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An Assessment of Collector-Drainage Water and Groundwater—An Application of CCME WQI Model

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Abstract

According to Victor Ernest Shelford's 'Law of Tolerance,' organisms within ecosystems thrive optimally when environmental conditions are favorable. Applying this principle to ecosystems and agro-ecosystems facing water scarcity or environmental challenges can significantly enhance their productivity. In these ecosystems, phytocenosis adjusts its conditions by utilizing water with varying salinity levels. Moreover, establishing optimal drinking water conditions for human populations within an ecosystem can help mitigate future negative succession processes. The purpose of this study is to evaluate the quality of two distinct water sources in the Amudarya district of the Republic of Karakalpakstan, Uzbekistan: collector-drainage water and groundwater at depths of 10 to 25 m. This research is highly relevant in the context of climate change, as improper management of water salinity, particularly in collector-drainage water, may exacerbate soil salinization and degrade drinking water quality. The primary methodology of this study is as follows: The Food and Agriculture Organization of the United Nations (FAO) standard for collector-drainage water is applied, and the water quality index is assessed using the CCME WQI model. The Canadian Council of Ministers of the Environment (CCME) model is adapted to assess groundwater quality using Uzbekistan's national drinking water quality standards. The results of two years of collected data, i.e., 2021 and 2023, show that the water quality index of collector-drainage water indicates that it has limited potential for use as secondary water for the irrigation of sensitive crops and has been classified as 'Poor'. As a result, salinity increased by 8.33% by 2023. In contrast, groundwater quality was rated as 'Fair' in 2021, showing a slight deterioration by 2023. Moreover, a comparative analysis of CCME WQI values for collector-drainage and groundwater in the region, in conjunction with findings from Ethiopia, India, Iraq, and Turkey, indicates a consistent decline in water quality, primarily due to agriculture and various other anthropogenic pollution sources, underscoring the critical need for sustainable water resource management. This study highlights the need to use organic fertilizers in agriculture to protect drinking water quality, improve crop yields, and promote soil health, while reducing reliance on chemical inputs. Furthermore, adopting WQI models under changing climatic conditions can improve agricultural productivity, enhance groundwater quality, and provide better environmental monitoring systems.

Keywords: collector-drainage water; groundwater; ecological factors; sensitive and insensitive crops; CCME WQI model

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1. Introduction

The quality of water resources in Central Asian countries is primarily influenced by geological and abiotic factors such as rainfall and anthropogenic activities, particularly agriculture. In several regions within this vast ecosystem, the scarcity of water resources necessitates the continuous monitoring and protection of surface and groundwater. Groundwater, often found at depths of 10–25 m in arid ecosystems, plays a critical role in supporting the adaptation of living organisms [1–9]. Given that Central Asia is predominantly an agricultural region, the rational use and improved condition of water and soil resources demand constant observation. For instance, approximately 70% of irrigated land in Uzbekistan is affected by salinity, which poses a significant challenge for sustainable agricultural practices [10–17]. Previous research highlighted that soil salinity has escalated, partly due to the use of groundwater for irrigation in agricultural lands [10,12,18–21].

In 2008, 17.4% of a total of 743.5 thousand hectares of land, and 27.5% of 1182.9 thousand hectares in 2010, were affected by high groundwater levels, with the water table rising to within 1–2 m of the soil surface. This issue is often exacerbated when groundwater seepage occurs near the surface [7,22–24].

In 2023, the State Committee for Land Resources, Geodesy, Cartography, and State Cadastres of Uzbekistan reported that 46.6% of irrigated land was saline, with 2.5% classified as strongly saline, 13.3% as moderately saline, and 30% as slightly saline.

The salinity and mineral content of the studied water bodies—collector-drainage water and groundwater at a depth of 10–25 m—are increasing, primarily due to anthropogenic factors, namely agricultural activities [6,10,16].

The Ministry of Water Management of Uzbekistan (MoWR) also reported that in 2023, the Amudarya district of the Republic of Karakalpakstan had a total of 39,515 hectares of irrigated land, with 70.6% classified as saline. In this area, 2.5% was highly saline land, 35% was moderately saline cropland, and 33.1% was slightly saline land.

In this ecosystem, the proximity of groundwater, Quaternary deposits, and agricultural practices are key factors influencing the mineralization of underground drinking water. Significant amounts of salt accumulate in the upper soil layers due to evaporation caused by seepage waters, resulting in the severe salinization of soil resources. This process is further aggravated by the crystallization of salts on the soil surface, primarily driven by sodium (Na^+) ions, which impede water infiltration [10–17,25,26].

The Quaternary deposits in the Amudarya delta, consisting of sand and soil, allow for easy surface water transfer, further contributing to the salinization problem [11–15].

Improper management of open drains in agricultural landscapes can raise groundwater levels, leading to the secondary salinization of cultivated areas. Groundwater resources in Uzbekistan have decreased by 40% between 1965 and 2002 due to overuse, and in the arid western and southern regions, groundwater consumption has exceeded sustainable limits. This overexploitation has exacerbated water scarcity in these regions, a problem that persists today [10,12–15].

Additionally, the discharge of collector-drainage waters into river ecosystems, combined with the misuse of chemicals in agriculture, has further degraded groundwater quality [17,24].

Consequently, clean underground water used for drinking purposes in regions such as Bukhara, Khorezm, and the Republic of Karakalpakstan no longer meets GOST standards for potable water [10–13,15,18,22].

Increased soil salinity severely degrades soil quality and reduces crop productivity. The rise in salinity, particularly during the crop growing season, delays yields and decreases agricultural output [1,3,11].

Soil salinity has become a major environmental issue in Central Asia, severely impacting agriculture and soil quality. The area of saline soil in the region covers almost 91.5 million hectares. The most severe cases of this problem occur in the south of the Republic of Kazakhstan and in the Republics of Uzbekistan and Turkmenistan. This increase in salinity is largely due to the drying up of the Aral Sea and unsustainable agricultural irrigation practices. These factors have led to a rise in salt accumulation in the soil, reducing soil fertility and crop yields, which threatens food security in the region. Addressing this issue requires sustainable farming and water management strategies to prevent further degradation [10,27,28].

On a global scale, soil salinity has rendered 20% of irrigated land across more than 100 countries unusable, with this figure continuing to rise due to climate change [15,29].

This study focuses on the collector-drainage waters and underground drinking water affected by salt-washing practices in agricultural fields within the agrocenoses of the Republic of Karakalpakstan.

The two main research objects identified in the study, the first object—collector-drainage water and the second object—groundwater, are located in the Amudarya region in the southern part of Karakalpakstan, Uzbekistan.

The Amudarya district is located in the southwestern part of Uzbekistan, covering an area of 1020 square kilometers. The climate is sharply continental, characterized by significant temperature variations between winter and summer. In January, the average temperature drops to between −16 °C and −20 °C, while in July, it rises to between 27 °C and 32 °C. The annual precipitation is very low and averages 100–110 mm. This causes the formation of dry climatic conditions in this region. Geographically, the district is situated at 39°13′30″ north latitude and 64°41′02″ east longitude [30].

The region experiences highly variable climatic conditions and is primarily focused on agricultural production. A large amount of cotton and wheat is grown in the agrocenoses. Given these conditions, there is a constant need to wash away the salts that accumulate in the upper layers of the soil.

1.1. Aims and Objectives of This Study

The main aim of this study is to assess the water quality index of the surface and groundwater in the Amudarya region of the Republic of Karakalpakstan. The objectives of this study are as follows:

1. To evaluate the salinity levels of collector-drainage and groundwater.
2. To analyze the changes in water quality during the phenological phases of agro-cenoses.
3. To assess the water quality of two research sites, according to FAO and WHO standards, using the CCME WQI model.
4. Develop recommendations based on the results of the research.

1.2. Statement of Problem

The Amudarya region of Karakapakstan is experiencing significant challenges with water quality in both its collector-drainage water and groundwater, which are critical for agricultural productivity and safe drinking water. However, there is insufficient understanding of the current status and trends of water quality in this region, particularly under the impacts of irrigation practices, climatic variations, and chemical inputs. The existing water quality data lacks comprehensive analysis using standard models, making it difficult to accurately assess and manage water quality. This study aims to apply the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) model to assess the water quality of collector-drainage water and groundwater, providing a clear understanding of their status, identifying critical pollutants, and suggesting sustainable management practices.

1.3. Justification for the Study

The Amudarya region of Karakalpakstan is a critical agricultural zone heavily dependent on collector-drainage water and groundwater for irrigation. However, the increasing use of chemical fertilizers, climate variability, and inefficient irrigation practices have raised concerns about the quality of these water sources. Given that water quality is directly linked to crop productivity, human health, and ecological sustainability, it is essential to have a clear understanding of its current status.

