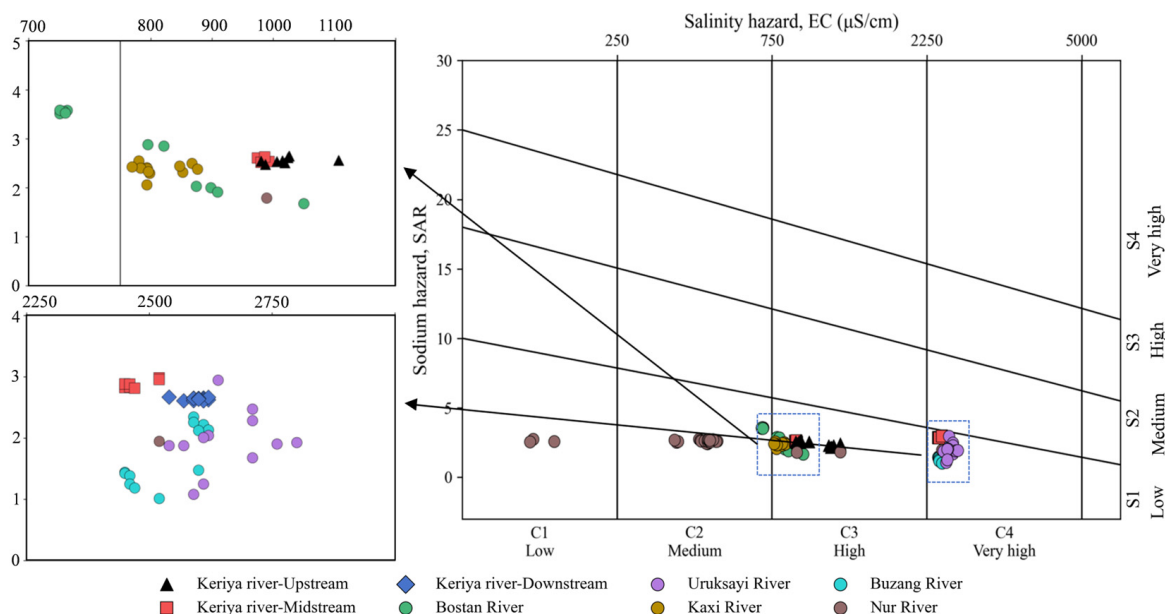


Figure 8. USSL diagram for irrigation water classification based on EC and SAR.

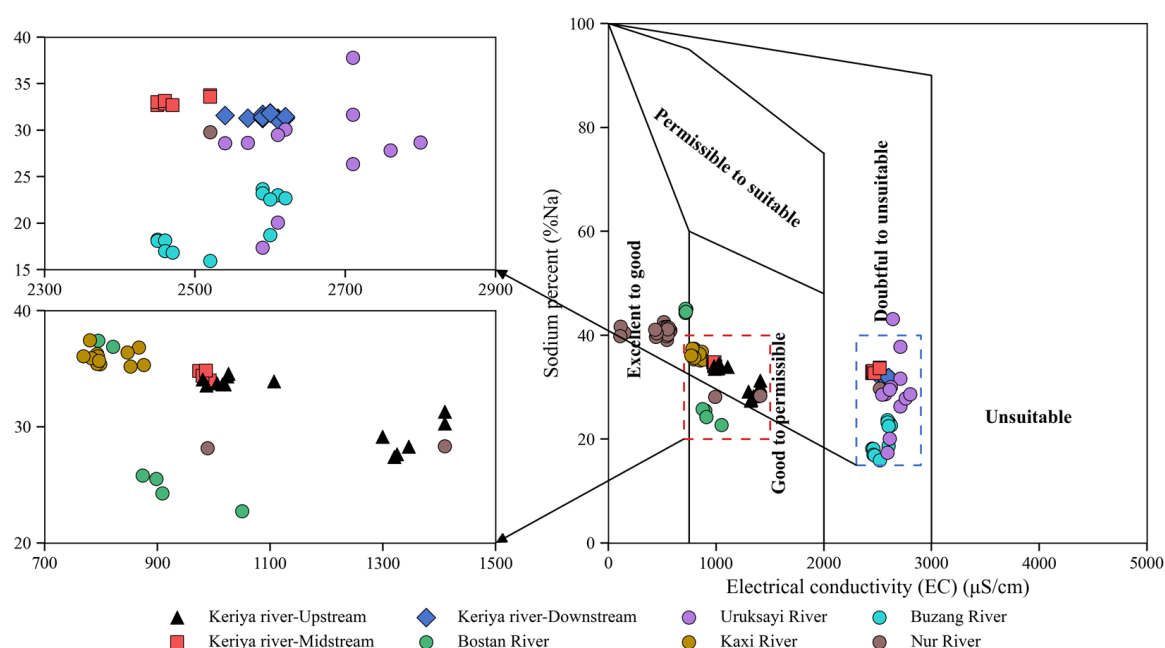


Figure 9. Wilcox diagram for irrigation water classification based on EC and SAR.

