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Evaluation of Groundwater Quality Using WQI Models and Its Application to Plants Vulnerable to Ecological Stress

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This study focuses on the groundwater found at depths of 10-20 meters in the Amudarya district of the Republic of Karakalpakstan, within Uzbekistan. The primary objective of the research is to determine the suitability of this water for irrigating plants that are not resistant to environmental stress. Water samples were collected from 12 wells over the period of 2020-2024, and laboratory analyses were conducted based on four key indicators: Total Dissolved Solids (TDS), chloride (Cl^-), potential of Hydrogen (pH), and nitrate (NO_3^-). To assess the overall water quality, the "Weighted Arithmetic Water Quality Index (WA-WQI)" and the "Canadian Council of Ministers of the Environment (CCME)" models were used. According to the research findings, the overall quality of groundwater in the Amudarya district falls under the "Unsuitable for drinking and fish culture" category according to the WA-WQI model and the "poor" category according to the CCME WQI model, limiting its use for irrigating plants with low tolerance. The novelty of this study lies in the confirmation that groundwater is unsuitable for irrigating plants that are not resistant to environmental stress. However, it can be used for irrigating certain semi-tolerant and tolerant plant species.

Key words: groundwater, ecological stress, salinity, Water Quality Index (WQI), FAO guidelines, sensitive and insensitive crops, agricultural productivity

Water is one of the most crucial natural resources on Earth, and ensuring and managing its quality is particularly important for maintaining the continuity of life in the biosphere. Water pollution can lead to significant ecological and economic problems in agricultural, industrial, and domestic use. Assessment of groundwater quality plays a major role in improving their ecological and economic efficiency. This article examines the agrotechnical and ecological characteristics of water based on laboratory results from 12 groundwater well samples located in the Amudarya district. The water quality was analyzed through indicators including Total Dissolved Solids (TDS), chloride (Cl⁻), nitrate (NO₃⁻), and pH levels.

In the arid regions of Uzbekistan, particularly in the Amudarya district of the Republic of Karakalpakstan, groundwater serves as an effective irrigation source for plants and is used to irrigate various crops. However, groundwater quality, especially in arid and semi-arid regions, can negatively impact the development of different ecological groups of plants due to salinity and other ecological stresses. Therefore, for efficient water use, it is necessary to properly assess water quality and consider plants' water requirements (Vineis *et al.*, 2011; Katel *et al.*, 2023; Yue *et al.*, 2020; Ullah *et al.*, 2021; Garcia-Caparros *et al.*, 2023; Rajabova *et al.*, 2024).

The article conducts analyses based on methods for assessing key water quality indicators, as well as methodology regarding plant water requirements corresponding to these indicators, and the FAO water quality guidelines from 1976. Additionally, the overall state of water quality is analyzed through the Water Quality Index (WQI) methodology. The article presents scientific approaches aimed at optimizing water resources for efficient water use and obtaining high yields from phytocenoses (Rajabova *et al.*, 2024; Owens, 2001).

MATERIALS AND METHODS

Water Sample Collection and Laboratory Analysis Methods

Water samples were collected according to the ISC-31861 (primary methodology) (Interstate Council for Standardization, Metrology and Certification, 2012). Sterilized plastic containers of 1 liter capacity were used for this purpose. The sampling locations consisted of 12 points in total, with water samples collected four times per year - in February (winter), May (spring), August (summer), and November (autumn) from designated stations. The designated locations are situated in various corners of the Amudaryo province. Table 1 presents the location and numbering of the sampling stations (S) within the province. Additionally, the geographic locations of the wells from which these water samples were collected can be observed on the map presented in Figure 1.

The wells are formed at depths ranging from 10-20 meters relative to ground level, and such groundwater is utilized by the local population for various purposes (potable water, food preparation, sanitation, crop irrigation, and others). Under laboratory conditions, water samples were analyzed for 4 parameters - Total Dissolved Solids (TDS), chloride (Cl⁻), hydrogen index (pH), and nitrate (NO₃⁻) (GOST 18164 - 72; GOST 4245 - 72; ISO 10523:2008; GOST 4192-82). The masses of these 4 indicators in 1 liter of water were analyzed according to the methodologies presented in Table 2 below.