While water quality monitoring is conducted in the region, the available data are often scattered, lack standardization, and provide limited insight into the overall water quality. The application of the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) model in this study is justified as it provides a standardized, comprehensive, and easily interpretable assessment of water quality.

This study will not only identify the current status of water quality but also highlight the major pollutants affecting it and propose sustainable management practices. Such information is critical for policymakers, water resource managers, and local farmers to ensure the sustainable use of water resources in the Amudarya region.

1.4. Research Questions

1. What is the current quality of collector-drainage water and groundwater in the Amudarya region of Karakalpakstan, determined based on the CCME WQI model?
2. What are the main pollutants affecting the quality of these water sources?
3. How do seasonal variations and agricultural practice influence the water quality of collector-drainage water and groundwater?
4. What sustainable water management practices can be recommended based on the assessment findings?

1.5. Research Significance

Water quality is a critical aspect of environmental sustainability, human health, and agricultural productivity. In regions dependent on irrigation, such as the Amudarya region of Karakalpakstan, understanding water quality dynamics is essential due to the heavy reliance on surface and groundwater resources for agricultural practices. Collector-drainage water, primarily derived from irrigation activities, and groundwater are the two primary water sources in this region. However, both sources face significant threats from salinity, nutrient contamination, and chemical residues resulting from intensive agricultural practices.

Despite the importance of these water resources, there is an insufficient understanding of their current status and trends, particularly under the impact of irrigation, climate variability, and the use of chemical inputs. Conventional water quality monitoring often provides fragmented data, making it difficult to assess the overall health of these water bodies and develop effective management strategies.

To address this gap, this study applies the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) model to assess the water quality of collector-drainage water and groundwater in the Amudarya region. The CCME WQI model offers a standardized approach to evaluating water quality by incorporating multiple parameters into a single, easy-to-interpret index. Through this approach, this study aims to provide a clear understanding of the current water quality status, identify critical pollutants, and recommend sustainable water management practices to ensure the long-term viability of water resources in the region.

2. Materials and Methods

2.1. Study Area and Laboratory Methods

Naturally, the quality of collector-drainage water is often very poor. This is because such water is primarily used in agriculture to improve the soil conditions of crop fields through the 'salt-washing method' by farmers or local populations. At times, when there is a shortage of surface water for irrigation, this water is typically used as an alternative. However, before using it, it is crucial to assess the water quality. Based on this assessment, measures to improve the water quality are then implemented. This study covered two years: 2021 and 2023. Since the results of the groundwater samples collected in 2022 were almost the same as those in 2021, the data for the year 2022 were excluded. In order to clearly distinguish significant differences between the annual groundwater sample data in the statistical analysis, the data for the year 2022 were not included in this study. To make the annual data of the two facilities the same, the data for collector-drainage water in 2022 were again not included.

Field studies were conducted to study the water composition of the two sites. In addition, data from the district sanitation and land reclamation departments were also used to collect sufficient data.

Collector-drainage water samples were taken monthly from a pond located in the area and analyzed in the Reclamation Expedition Laboratory and the Sanitary Hygiene Laboratory. Water samples were taken horizontally from the pond using special devices with grippers. Glass bottles with 1 L volume were used to collect water samples. Groundwater samples were collected from a total of 12 observation wells located in the area. Water samples were taken vertically from the wells. Sterilized plastic bottles with 1 L volume were used to collect samples. The map shown in Figure 1 below shows the geographical location of the Amudarya district and the two study sites from which water samples were taken. In addition, Figure S1 in the Supplementary Materials section presents a small image of the water sampling process, while Figure S2 illustrates the laboratory analysis of the collected water samples.

This research used laboratory analysis data on a total of 9 quality indicators of the collector-drainage water (EC, HCO_3^-, Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, Na^+, SAR, SAR (EC)).

Water quality was analyzed based on a total of 9 physicochemical indicators of groundwater (TH, Cl^-, SO_4^{2-}, TDS, F^-, Fe^{2+}, NO_3^-, Cu^{2+}, pH). These indicators for the composition of the two types of water were important in determining the overall quality of the water.

Below is a brief description of the main reagents and instruments used to determine the parameters in the composition of collector-drainage water in a laboratory setting, for a 1 L volume.

1. EC: Determined using a Conductometer [31,32].
2. HCO_3^-: Determined by titration with sodium bicarbonate ($NaHCO_3$) or sodium sulfate (Na_2SO_4) [33].
3. Cl^-: Determined by titration with silver nitrate ($AgNO_3$) [34].
4. SO_4^{2-}: Two drops of methyl orange ($C_{17}H_{19}N_3O_2$) and 2 N hydrochloric acid (HCl) were added, the mixture was boiled, then 10% barium chloride ($BaCl_2$) was added, and the solution was kept for one day. Afterward, it was boiled with distilled water (H_2O), washed five times, filtered through filter paper, and then placed in a crucible and ignited in a muffle furnace [35].
5. Ca^{2+} and Mg^{2+}: Determined by titration with Trilon B ($Na_3C_6H_5O_7$).
6. Na^+: Several methods are available for determining sodium ions. Among them, flame photometry, ion-selective electrodes (ISE), and caprotozel-colorimetric methods are commonly used. In flame photometry, sodium ions are atomized in the flame, and

their spectral lines are measured to determine concentration. In the ISE method, a specific electrode measures the potential difference of sodium ions. In the caprotozel-colorimetric method, sodium ions react with colored reagents, causing a color change that is used to determine their concentration [36].

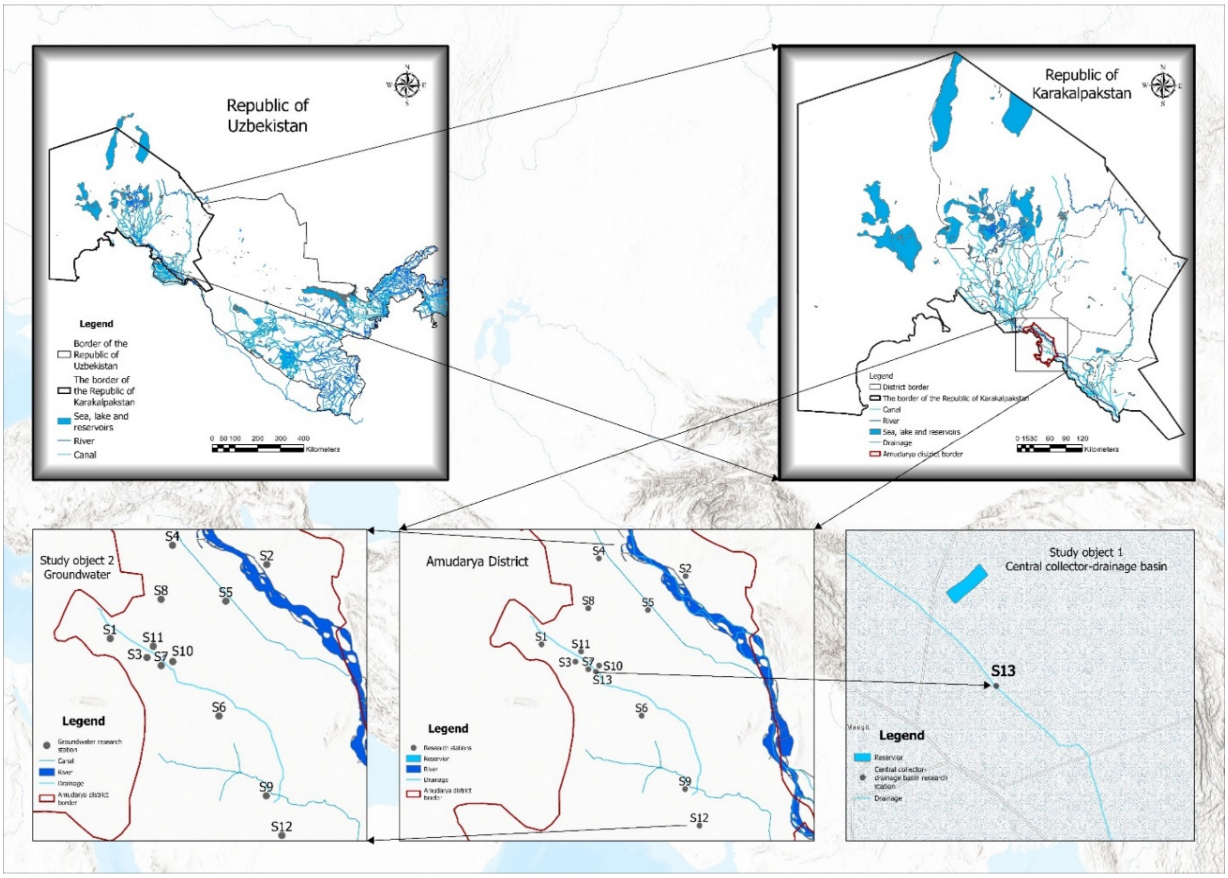


Figure 1. Sampling locations of study area (Uzbekistan, Republic of Karakalpakstan, Amudarya District).