4. Discussion

Although the six rivers all originate from the northern slope of the Kunlun Mountains and are mainly recharged by glacier and snow meltwater, they show pronounced spatial differences in TDS, major ion composition, and hydrochemical facies. These differences indicate that river hydrochemistry in the study area is controlled not only by regional climatic conditions, but also by basin lithology, river length, hydrological connectivity, evaporation, and groundwater–surface water interactions. The mean TDS concentrations of the six rivers range from 443 to 1343 mg L^{−1}, which are higher than the average values reported for major rivers in northwestern China [2,51], indicating relatively strong mineralization under arid climatic conditions. In the mountainous headwaters, weathering of Precambrian metamorphic rocks, granites, and carbonate rocks provides Ca²⁺, Mg²⁺, and HCO₃[−]. After the rivers enter the alluvial–proluvial plains, evaporite minerals such as gypsum and halite become more important sources of SO₄^{2−}, Na⁺, and Cl[−] [35]. Therefore, the general hydrochemical background of the six rivers reflects the combined effects of rock weathering, evaporite dissolution, evaporation, and ion exchange.

Among the six rivers, the Keriya River has the longest flow path and traverses mountainous areas, oases, and desert reaches. Along this mountain–oasis–desert gradient, vegetation cover decreases toward the middle and lower reaches, where sparse herbaceous and halophytic vegetation increases surface exposure and favors evaporation and salt mobilization from soils [44]. In the Yutian Oasis, meadow soils and brown desert soils are widely distributed and commonly affected by salinization. Long-term irrigation and leaching may continuously release soluble ions, especially Na⁺, Cl[−], and SO₄^{2−}, into surface water and shallow groundwater [52]. These factors provide the hydrochemical background for the shift from Ca–SO₄-type water in the upper reaches to Na–Cl–SO₄-rich water in the middle and lower reaches of the Keriya River. In contrast, the Bostan, Nur, Kaxi, Buzang, and Uruksayi rivers have shorter flow paths, smaller drainage areas, and more limited elevation gradients; therefore, their hydrochemical evolution is generally weaker than that of the Keriya River. Among them, the Uruksayi River has the highest mineralization, which may be related to its relatively large drainage area, seasonal runoff concentration from June to August, strong evaporation, and reduced dilution during low-flow periods. After flowing through Uruksayi Township, the river also receives inflow from several tributaries, including the Yulong Dailiya River, Yulong Kandailiya River, and Wutan Lake Dailiya River [53]. These tributary inputs may extend water–rock interaction, enhance salt leaching, and promote the enrichment of Na⁺, Cl[−], and SO₄^{2−}. Grassland degradation, land desertification, and ecological fragility in the mountainous region may further facilitate salt accumulation and transport into the river system. By comparison, the Bostan River shows lower mineralization because of its shorter flow path and carbonate-dominated drainage area, whereas the Nur River is mainly recharged by glacier and snowmelt with relatively low initial dissolved salt concentrations. Regulation by the Nur Water Conservancy Project may further enhance dilution by releasing low-mineralization water during the dry season and irrigation period. Therefore, the overall differences in hydrochemical composition among the rivers are primarily related to lithology, flow path length, evaporation intensity, drainage area, tributary inflow, and water-source mixing.

Abrupt changes in ion concentrations at some sampling sites further indicate the influence of local hydrological conditions on river hydrochemistry. In the Keriya River, Na⁺, Cl[−], SO₄^{2−}, and HCO₃[−] concentrations increase markedly after KR-19, where the river enters the Yutian Oasis and flows near Yutian County town. Because ion concentrations remain relatively stable from KR-1 to KR-18, the several-fold increase after KR-19 is difficult to explain solely by evaporative concentration, water–rock interaction, evaporite dissolution, or cation exchange. Instead, it may be associated with external inputs related to oasis