Optimal Water Requirements for Plants with Low and High Tolerance

The FAO developed a methodology based on its 1976 water quality guidelines. This methodology primarily proposes effective irrigation strategies for crops in arid, semi-arid, and agriculturally-oriented regions. This methodology provides opportunities for temporary but effective crop management using water resources, particularly in conditions of intensifying climate change and water scarcity (Ayers & Westcot, 1985; Noori *et al.*, 2020; Shannon & Grieve, 1998; Munns & Gilliham, 2015; Abdelrhman *et al.*, 2024; Bahlool *et al.*, 2014; Roussi *et al.*, 2024).

This approach helps maximize yields under limited water resources and establish productive agrocenoses in efficient agriculture in areas with challenging growth conditions. The advantage of this methodology is that it has been developed based on recent scientific research

results and is oriented toward analyzing water quality with moderate and severe restrictions and their practical application. It takes into account the optimal water requirements for different classes of plants. For tolerant plants, even when water quality severe restrictions are within the specified values under conditions of high pollution and other ecological stresses, high yields can be obtained through effective management and specific plant selection. These guidelines can be successfully applied in irrigation for tolerant plants. However, for plants with low tolerance, under conditions of deteriorated water quality, a high level of management and practice is required. This includes conducting field trials, rigorous analysis of results, and in-depth analysis of laboratory indicators (Garcia-Caparros *et al.*, 2023; Owens *et al.*, 2001; Noori *et al.*, 2020; Ueda *et al.*, 2016). According to FAO guidelines, in assessing plants' adaptability to water quality indicators, their tolerance level (resistance to salinity and other ecological stress factors) is crucial (Abadi *et al.*, 2020).

Water supply management is crucial for optimizing growth conditions based on the water requirements of each plant species. While some plants are drought-resistant, others require regular irrigation. Table 3 presents a list of plants categorized by their resistance levels to various ecological stresses. Tolerant plants are resistant to high TDS and chloride levels, and they can develop even under high salinity conditions. For example, *Hordeum vulgare, Gossypium spp., Cyamopsis tetragonoloba* and others (Ojukwu *et al.*, 2021; Mohseni *et al.*, 2024; Alexakis, 2022; Uddin *et al.*, 2023.

Semi-tolerant plants represent an ecological group that can adapt to moderate salinity conditions, requiring moderate levels of water and salinity for proper development.

Sensitive (low tolerance level) plants are susceptible to high levels of salt, chloride, or nitrate, and their growth slows or ceases with increasing salinity (for example, *Citrus spp., Pisum sativum, Allium sativum*) (Abadi *et al.*, 2020).

Mechanism of Using WQI Models

The Weighted Arithmetic Water Quality Index (WA-WQI) Model

The WA-WQI model determines weight and quality ratings based on designated quality indicators and expresses overall water quality in a single number. The WQI calculation process in this model consists of 4 stages (Ueda *et al.*, 2016; Ojukwu *et al.*, 2021; Alexakis *et al.*, 2022).

Stage 1: Calculation of relative weight (k_i) for designated or desired water quality indicators.

$$k_i = \frac{v_i}{S_i}$$

v_i - quantity of desired indicators (weights of desired quality parameters present in 1 l volume of water)

S_i - ideal or standard value for desired indicators

k_i - relative weight indicator for desired indicators, where if the k_i value is close to 1, the weight of the desired parameter is close to the ideal or optimal value

Stage 2: Calculation of the weight for each quality parameter.

In other words, this stage determines the role of each designated indicator in overall Water Quality (WQ).

$$w_i = \frac{k_i}{\sum_{i=1}^{n} k_i}$$

w_i - the significance level of the relative weight;

k_i - the relative weight (calculated value in the 1st stage, representing the relative importance indicator or relative weight);

$\sum_{i=1}^{n} k_i$ - the total sum (the sum of the relative weights of all defined indicators).

Stage 3: Calculating the quality level of each indicator.

$$Q_i = \frac{v_i}{S_i} \times 100$$

Q_i- the quality level of any parameter. This quality level ranges from 0 to 100 percent (100%). The closer the measured amount of quality indicators in laboratory analysis results is to the ideal value, the better the water quality, achieving up to 100% positivity.

v_i- the quantity of any indicator (the weight of any quality parameter present in 1 liter of water).

S_i- the ideal or standard value for any indicator (as defined in Uz ISC 133:2024).