To ensure the reliability and consistency of laboratory results in water quality assessment, standardized analytical methods are essential. For this purpose, internationally recognized standards are used to determine key physical and chemical parameters of groundwater or drinking water. These standards help in achieving comparable results across different laboratories and studies. The most relevant standards applied to the analysis of the nine main groundwater quality indicators are summarized in Table 1 below.

Table 1. Internationally recognized standards for laboratory methods used to analyze the nine main quality parameters of groundwater (or drinking water).

No.	Groundwater	
	Quality Indicators	**Standards**
1	TH	GOST 4151-72 (https://docs.cntd.ru/document/1200012550, accessed on 26 May 2025)
2	Cl^{-}	GOST 4245-72 (https://docs.cntd.ru/document/1200008214, accessed on 26 May 2025)
3	SO_4^{2-}	GOST 4389-72 (https://docs.cntd.ru/document/1200008215, accessed on 26 May 2025)
4	TDS	GOST 18164-72 (https://docs.cntd.ru/document/1200012556, accessed on 26 May 2025)

Table 1. *Cont.*

No.	Groundwater	
	Quality Indicators	Standards
5	F^-	GOST 4386-89 (https://docs.cntd.ru/document/1200012569, accessed on 26 May 2025)
6	Fe^{2+}	GOST 4011-72 (https://docs.cntd.ru/document/1200008210, accessed on 26 May 2025)
7	NO_3^-	GOST 33045-2014 (https://meganorm.ru/Data2/1/4293766/4293766954.htm, accessed on 26 May 2025)
8	Cu^{2+}	GOST 4388-72 (https://docs.cntd.ru/document/1200012572, accessed on 26 May 2025)
9	pH	GOST ISO 10523 (https://files.stroyinf.ru/Index2/1/4293739/4293739330.htm, accessed on 26 May 2025)

The results of the laboratory analysis of central collector-drainage water samples from the Amudarya district are presented in Table 2. This table outlines the measured values of nine key water quality indicators, which serve as the basis for assessing the chemical composition and overall suitability of the water for agricultural and environmental purposes.

Table 2. Average amounts of central collector-drainage water in the Amudarya district according to nine quality indicators.

Data	EC	HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^+	SAR	SAR (EC)
2021-01	5.01	8.73	19.06	20.04	18.33	13.00	16.74	4.23	4.23
2021-02	5.45	6.23	16.73	29.50	17.67	16.33	18.74	4.54	4.54
2021-03	5.38	6.37	21.85	24.60	15.67	18.33	19.12	4.64	4.64
2021-04	4.81	4.70	18.59	23.46	16.33	9.33	21.27	5.94	5.94
2021-05	4.19	5.90	14.87	19.70	15.33	12.67	12.70	3.39	3.39
2021-06	8.75	4.23	32.07	48.52	14.33	14.00	56.74	15.08	15.07
2021-07	6.49	4.40	23.24	35.42	13.67	14.00	35.64	9.58	9.58
2021-08	5.92	4.27	20.92	32.12	18.00	11.67	27.85	7.23	7.23
2021-09	4.46	3.17	16.27	23.92	11.67	12.33	19.56	5.65	5.65
2021-10	6.59	6.07	22.77	35.08	14.67	13.33	36.16	9.66	9.66
2021-11	5.34	5.27	20.45	25.63	17.00	9.33	25.19	6.94	6.94
2021-12	4.46	3.17	16.27	26.38	14.67	13.33	26.38	7.05	7.05
2023-01	5.07	5.10	18.13	27.78	13.67	5.58	15.36	4.95	4.95
2023-02	5.57	7.07	20.92	26.92	18.33	4.75	17.89	5.27	5.27
2023-03	4.86	5.27	18.13	25.35	17.67	4.58	13.05	3.91	3.91
2023-04	5.81	6.10	23.70	30.36	19.33	8.33	8.02	2.16	2.16
2023-05	6.69	5.67	29.75	31.91	17.33	5.75	27.37	8.06	8.06
2023-06	6.08	5.37	25.10	30.66	15.67	5.33	24.48	7.55	7.55
2023-07	6.54	5.07	22.77	35.97	12.00	4.58	33.77	11.70	11.73
2023-08	5.71	5.67	21.38	29.80	16.00	4.58	22.83	7.12	7.11
2023-09	5.36	4.77	20.45	28.67	20.67	4.75	14.54	4.08	4.08
2023-10	5.69	5.53	23.24	29.78	19.33	7.25	10.68	2.93	2.93
2023-11	5.38	8.95	30.68	40.49	31.50	6.00	25.04	5.78	5.78
2023-12	5.00	6.93	18.13	25.47	21.67	5.75	6.24	1.68	1.68
Units	dS/m	mEq/L							

2.2. Calculation of SAR

The sodium adsorption ratio (SAR) is a key parameter for evaluating the potential impact of irrigation water on soil structure. High SAR levels lead to increased sodium accumulation in the soil, which adversely affects soil infiltration and percolation, thereby causing soil compaction and reduced aeration, both of which are detrimental to plant health. In addition, electrical conductivity (ECw) and total dissolved solids (TDS) are critical for assessing salt-related risks in water. While a high ECw can help mitigate the adverse effects of sodium, it simultaneously deteriorates overall water quality [1–3,37].

$$SAR = \frac{Na^{+}}{\left\{\frac{\left([Ca^{+2}]+[M_g^{+2}]\right)}{2}\right\}^{1/2}} \quad (1)$$

The formula for calculating SAR is based on the ratio of sodium to the calcium and magnesium concentrations. Prior to SAR calculation, the masses of Na^+, Ca^{+2}, and Mg^{+2} ions, originally measured in mg/L, are converted to milliequivalents per liter (mEq/L) for consistency with international standards. This conversion facilitates the accurate analysis of water quality parameters. For example, according to the FAO standards, the limits for SAR in irrigation water—categorized as low, medium, and high for 'Sensitive and Insensitive Crops'—are expressed in mEq/L. The table below outlines the conversions from mg/L to mEq/L for several key parameters [1–5].

As shown in Table 3, the atomic weights, valencies, and concentrations of key cations and anions were used to calculate important indices such as SAR. This standardized approach ensures that SAR and its related parameters are interpreted accurately, contributing to the effective management of soil and water resources in agricultural systems.

Table 3. Atomic and molecular weights of the common cations and anions and their valencies.

Ion	Atomic Weight (AW)	Valence (V)	Laboratory Analysis Results (mg/L)
HCO_3^-	61.02	1	311.1
Cl^-	35.45	1	643.5
SO_4^{2-}	96.06	2	1333.32
Ca^{2+}	40.08	2	273.33
Mg^{2+}	24.31	2	268.00
Na^+	22.99	1	353.22

When converting ion concentrations from mg/L to milliequivalents per liter (mEq/L), the process involves using the atomic masses and valence of each ion, as listed in Dmitry Mendeleev's periodic table. The calculation method entails dividing the ion's concentration (in mg/L) by its atomic mass and valence, which allows for standardized comparison with laboratory results.

This procedure can be outlined as follows:

1. Determine the atomic mass and valence of each ion based on Mendeleev's periodic table.
2. Divide the ion concentration (mg/L) by its corresponding atomic mass to obtain the value in equivalents.
3. Adjust for valence by dividing by the ion's valence to convert the result to mEq/L. This method ensures an accurate comparison with laboratory-derived values and aligns the results with international standards for water quality analysis [37].
   e.g., HCO_3^- (mEq/L) = (1/61.02) × 311.1 = 5.10.

2.3. Importance Level of Quality Indicators

2.3.1. Collector-Drainage Water Quality Indicators

Enhancing the potential of irrigation water helps to study its impact on groundwater quality, crop yield, and soil health by determining compliance with the parameters that define water quality. Below is an analysis of the tolerance ranges of certain water quality parameters in irrigation water relative to plants [38]:

Electrical Conductivity (ECw):

In agriculture, EC is often used to evaluate the quality of irrigation water. High ECw values lead to increased salinity, resulting in a decline in groundwater quality, soil salinization, and restricted plant ability to absorb water from the soil. This ultimately disrupts the uptake of water and nutrients by plants. The optimal EC range for irrigation water is generally considered to be between 0 and 3 dS/m.