irrigation activities, including possible irrigation return flow and mixing with relatively mineralized shallow groundwater. A smaller anomaly occurs near KR-26, where Na^+ , Cl^- , and SO_4^{2-} continue to increase whereas HCO_3^- decreases. This section is close to the oasis margin and gradually transitions toward the downstream reach, with industrial activities occurring near villages along the river. Therefore, this change may be associated with enhanced evaporative concentration in the lower reach, calcite precipitation, or localized industrial influence. The other five rivers also show abrupt or discontinuous hydrochemical changes at some sampling sites. In the Bostan River, SO_4^{2-} and Ca^{2+} decrease markedly between BS-3 and BS-4, possibly due to dilution by low-mineralization water. Lateral inflow from tributaries such as the Kalasu River or groundwater exchange may provide a relatively low-solute water source. The renewed increase in ion concentrations from BS-10 to BS-12 occurs where the river flows near several villages and surrounding human activities become more intense. These activities may promote salt mobilization and solute input, causing river hydrochemistry to shift again toward higher mineralization. In the Uruksayi River, the abrupt increase in ion concentrations at UK-11 followed by a rapid decrease at UK-12 may be related to local channel morphology. Near UK-11, the river splits into two channels, and the channel morphology may influence local mixing processes, making the contribution of a mineralized water source more apparent. At UK-12, the two channels merge again, and more complete mixing and dilution may cause the high ion concentrations observed at UK-11 to decrease rapidly. In the Kaxi River, several ions decrease synchronously at KX-9. This site has not yet entered the downstream desert reach and is located in a riparian zone with relatively well-developed vegetation on both banks. The decrease in ion concentrations may be attributed to dilution by relatively low-mineralization water sources or to local geochemical processes that remove dissolved ions, such as mineral precipitation or ion exchange. In the Buzang River, ion concentrations do not continue to increase at the final sampling site, possibly because tributary inflow from the Akesayi River branch between BZ-11 and BZ-12 introduces relatively dilute water and produces a dilution effect. In the Nur River, Na^+ , Cl^- , and SO_4^{2-} decrease markedly after NR-6, suggesting that this change is unlikely to be dominated by water–rock interaction and is possibly related to the influence of nearby reservoir regulation.

Correlation analysis and PHREEQC simulation further indicate that the Keriya River is affected by multiple geochemical processes. Ca^{2+} is significantly negatively correlated with Na^+ , Cl^- , and SO_4^{2-} in the Keriya River, unlike the relationships observed in the other five rivers. This pattern suggests a shift from Ca-dominated water in the upper reach toward Na- and Cl-rich water in the middle and lower reaches. The negative relationship between $(\text{Ca}^{2+} + \text{Mg}^{2+} - \text{HCO}_3^- - \text{SO}_4^{2-})$ and $(\text{Na}^+ + \text{K}^+ - \text{Cl}^-)$, together with the PHREEQC inverse modeling results, supports the occurrence of evaporite dissolution, carbonate precipitation, and cation exchange. Halite and gypsum dissolution contribute Na^+ , Cl^- , and SO_4^{2-} , whereas carbonate precipitation and cation exchange partly remove Ca^{2+} and promote Na^+ enrichment. These geochemical reactions provide an important basis for understanding the hydrochemical characteristics of the Keriya River, while local hydrological inputs and short-distance mixing may further modify ion concentrations at specific reaches. Therefore, the hydrochemical evolution of the Keriya River should be interpreted as the combined result of natural geochemical processes and possible local external influences. Similar hydrochemical complexity has been reported in other arid river systems, including the Pecos River in the United States, the Cooper Creek and Warrego River systems in Australia, and the Syr Darya River in Central Asia [54–56]. These rivers are all located in arid or semi-arid environments where evaporation, water–rock interaction, and soluble salt accumulation can strongly influence river chemistry. However, the dominant mechanisms differ among systems. In the Pecos River, salinity increase has been mainly linked

to groundwater–surface water interaction and the inflow of saline groundwater. In the Cooper Creek and Warrego River systems, hydrochemical variability is strongly controlled by episodic floods, no-flow periods, and changes in channel connectivity, which regulate dilution, concentration, and salt redistribution. In the Syr Darya River, river chemistry is substantially affected by intensive irrigation, return flow, reservoir regulation, and water diversion in a highly managed arid basin. By comparison, the Keriya River flows through a typical mountain–oasis–desert continuum, where evaporite-bearing alluvial–proluvial sediments, saline oasis soils, irrigation activities, shallow groundwater exchange, and local hydrological mixing jointly shape river hydrochemistry. Therefore, although arid-zone rivers may share some common controls, such as evaporation and water–rock interaction, their hydrochemical evolution pathways are strongly dependent on local geological settings, hydrological connectivity, and human activities.