Stage 4: Calculation of the Weighted Arithmetic Water Quality Index (WA-WQI).

$$WQI = \sum_{i=1}^{n} w_i Q_i$$

w_i – Determines the relative weight significance of a given quality parameter within the overall water quality value (the sum of the weights for all specified parameters must equal 1).

Q_i – The quality level of a given parameter, expressed as a percentage (%) within a range of 0 to 100.

WQI - The overall Water Quality Index, calculated as the sum of the quality levels of all parameters weighted by their relative significance. A higher WQI value indicates positive water quality (better water quality), while a lower value indicates negative water quality (poorer water quality). The values derived from the WA-WQI model are classified into ranges between 0 and 100, as shown in Table 4.

Canadian Council of Ministers of the Environ (CCME) WQI

This model is primarily designed to assess the quality of surface water. The calculation of the WQI in this method is based on the combination (root mean square) of the following three factors:

Calculation of the Index

Step 1: F_1- Percentage of parameters exceeding the standard (Scope).

$$F_1 = \frac{Number\ of\ parametres\ exceeding\ the\ standard}{Total\ number\ of\ parametres} \times 100$$

Step 2: F_2- Percentage of tests exceeding the standard (Frequency).

$$F_2 = \frac{Number\ of\ test\ results\ deviating\ from\ the\ norm}{Total\ number\ of\ test\ results} \times 100$$

Step 3: F_3- the extent to which test results deviate from the standard (Amplitude). The calculation of Amplitude involves three steps:

3.1. Excursion – This measures the magnitude by which individual test results exceed the standard value:

$$excursion = \frac{The\ i-test\ result\ deviating\ from\ the\ standard}{i-\ test\ standard} - 1$$

3.2. Normalized Sum of Excursions nse**:** This represents the normalized measurement of the deviation of water parameters from the standard values:

$$nse = \frac{\sum_{i=1}^{n} excursion_i}{Total\ number\ of\ test\ results}$$

Here, $\sum_{i=1}^{n} excursio\,n_i$- represents the deviation of the parameter from its normative (standard) value; Normalized Sum of Excursions (nse) is the normalized measure of these deviations.

3.3. The express the value of the nse as a percentage, the value of F_3 is calculated as in Table 5.

RESULTS AND DISCUSSION

Laboratory Analysis Results

Based on the results of samples taken from the observation wells, the use of the water for irrigation of various crops is found to be limited. For instance, it was determined that the water is unsuitable for irrigating plants with low tolerance to environmental stresses. Such water types can not only act as limiting factors for the optimal range of plant growth but may also negatively impact the overall soil condition within agroecosystems. The composition of water from all 12 wells does not meet the required standards for chloride, nitrate, and TDS indicators, as per FAO guidelines. Table 6 below presents the laboratory analysis results obtained from 2020 to 2024.

Plants with typically low tolerance thresholds cannot

adapt to adverse ecological stresses or may experience reduced overall productivity. Primary indicators manifest initially in morphological parameters (Anjum *et al.*, 2003).

For instance, as shown in Table 6, three parameters in water composition - NO_3^-, TDS, and Cl^- - do not create unfavorable conditions for tolerant plant development. However, these factors may become limiting for stress-sensitive plants' growth and yield potential. Figure 3 illustrates the fluctuating trends of each quality parameter measured in water samples from 12 wells.

As evident from the diagram above, the TDS value is higher compared to other parameters. This may create unfavorable conditions for stress-sensitive plants, as TDS encompasses various salts and minerals that may be unnecessary or detrimental to plant growth. High pH combined with elevated TDS can impede nutrient absorption through the root system. Conversely, highly acidic water (low pH) can also negatively impact nutrient uptake. High chloride content in water can similarly create adverse conditions for plants. While chloride is an essential micronutrient, excessive amounts can be harmful, potentially causing morphological changes such as leaf reduction and thickening, decreased plant growth, premature leaf chlorosis, and defoliation. Chloride toxicity primarily disrupts plant metabolism, photosynthesis, respiration, and ionic balance (e.g., sodium, potassium, calcium, and nitrates). Excessive chloride levels can hinder nutrient uptake (particularly nitrates and phosphates) through roots, compromising plant health (Carillo & Rouphael, 2022; Ismoilova *et al.*, 2024).

Elevated nitrate concentrations can adversely affect root system development and growth, specifically reducing root length and limiting lateral root development. Nitrates can modify plant hormones "auxin" and "cytokinin" inhibiting or slowing root growth. Furthermore, excess nitrates intensify oxidative stress, reducing plants' nutrient absorption capacity. Therefore, managing water nitrate levels is crucial for creating optimal growth conditions.