Calcium (Ca^{2+}):

Measured in milliequivalents per liter (me/L), the optimal concentration for plants is typically between 0 and 20 me/L. Calcium is essential for maintaining the integrity of plant cell walls and for root development.

Magnesium (Mg^{2+}):

The optimal amount of magnesium in irrigation water is usually between 0 and 5 me/L for plants. Magnesium is crucial for photosynthesis and enzyme function. A deficiency leads to chlorosis—a condition where plant leaves lose their green color due to a lack of chlorophyll, slowing down photosynthesis. As a result, leaves turn yellow, become smaller, fall off prematurely, and root hairs die. Excessive magnesium can also lead to increased total hardness (TH) in groundwater.

Bicarbonate (HCO_3^-):

The impact of bicarbonate on water quality is significant, as high levels (above 100 ppm) in irrigation water can lead to serious problems. When soils dry, bicarbonate reacts with calcium, causing sodium to become relatively dominant. This results in the formation of a thin, sodium-rich surface layer, which restricts water infiltration and increases surface runoff. Additionally, bicarbonate has a toxic effect on roots, slows down plant growth, and reduces the uptake of phosphorus and micronutrients. Under rapid evaporation conditions, white calcium carbonate deposits may form on plants and fruits. Therefore, bicarbonate levels exceeding 200 ppm pose a serious threat to water quality.

Chloride ions (Cl^-)

From a scientific perspective, the impact of chloride on water quality is significant, as high concentrations of chloride ions (Cl^-) negatively affect the physiological processes of plants. Specifically, chloride levels exceeding 200 ppm are considered phytotoxic for many row crops. In overhead (sprinkler) irrigation systems, the direct exposure of foliage to chloride can lead to leaf burn (necrosis) or leaf drop, especially under high evaporation conditions. In contrast, such adverse effects are less pronounced in gravity (surface or furrow) irrigation methods. Although plant species vary in their tolerance to chloride, most cultivated crops can grow normally when chloride concentrations remain below 200 ppm. Therefore, exceeding this threshold in irrigation water can lead to a decline in water quality and adversely affect crop productivity.

2.3.2. Groundwater Quality Indicators

In the assessment of groundwater quality, not only the chemical composition but also the hydrogeological conditions play crucial roles. In particular, there is a strong correlation between water table elevation, soil moisture, and the degree of salinization. In saline soils, when the water table is close to the surface, salts tend to rise through capillary action, leading to soil degradation and a deterioration in groundwater quality.

In this study, groundwater samples were taken from wells located at depths ranging from 10 to 25 m below the surface. A comparison between the water samples taken at 10 m and those from 25 m revealed significant differences. It became evident that as the depth of groundwater increased, the water quality tended to improve. However, this was accompanied by a parallel increase in water mineralization [39,40].

Total hardness (TH):

The total hardness (TH) of drinking water significantly influences both its quality and practical use in daily life. TH is primarily determined by the concentrations of calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions. Elevated levels of these ions reduce soap lathering efficiency and lead to the formation of scale deposits in pipes and heating systems, thereby decreasing the efficiency of heat exchange processes. Conversely, excessively soft water (very low hardness) can induce corrosion in metal pipelines, increasing the risk of heavy metals such as lead and copper leaching into the drinking water [41].

Total dissolved solids (TDS):

The concentration of total dissolved solids (TDS) in drinking water directly affects its taste, quality, and safety. TDS primarily consists of beneficial ions such as calcium, magnesium, sodium, and potassium. However, when present in concentrations exceeding recommended limits (typically above 1000 mg/L), elevated TDS levels may indicate contamination from anthropogenic sources such as agricultural runoff and the excessive use of fertilizers. High TDS not only deteriorates the organoleptic properties of water (taste and odor) but also contributes to the formation of scale deposits in heating systems and may increase the presence of harmful heavy metals, such as nitrates or lead, posing potential health risks [42].

Sulfate ions ($SO_4{}^{2-}$):

High concentrations of sulfate in drinking water are considered hazardous to human health. When sulfate levels exceed 500 mg/L, they can cause health issues such as diarrhea, nausea, and inflammation of the intestines. Therefore, regularly monitoring the sulfate content in drinking water is crucial for ensuring water quality and public health [43].

Nitrate anions ($NO_3{}^{-}$):

High nitrate concentrations in drinking water pose significant health risks, especially in agricultural regions. Elevated nitrate levels can lead to methemoglobinemia (blue baby syndrome), cancer, and other adverse health effects. Therefore, the continuous monitoring of nitrate levels in drinking water is crucial to ensure public health safety [44].

Copper cations (Cu^{2+}):

High concentrations of copper in drinking water can lead to health issues such as gastrointestinal problems and liver and kidney damage. However, low concentrations of copper are beneficial for the body, supporting the activity of metalloenzymes and proteins [45].

Iron cations (Fe^{2+}):

Elevated concentrations of iron in water do not pose an immediate direct health risk; however, they may increase water hardness, which can cause issues in daily use. Increased iron levels can interact with other minerals in the water, potentially disrupting the mineral balance in the human body. Additionally, excessive iron intake may lead to gastrointestinal issues, including problems in the stomach and intestines [46].

2.4. Adaptation of the CCME WQI Model to the Food and Agriculture Organization Standard for Crop Irrigation

To draw comprehensive conclusions from complex monthly and annual statistical data on the studied water bodies, "The Water Quality Index of the Canadian Council of Ministers of the Environment (CCME WQI)" was adapted to suit the specific environmental and hydrological conditions of Uzbekistan. This model is recognized as an effective tool for assessing water quality.

The CCME WQI integrates three key components: Scope (F_1), Frequency (F_2), and Amplitude (F_3). These elements are crucial in quantifying the extent of water quality deviations. Specifically, the model allows for the expression of negative water quality changes by evaluating these factors, thereby providing a structured and standardized approach to water quality assessment [26,45–48].

Calculate the index

Step 1. Calculating the scope value (F_1):

$$F_1 = \left(\frac{\text{number offailed variables}}{\text{Total number of variables}}\right) \times 100 \quad (2)$$

Step 2. F_2:

$$F_2 = \left(\frac{\text{number offailed tests}}{\text{Total number of tests}}\right) \times 100 \quad (3)$$

Step 3.1. F_3:

$$\text{excursion}_i = \left(\frac{\text{Failed test value}_i}{\text{Objective}_i}\right) - 1 \quad (4)$$

Step 3.2.:

$$\text{nse} = \frac{\sum_{i=1}^{n} \text{excursion}_i}{\text{total number of tests}} \quad (5)$$

Step 3.3.:

$$F_3 = \left(\frac{\text{nse}}{0.01\text{nse} + 0.01}\right) \quad (6)$$

Calculation of total water quality based on F_1, F_2, and F_3:

$$\text{CCME WQI} = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732}\right) \quad (7)$$

Using the CCME-WQI values, water quality classification is divided into five classes, as follows:

1. 95–100 (Excellent): Water quality is protected with a virtual absence of threat or impairment; conditions are very close to natural or pristine levels.
2. 80–94 (Good): Water quality is protected with only a minor degree of threat or impairment; conditions rarely depart from natural or desirable levels.
3. 65–79 (Fair): Water quality is usually protected but occasionally threatened or impaired; conditions sometimes depart from natural or desirable levels.
4. 45–64 (Marginal): Water quality is frequently threatened or impaired; conditions often depart from natural or desirable levels.
5. 0–44 (Poor): Water quality is almost always threatened or impaired; conditions usually depart from natural or desirable levels.

The water quality index (WQI) for Object 1 was specifically formulated to assess the suitability of water for 'sensitive and insensitive crops' cultivated within agricultural systems, while Object 2 was tailored to evaluate the water quality for human consumption. This differentiation arose from the declining water levels in the Amu Darya River, which necessitated the utilization of collector-drainage water as a supplementary irrigation source in agriculture.

Utilizing the CCME WQI model to ascertain the overall quality of Object 1 facilitated the application of natural treatment methods, thereby enabling its use as secondary water and aiding in the normalization of salinity concentrations. The categorization established through the CCME WQI provided a framework for determining the feasibility of utilizing these waters for crop irrigation within agrocenoses. Notably, saline water can be effectively employed for irrigating certain crops that are capable of thriving in saline environments. The appropriate management of saline conditions creates optimal growing conditions for salt-tolerant plants, thereby enhancing agricultural productivity in areas developed based on the CCME WQI model [20,21,23,26,39]. Table 4 below presents the levels of impact on crops of some quality indicators in irrigation water according to FAO standards [38].

Table 4. Methods for assessing the quality of irrigation water according to the FAO guideline.