The irrigation water quality assessment indicates that the Keriya River generally has potential for agricultural irrigation. However, irrigation suitability decreases in parts of the middle and lower reaches, mainly because of increased salinity rather than a proportional increase in sodium hazard. Previous studies have shown that agricultural irrigation accounts for approximately 98% of total water consumption in the Yutian Oasis, while irrigation withdrawals account for about 63% of the natural runoff of the Keriya River [57]. Intensive irrigation may reduce river discharge, enhance evaporative concentration, and promote the return of saline water to the river system. Therefore, water-quality monitoring should be strengthened from the oasis section to the lower desert reach, and appropriate irrigation and drainage management should be adopted to reduce the risk of soil salinization.

This study was primarily based on samples collected during the summer season and did not quantitatively distinguish the relative contributions of natural processes and anthropogenic activities. In addition, the interpretation of abrupt hydrochemical changes is partly constrained by the limited availability of detailed field information on the surrounding environment of the sampling sites, including nearby tributaries and local hydrological conditions. Therefore, the proposed explanations should be regarded as possible mechanisms and further examined through future field investigations. Future research should combine long-term hydrochemical monitoring, stable isotope analyses, groundwater observations, and more detailed pre-sampling surveys of the surrounding environment to better quantify the mechanisms controlling hydrochemical evolution in arid inland rivers.

5. Conclusions

The six rivers in the study area are generally weakly alkaline, with a mean pH of 8.04 and TDS values ranging from 36 to 1620 mg L^{−1}. Clear spatial differences in hydrochemical characteristics were observed among the rivers. The Keriya River showed the most pronounced hydrochemical contrast between the upper and middle–lower reaches, with hydrochemical facies shifting from Ca–SO₄ type to Na–Cl–SO₄ type. The Bostan and Nur rivers were mainly characterized by Ca–SO₄·HCO₃-type water, the Uruksayi and Buzang rivers by Ca·Na–SO₄·Cl-type water, and the Kaxi River by mixed Na·Ca–Cl·SO₄·HCO₃-type water. The Kaxi River exhibited the most stable hydrochemical composition, characterized by the weakest overall slopes of major ion concentrations among the six rivers. In contrast, the Uruksayi River showed the highest mineralization, with a mean TDS of 1343 mg L^{−1}, and displayed the largest overall longitudinal slopes of major ion concentrations.

Correlation analysis, Gibbs diagrams, and ion-ratio analysis indicate that the dominant hydrochemical processes differ among the six rivers. Carbonate weathering is more important in the Bostan and Nur rivers, the Kaxi River is mainly controlled by rock weathering with a secondary influence of evaporative concentration, and evaporite dissolution is

more pronounced in the Uruksayi and Buzang rivers. In the Keriya River, the increases in $\text{Cl}^-/(\text{Cl}^- + \text{HCO}_3^-)$, $\text{Na}^+/(\text{Na}^+ + \text{Ca}^{2+})$, and TDS from the upper to the middle–lower reaches indicate stronger evaporite dissolution, evaporative concentration, and Na enrichment. PHREEQC inverse mass-balance modeling further shows that halite dissolution, gypsum dissolution, dolomite dissolution, calcite precipitation, and forward cation exchange jointly influence the hydrochemical composition of the Keriya River. In addition to natural factors, river hydrochemistry may also be influenced by human activities and various other external inputs.

Principal component analysis extracted two principal components explaining 86.0% of the total variance. PC1 represents the overall enrichment of major dissolved ions and the degree of mineralization, with the middle and lower reaches of the Keriya River showing relatively high scores. PC2 reflects carbonate-related hydrochemical variations, with the Bostan River showing the highest scores.

The irrigation suitability assessment indicates that all river waters belong to the S1 sodium hazard class, whereas salinity hazard varies considerably among rivers. The Nur River provides the most suitable irrigation water, whereas irrigation use of the Uruksayi River, Buzang River, and the middle–lower reaches of the Keriya River is more strongly constrained by elevated salinity. These results provide scientific support for regional water-resource allocation, irrigation management, and salinity control along the southern margin of the Tarim Basin.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w18151896/s1>, Table S1: Geographical coordinates: geographical coordinates of sampling sites and distances between adjacent sampling points along each river; Table S2: Trend–line equations for major ion variations along the river courses; Figure S1. Relationships between Ca^{2+} and EC, SO_4^{2-} and EC.

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