Parameter	Units	Degree of Restriction on Use		
		None	Slight to Moderate	Severe
EC	dS/m	<0.7	0.7–3.0	>3.0
HCO_3^-	mEq/L	<1.5	1.5–8.5	>8.5
Cl^-	mEq/L	<4	4–10	>10
Na^+	mEq/L	<3	3–9	>9
SAR	mEq/L	<3	3–9	>9

The classification of collector-drainage water quality based on electrical conductivity of water (ECw) and sodium adsorption ratio (SAR) is presented in Table 5. According to the FAO guidelines, this classification provides a framework for determining the severity of salinity and sodicity hazards in irrigation water, which is essential for sustainable agricultural water management.

Table 5. Evaluation of collector-drainage water quality using ECw and SAR (FAO).

			None	Slight to Moderate	Severe
SAR	0–3	EC_w	>0.7	0.7–0.2	<0.2
	3–6		>1.2	1.2–0.3	<0.3
	6–12		>1.9	1.9–0.5	<0.5
	12–20		>2.9	2.9–1.3	<1.3
	20–40		>5.0	5.0–2.9	<2.9

3. Results

3.1. Calculation of the Collector-Drainage Water Quality Index with the CCME WQI Method

The annual water quality index (WQI) values for the years 2021 to 2023 were calculated for Object 1, encompassing 'Sensitive' and 'Insensitive crops', in accordance with FAO standards. The outcomes of these calculations are summarized in Table 6, where values that fall outside of the FAO guidelines are highlighted in red. The formulation of the CCME WQI model, as described in Section 2, was utilized for this analysis. To enhance efficiency in developing the water quality indices and ensure precision in the results, the Excel program was employed for the automation of the calculation process. Leveraging the capabilities of this software facilitated the execution of the subsequent computational tasks.

Table 6 presents the WQI calculation data for six key physicochemical indicators of the 'Central' collector-drainage water (study Object 1) from the Amudarya district over the period January 2021 to December 2023. The parameters measured monthly include electrical conductivity (EC), bicarbonate (HCO_3^-), chloride (Cl^-), sodium (Na^+), sodium adsorption ratio (SAR), and SAR adjusted by EC (SAR (EC)). The values are compared against FAO irrigation water quality standards provided at the bottom of the table. This detailed data enables assessment of temporal variations in water quality and helps evaluate its suitability for irrigation of sensitive crops by identifying potential salinity and sodicity risks in the water source.

Table 6. WQI calculation table of nine physicochemical indicators of 'Central' collector-drainage water (study Object 1) in the Amudarya district in relation to 'sensitive crops'.

Data	EC	HCO_3^-	Cl^-	Na^+	SAR	SAR (EC)
2021-01	5.07	5.10	18.13	15.36	4.95	4.95
2021-02	5.57	7.07	20.91	17.89	5.27	5.27
2021-03	4.86	5.27	18.13	13.05	3.91	3.91
2021-04	5.81	6.10	23.70	8.02	2.16	2.16
2021-05	6.69	5.67	29.75	27.37	8.06	8.06
2021-06	6.08	5.37	25.09	24.47	7.55	7.55
2021-07	6.55	5.07	22.77	33.77	11.73	11.73
2021-08	5.71	5.67	21.38	22.82	7.11	7.11
2021-09	5.36	4.77	20.45	14.54	4.08	4.08
2021-10	5.69	5.53	23.24	10.68	2.93	2.93
2021-11	5.37	8.95	30.68	25.04	5.78	5.78
2021-12	5.00	6.93	18.13	6.24	1.68	1.68
2023-01	5.01	8.73	19.06	16.74	4.23	4.23
2023-02	5.45	6.23	16.73	18.74	4.54	4.54
2023-03	5.38	6.37	21.84	19.12	4.64	4.64
2023-04	4.81	4.70	18.59	21.27	5.94	5.94
2023-05	4.19	5.90	14.87	12.69	3.39	3.39
2023-06	8.75	4.23	32.07	56.74	15.07	15.07
2023-07	6.49	4.40	23.24	35.64	9.58	9.58
2023-08	5.92	4.27	20.91	27.85	7.23	7.23
2023-09	4.46	3.17	16.27	19.57	5.65	5.65
2023-10	6.59	6.07	22.77	36.16	9.66	9.66
2023-11	5.34	5.27	20.45	25.19	6.94	6.94
2023-12	4.46	3.17	16.27	26.38	7.05	7.05
FAO standard	0.7	1.5	4	3	3	3
Units	dS/m			mEq/L		

Note: Values of indicators that do not comply with the FAO guidelines are marked in red.

The data presented in Table 6 indicate that, during the year 2021, a total of six indicators failed to comply with the FAO guidelines. Thus, the values can be summarized as follows:

X = 6, Y = 6,

Z = 72, E = 66.

Step 1. F_1 = 100.

Step 2. F_2 = 91.67.

Step 3.1. C = $excursion_i$ = 258.60.

Step 3.2.

nse = 3.59.

The results of the final calculation for the F3 component of the WQI are summarized in Table 7.

Table 7. Step 3.3.: The value of F3.

nse Value	0.01 × nse	0.01 × nse + 0.01	F3
3.59	0.04	0.05	78.22

Table 8 presents the Water Quality Index (WQI) calculations based on commonly used physicochemical parameters for the collector-drainage water samples. This table summarizes the results that help evaluate the overall water quality and its suitability for agricultural use.

Table 8. WQI calculation using common parameters.

Component of CCME WQI	Value	Square Value
F1	100	10,000.00
F2	91.67	8402.78
F3	78.22	6118.59
	SUM	24,521.37
	Square Root Value	156.59
	Divide by 1.732	1.732
	D	90.41
		100
CCME WQI (study Object 1)		9.59

The Water Quality Index (WQI) values for the years 2021 to 2023 were calculated using Excel, yielding the following results:

Table 9 presents the results obtained from the CCME Water Quality Index (WQI) model applied to the collected water samples.

Table 9. The results of the CCME WQI model.

Years	Parameters			WQI	Sinflanishi
	F1	F2	F3		
2021	100	91.67	78.22	9.59	Poor
2023	100	100	79.96	6.20	Poor

3.2. Determining the Overall Water Quality Index of the Second Facility Through the CCME WQI Model

Object 2 was evaluated in accordance with the drinking water quality standards outlined in the National Standard of Uzbekistan No. 133:2024. The analysis revealed that the underground drinking water failed to meet both the National Standard and World Health Organization (WHO) guidelines [27,48–50]. During the sampling process from the wells associated with Object 2, interviews conducted with local residents indicated a significant reliance on this underground water source for drinking purposes. However, projections suggested that within the next five years, the quality of this water source may deteriorate to an unusable level. Utilizing the CCME WQI model, the groundwater quality index was established based on nine parameters: (Cl^-, SO_4^{2-}, TDS, F^-, Fe^{+2}, NO_3^-, Cu^{+2}, and pH). Table 10 below presents the analytical results of groundwater samples collected in 2021 and 2023 across these nine indicators.

In 2021, a total of three indicators associated with Object 2 were found to be non-compliant with the national standard. Therefore, the values were defined as follows: X = 3, Y = 9, Z = 108, and

E = 19.

Step 1. $F_1 = 33.33$.

Step 2. $F_2 = 17.59$.

Step 3.1. $C = excursion_i = 10.29$.

Step 3.2.

nse = 0.095.

Table 10. Calculation of WQI using the average amount of nine quality indicators (Object 2).

Data	Parameters								
	TH	**Cl^-**	**SO_4^{2-}**	**TDS**	**F^-**	**Fe^{2+}**	**NO_3^-**	**Cu^{2+}**	**pH**
2021-01	650.00	275.00	271.00	1260.00	0.18	0.16	9.70	0.13	7.80
2021-02	1105.00	308.00	364.20	1443.00	0.12	0.08	9.80	0.15	7.70
2021-03	600.00	221.00	271.00	1200.00	0.16	0.18	10.20	0.20	7.70
2021-04	1100.00	380.00	334.00	1700.00	0.15	0.17	10.70	0.14	7.70
2021-05	690.00	308.60	163.20	1280.00	0.19	0.13	9.90	0.18	8.00
2021-06	1500.00	525.00	143.20	1900.00	0.18	0.22	11.00	0.18	7.90
2021-07	1450.00	535.00	258.00	1650.00	0.19	0.30	10.80	0.21	8.03
2021-08	855.00	357.20	143.20	1650.00	0.17	0.22	11.30	0.13	8.10
2021-09	550.00	218.00	234.70	1095.00	0.12	0.07	9.10	0.13	7.90
2021-10	645.00	240.00	179.00	1206.00	0.14	0.08	10.10	0.12	7.90
2021-11	635.00	273.00	268.00	1190.00	0.08	0.13	9.40	0.07	7.90
2021-12	420.00	262.00	220.00	610.00	0.12	0.04	8.60	0.05	6.90
2023-01	1130.00	521.00	321.60	1530.00	0.19	0.18	12.40	0.24	7.90
2023-02	1095.00	350.00	259.20	1320.00	0.18	0.24	8.90	0.17	7.80
2023-03	1500.00	430.50	187.50	2740.00	0.16	0.13	11.10	0.17	7.80
2023-04	1040.00	304.50	240.00	1530.00	0.13	0.14	9.10	0.14	7.90
2023-05	1600.00	651.00	196.80	2540.00	0.17	0.10	10.80	0.24	7.80
2023-06	1100.00	420.00	321.60	1940.00	0.20	0.30	12.00	0.26	7.90
2023-07	1205.00	350.00	169.00	1690.00	0.13	0.08	12.00	0.15	7.80
2023-08	675.00	232.50	168.00	1100.00	0.23	0.08	8.90	0.14	7.90
2023-09	1050.00	378.50	187.50	1712.00	0.13	0.09	10.30	0.13	7.80
2023-10	685.00	304.50	196.80	1520.00	0.12	0.18	11.50	0.14	7.80
2023-11	695.00	395.50	321.60	1100.00	0.22	0.22	13.70	0.20	7.90
2023-12	570.00	245.00	196.00	1060.00	0.14	0.16	9.10	0.12	7.90
WHO Standard	300	250	250	1000	1.5	0.3	50	2	8.5
Units	mg/L								pH
UzSSt: 133:2024	500	350	500	1500	0.7	0.3	45	1	9
Units	mg-eq/L	mg/L							pH

Note: Amounts that do not meet the National Standard of Uzbekistan [49] are marked in red.

Table 11 illustrates the detailed calculation of the F3 value, which is a critical component of Step 3.3 in the water quality index (WQI) evaluation process. This step involves quantifying the specific factor F3 used to integrate multiple water quality parameters into the overall assessment, thereby contributing to a comprehensive understanding of water quality status.

Table 11. Step 3.3.: Calculation of F_3.

nse Value	0.01 × nse	0.01 × nse + 0.01	F3
0.095	0.001	0.011	8.70

Table 12 presents the comprehensive calculation of the Water Quality Index (WQI), consolidating all relevant parameters and steps into a final quantitative assessment. This table summarizes the overall water quality status based on the integration of individual indicator values, providing a clear and concise evaluation useful for water resource management and decision-making.

Table 12. Total calculation of WQI.

Component of CCME WQI	Value	Square Value
F1	33.33	1111.11
F2	17.59	309.50
F3	8.70	75.74
	SUM	1496.35
	Square Root Value	38.68
	Divide by 1.732	1.732
	D	22.33
		100
CCME WQI (Object 2)		77.67

Table 13 summarizes the general quality indices of underground drinking water derived using the CCME WQI model, providing a comprehensive assessment of groundwater suitability for drinking purposes.

Table 13. General quality indices of underground drinking water obtained using the CCME WQI model.

Years	Parameters			WQI	Classification
	F1	F2	F3		
2021	33.33	17.59	8.70	77.67	Fair
2023	33.33	24.07	13.47	75.02	Fair

4. Discussion

4.1. Correlation Coefficients

The Amudarya district is geographically situated in the lower region of Uzbekistan, resulting in a high level of underground seepage water near the soil surface. This proximity contributes to widespread soil salinity. Consequently, the practice of salt-washing to mitigate excess surface salt accumulation is routinely employed in this area. Here, 'underground seepage water' emerges as a critical factor adversely affecting both study objects. Typically, an increase in salinity within collector-drainage waters would correspond to a decrease in salinity in Object 2. However, a decrease in the salinity levels of the collector-drainage water, coupled with an increase in the salinity levels of the underground groundwater, indicates a problematic scenario. The correlation coefficients for Objects 1 and 2 are presented in the accompanying correlation matrix Tables 14 and 15.

Table 14. Correlation coefficients of six quality indicators in the collector-drainage water.

Variables	EC	HCO_3^-	Cl^-	Na^+	SAR	SAR (EC)
EC	1.000					
HCO_3^-	−0.092	1.000				
Cl^-	0.795	0.206	1.000			
Na^+	0.777	−0.312	0.571	1.000		
SAR	0.775	−0.365	0.538	0.974	1.000	
SAR (EC)	0.775	−0.365	0.538	0.974	1.000	1.000

Table 15. Correlation coefficients of nine quality indicators in groundwater.

Variables	TH	Cl^-	SO_4^{2-}	TDS	F^-	Fe^{2+}	NO_3^-	Cu^{2+}	pH
TH	1.000								
Cl^-	0.856	1.000							
SO_4^{2-}	−0.008	0.043	1.000						
TDS	0.861	0.727	−0.136	1.000					
F^-	0.216	0.367	0.030	0.137	1.000				
Fe^{2+}	0.303	0.409	0.270	0.213	0.501	1.000			
NO_3^-	0.367	0.550	0.184	0.420	0.373	0.447	1.000		
Cu^{2+}	0.577	0.674	0.266	0.534	0.653	0.570	0.601	1.000	
pH	0.243	0.201	−0.136	0.304	0.330	0.441	0.306	0.415	1.000

An analysis of the correlation coefficients presented in Tables 10 and 11 indicates a strong positive correlation among several indicators in Object 1, including electrical conductivity (EC), chloride (Cl^-), sodium (Na^+), and sodium adsorption ratio (SAR). Conversely, most relationships involving bicarbonate (HCO_3^-) exhibited an inverse correlation, with the exception of there being a correlation coefficient of 0.206 between HCO_3^- and Cl^-. In Object 2, robust positive correlations are observed among total hardness (TH), chloride (Cl^-), and total dissolved solids (TDS). The sulfate (SO_4^{2-}) anion shows a negligible correlation with other indicators, while a weak negative correlation is identified between TDS and pH. Furthermore, a positive neutral correlation is noted for the fluoride (F^-) anion, particularly between ferrous (Fe^{2+}) and cupric (Cu^{2+}) ions, with other parameters exhibiting weak positive correlations. The spatial distribution of these correlation coefficients for both objects is illustrated in Figure 2.

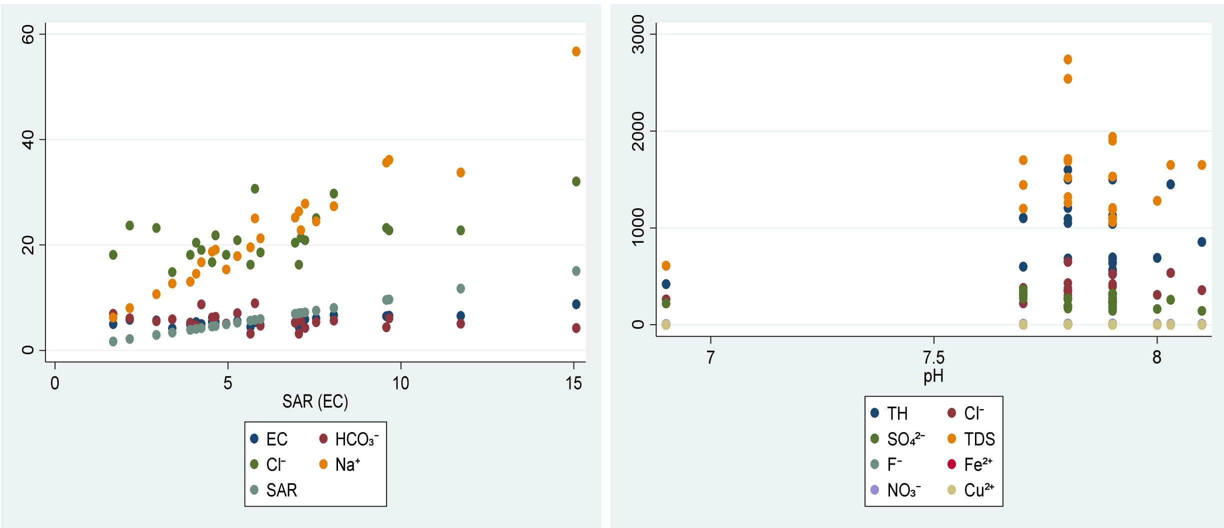


Figure 2. Spatial structure of collector-drainage water and groundwater.

The left graph illustrates the spatial distribution of indicators within Object 1, specifically the collector-drainage water. This visualization highlights the correlation levels among the various indicators, allowing for an assessment of their spatial interrelationships.

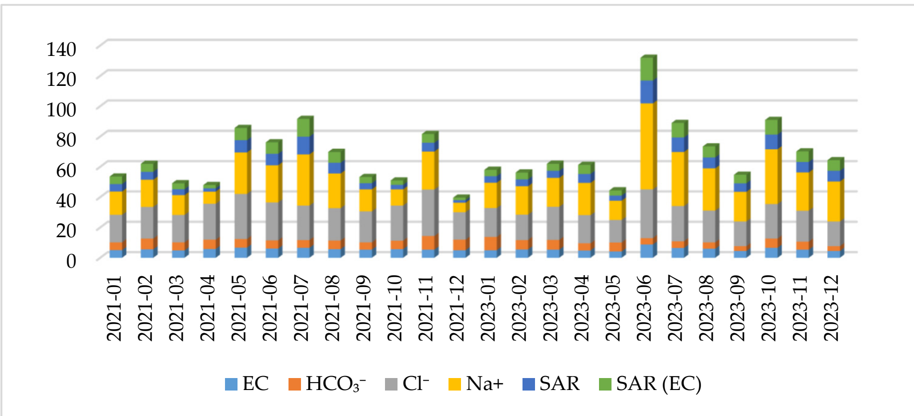
4.2. General Comparison

During the years 2021 and 2023, the overall water quality index (WQI) for Object 1 categorized it within the fifth tier of the CCME WQI model, denoting a 'Poor' status in relation to sensitive crops. This classification was primarily influenced by the non-compliance of almost all six quality indicators with the standards established by the

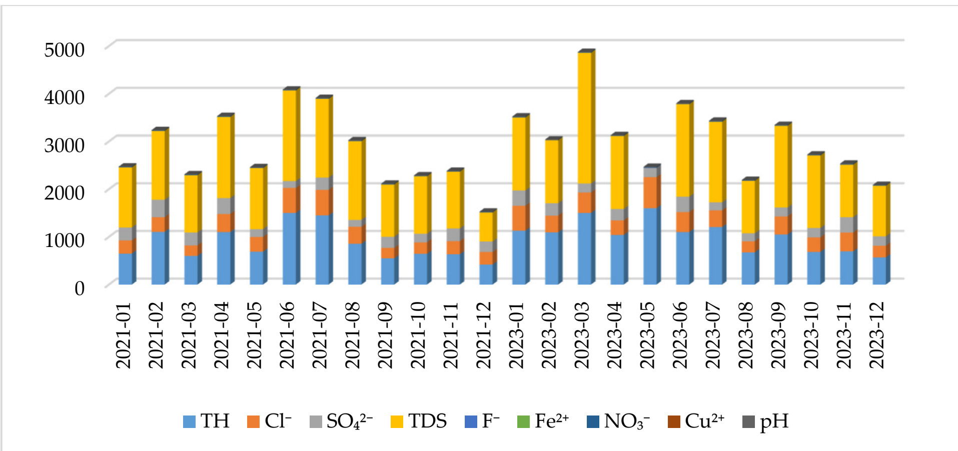
FAO guidelines. Specifically, in 2021, the total number of indicators failing to meet the required standards over a twelve-month period was 66, representing 91.67% of the total (as indicated by the values highlighted in red in Table 6). In 2023, this figure rose to 72, indicating a full 100% non-compliance. A comparative analysis of these two years revealed an increase in salinity levels for Object 1, with a rise of 8.33% observed in 2023 compared to 2021. Furthermore, when evaluating the WQI concerning insensitive crops as per the FAO-established ranges, the classification remained at the 'Poor' level for both years. The total WQI values for these crops were in the ratio of 1.117:1 (30.74 in 2021 compared to 27.53 in 2023), reflecting a reduction in salinity of 3.21 for insensitive crops. However, this difference was not substantial when considering random fluctuations within the dataset.

These findings suggest that inadequate irrigation practices, characterized by the use of collector-drainage water with elevated salinity levels without proper treatment, exacerbate soil salinity. As a result, this 'secondary water' undergoes filtration through Quaternary deposits, adversely affecting the quality of groundwater originating from depths of 10 m.

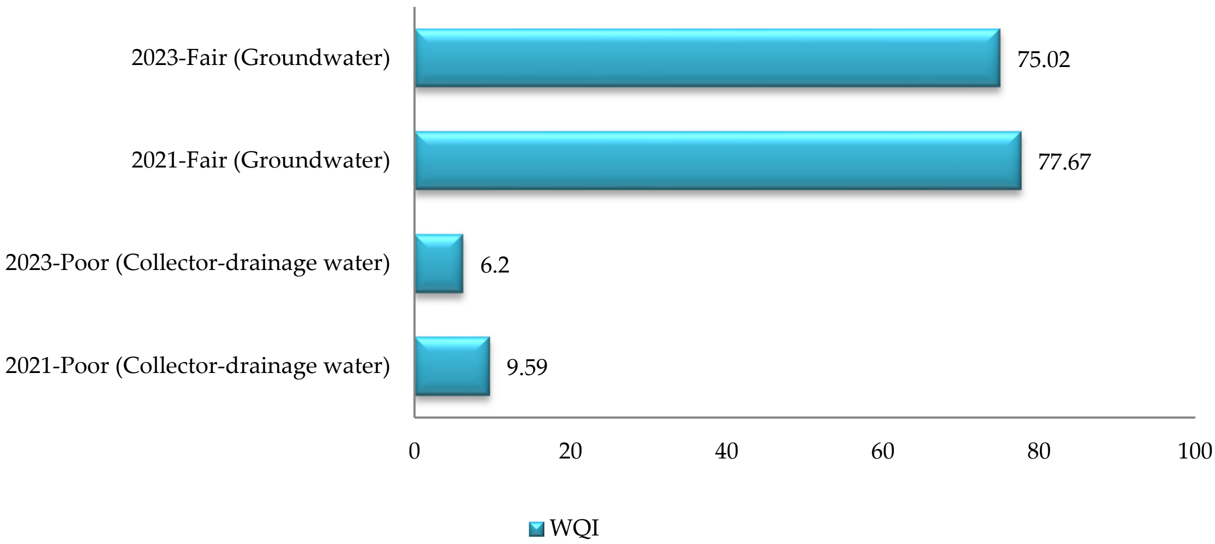
In examining the results for Object 2, which pertains to underground drinking water, the CCME WQI model indicated that the overall quality index in 2021 placed it within category three, classified as 'Fair'. The non-compliance of three specific indicators—total hardness (TH), total dissolved solids (TDS), and chloride (Cl^-)—with the National Standard primarily contributed to this classification. This pattern persisted in 2023, and a comparative analysis of the two years revealed a ratio of 1.035:1 (77.67 in 2021 compared to 75.01821401 in 2023), indicating a slight decline in the quality of Object 2 over this period. The persistent non-compliance of the three indicators in 2023 reinforced the challenges facing underground drinking water quality. Trends for both objects are further illustrated in Schemes 1–3 below.



Scheme 1. Trends of increasing and decreasing salinity levels of study Object 1.



Scheme 2. Tendencies to decrease and increase in nine indicators of Object 2.



Scheme 3. Total annual water quality indices of the collector-drainage water and groundwater.

Scheme 1 illustrates that the concentration of Na^+ cations in Object 1 presents a greater risk compared to the other analyzed indicators. Additionally, among the nine indicators assessed, only total dissolved solids (TDS) and total hardness (TH) exhibited the most significant increasing trends during the periods of 2021 and 2023.

4.3. Global Comparison of Water Quality Indices (CCME WQI) for Collector-Drainage and Groundwater

The comparison of the overall water quality index (CCME WQI) values for collector-drainage water and groundwater in the Amudarya district provides crucial insights into the quality of both water types. For the collector-drainage water in the Amudarya district, the CCME WQI values were 9.6 in 2021 and 6.2 in 2023, both of which classify the water quality as 'Poor'. This indicates a high level of pollution in the area, primarily due to contaminants such as nitrates, sulfates, and electrical conductivity.

In contrast, the groundwater in the same region showed CCME WQI values of 77.67 in 2021 and 75.02 in 2023, which are classified as 'Fair'. This indicates that the water quality was relatively better than that of the collector-drainage water, although the groundwater remained unsuitable for drinking due to the presence of nitrates, sulfates, and other pollutants. These results may be linked to agricultural activities in the area.

The water quality in the Amudarya district, particularly for collector-drainage water and groundwater, has provided important findings when compared with research conducted in other countries. Specifically, studies on the Elgo River (Ethiopia) indicated that the river water quality, based on the CCME WQI, ranged from 36.6 to 38.38, which fell within the 'Poor' category. The main pollutants identified were turbidity, total suspended solids, color, coliform bacteria, and organic materials. The research also assessed the irrigation water quality, where IWQI values were rated as 'Good' (81.4) during the dry season and 'Poor' (62.14) during the rainy season [51].

Additionally, the quality of the Tigris River water in the Baghdad area was studied from July 2017 to April 2018 based on various physicochemical parameters and evaluated using the CCME WQI. The results showed that the river water was classified as 'Fair' (WQI = 65–79) for aquatic life (living organisms in water) and "Poor" (WQI = 45–64) for drinking purposes. The primary pollutants responsible for this classification included total dissolved solids (TDS), turbidity (murkiness), alkalinity, and calcium, magnesium, phosphate, and sulfate levels exceeding the established ecological standards. The sources of pollution were mainly anthropogenic activities (industrial and domestic waste) and climate change. The CCME WQI results provide an easy and rapid means to assess river water status and track changes in water quality over time and space in ecosystems [52].

The Baitarani River (Odisha, India) is facing severe ecological challenges due to strong anthropogenic impacts. A study conducted between 2021 and 2024 evaluated the water quality of the river during the post-monsoon season. A total of 15 physicochemical parameters were measured from 13 sampling points, and water quality was assessed using the WA-WQI, CCME-WQI, and IWQI indices. The results showed that during the post-monsoon season, the CCME-WQI values ranged from 23 to 97, with water quality assessed from 'Excellent' to 'Very Poor'. The principal component analysis (PCA) and cluster analysis (CA) methods identified key pollutants such as turbidity, electrical conductivity (EC), total dissolved solids (TDS), and minerals. The study found that 61.54% (WA-WQI), 76.92% (IWQI), and 53.85% (CCME-WQI) of the sampling points had a water quality deemed unsuitable. Therefore, the research recommended reducing sewage waste and introducing small-scale purification systems. This study provided essential data for the sustainable management of the river basin [53].

In the Okhla industrial region of Delhi, India, water quality was evaluated based on 12 groundwater samples collected in 2020 across different seasons (pre-monsoon, monsoon, and post-monsoon). The CCME WQI (Canadian Council of Ministers of the Environment Water Quality Index) was used for the assessment. The results showed CCME WQI values ranging from 0 to 100, with the lowest quality (43) for sample A9 and the highest (100) for samples A1, A2, and A10. The average index value across all stations was approximately 74.1, indicating that the water quality was generally 'Fair'. The results highlighted that groundwater in industrial areas, such as Okhla, is more prone to pollution, primarily due to high concentrations of TDS, nitrates, and fluoride, which contribute to the deterioration of water quality. Therefore, controlling industrial waste, improving water treatment systems, and implementing regular monitoring are necessary to ensure safe drinking water for the population [54].

A study conducted in the Kızılırmak Delta (Turkey) assessed the chemical composition, spatial distribution, and suitability of groundwater for drinking purposes. Eleven key parameters (NO_3^-, Ca^{2+}, Mg^{2+}, Na^+, Cl^-, K^+, HCO_3^-, SO_4^{2-}, hardness, electrical conductivity (EC), and pH) were analyzed, and the water quality index (WQI) values were calculated using the Canadian Council of Ministers of the Environment (CCME) methodology. The study found that most wells had CCME WQI values ranging from 32.9 to 77.7, categorizing the water as 'Poor' and 'Fair', indicating that it was unsuitable for drinking purposes. The high concentrations of ions such as Ca^{2+}, Mg^{2+}, and SO_4^{2-} were responsible for the deterioration in water quality. In particular, the western region showed poor water quality, and according to CCME maps, these areas were unsuitable for both drinking and irrigation. Additionally, pH, hardness, and nitrate concentrations exceeded the prescribed standards at some points. Overall, the CCME WQI assessment of groundwater provided critical information about areas with poor water quality and the necessary steps to ensure safe usage [55]. Table 16 provides an international comparison of water quality (WQ) using the CCME Water Quality Index (WQI) model, highlighting differences among various countries or regions. The following table presents key indicators and their comparative values across these locations.

Table 16. Regional comparison of the WQ using the CCME WQI model.

Location	Water Type	Water Source	Year(s)	CCME WQI Value	Quality Category	Main Pollutants	Notes
Amudarya District (Uzbekistan)	Surface Water	Collector-drainage water	2021 and 2023	9.6–6.2	Poor	Nitrates, sulfates, electrical conductivity (EC)	Highly polluted, not suitable for irrigation or other uses
Amudarya District (Uzbekistan)	Groundwater	Well water	2021 and 2023	77.67–75.02	Fair	Nitrates, sulfates, other inorganic pollutants	Better than drainage water, but not safe for drinking
Elgo River (Ethiopia)	Surface Water	River water	2023	36.60–38.38	Poor	Turbidity, TSS, color, coliforms, organic matter	Poor water quality, especially in rainy seasons
Tigris River (Baghdad, Iraq)	Surface Water	River water	2017–2018	45–79	Fair/Poor	TDS, turbidity, alkalinity, Ca^{2+}, Mg^{2+}, phosphates, sulfates	Poor for drinking, Fair for aquatic life
Baitarani River (India)	Surface Water	River water	2021–2024	23–97	Very Poor–Excellent	Turbidity, EC, TDS, minerals	Total of 53.85% of sites rated as unfit for use based on CCME-WQI
Delhi Region (India)	Groundwater	Well water	2020	43–100	Poor–Excellent	TDS, nitrates, fluoride	Groundwater near industrial areas highly polluted; average index: 74.1 (Fair)
Kızılırmak Delta (Turkey)	Groundwater	Well water	2016	32.90–77.70	Poor–Fair	Nitrates, Ca^{2+}, Mg^{2+}, sulfates, EC, hardness, pH	Western zones especially unsuitable for drinking or irrigation

5. Conclusions

The application of Victor Ernest Shelford's 'Law of Tolerance' has proven instrumental in assessing the ecological impact of groundwater and collector-drainage water quality on local flora within the Amudarya district. This study's findings demonstrate that the physicochemical characteristics of collector-drainage water are categorized as 'Poor' according to the water quality index (WQI), presenting substantial barriers to creating a viable growth environment for both 'Sensitive' and 'Insensitive' crops. The groundwater quality index, evaluated through the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) model, is classified as 'Fair', denoting its unsuitability for potable use. Elevated levels of total hardness (TH), total dissolved solids (TDS), and chloride (Cl^-) concentrations are significant limiting factors, in alignment with the Law of Tolerance, which consequently hinders the local population's ability to utilize this water resource for daily consumption.

To enhance the ecological sustainability of the study sites, the findings suggest prioritizing the use of organic fertilizers over chemical inputs in agricultural practices. This study provides valuable insights into optimizing environmental monitoring methodologies for assessing the ecological conditions of both surface and groundwater using the CCME WQI model. The results support the development of effective salinity management strategies and reinforce the importance of sustainable land and water use. These measures are vital for promoting agro-ecological stability and ensuring long-term environmental resilience in the affected ecosystems.

When the results of this study are compared with international findings, it becomes evident that the pollution of both surface and groundwater is primarily driven by agricultural activities, industrial discharges, and natural geochemical processes. Water quality indicators derived from the CCME WQI model vary depending on the intended use of the water; while such waters are often unsuitable for drinking, they may still be partially acceptable for irrigation purposes.

6. Recommendations

The following recommendations are proposed based on this study's findings, aimed at enhancing water quality, ecological stability, and agricultural sustainability:

1. The WQI categorization of Object 1 as 'Poor' underscores the need to reduce salinity concentrations, facilitating irrigation for specific salt-tolerant crops. This measure would improve local water quality, as Object 2 attains a 'Fair' WQI rating, and promote water reutilization under conditions of scarcity.
2. Introducing crops classified as 'insensitive' to high salinity levels could improve water and soil quality by managing salt accumulation. The implementation of sequestration ponds for salts associated with Object 1 and agricultural zones (agrocenoses) would help to prevent excessive soil salinization.
3. Long-term monitoring is essential to evaluate the impact of salt-insensitive crops on water quality and to mitigate potential environmental consequences. Such an approach will contribute to water conservation and sustainable agricultural practices.
4. Recognizing that surface water pollution significantly affects groundwater quality, addressing the elevated levels of certain anions (Cl^-) and cations (Ca^{2+}, Mg^{2+}) in groundwater is critical to maintaining water availability and reducing reliance on potable water.
5. To support both the quality of potable water in agricultural regions and crop yields, the increased application of organic fertilizers is essential, alongside minimizing the reliance on chemical inputs where feasible. This approach will contribute to improved soil health and long-term agricultural sustainability.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w17152191/s1. Figure S1. Image from the process of collecting groundwater samples. Figure S2. A small description from the analysis of water samples in the Sanitary and Hygiene Laboratory.

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