Analysis of The WQI Model Results

Determining overall water quality is essential for irrigating various crops in agrocenoses. Different WQI models are used to determine water quality indices. Their advantage lies in synthesizing quality indicators based on significance levels, expressing water quality in a single number. In this study, groundwater quality indices were developed primarily for ecologically stress-sensitive plants (Di Rubbo *et al.*, 2013; Ueda *et al.*, 2016; Ojukwu *et al.*, 2021; Alexakis *et al.* 2022). Specifically, plants with low tolerance levels or "sensitive crops". WA-WQI and CCME WQI models were used to calculate WQIs (Table X), using FAO standards for both sensitive and insensitive crops, as shown in Table 3 above.

Table 1. Water Sampling Stations

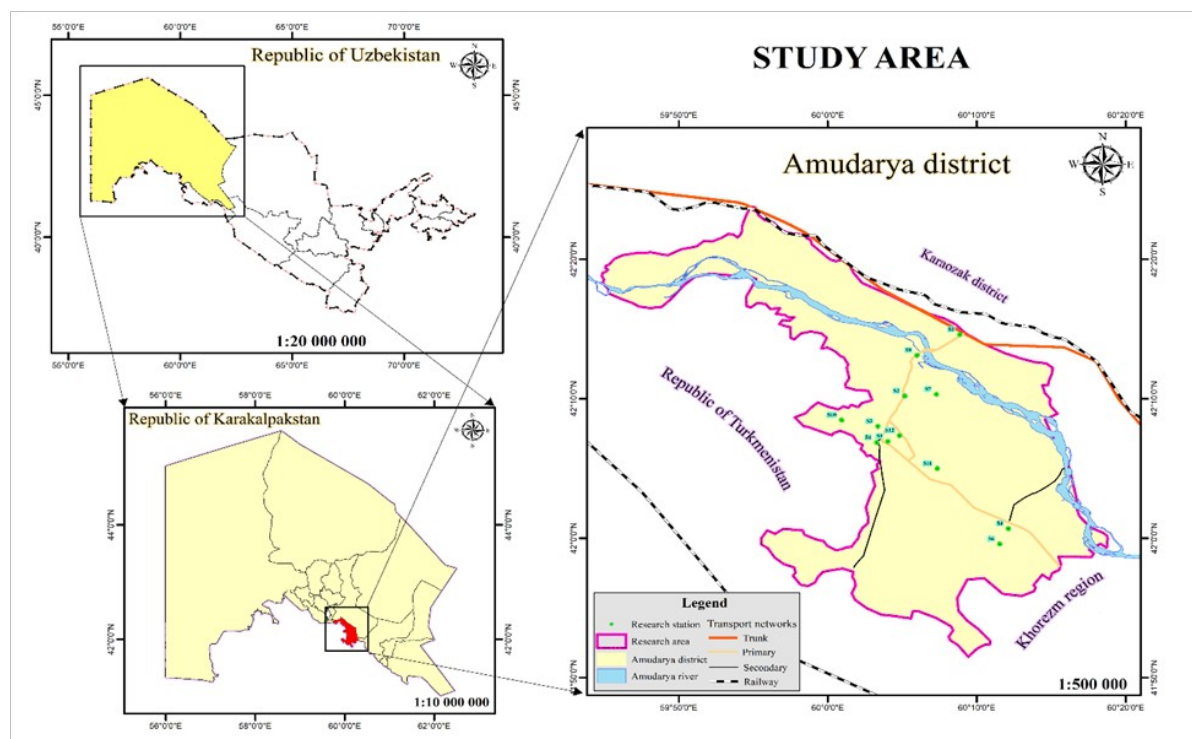| Numbering of stations	Abbreviations
Station 1	S1
Station 2	S2
Station 3	S3
Station 4	S4
Station 5	S5
Station 6	S6
Station 7	S7
Station 8	S8
Station 9	S9
Station 10	S10
Station 11	S11
Station 12	S12

Figure 1: The geographical distribution of a total of 12 monitoring wells located in the Amudarya district of the Republic of Karakalpakstan, within the Republic of Uzbekistan.

Table 2. Methods and Equipment for Determining Water Quality Indicators in Laboratory Conditions and Guidelines for Evaluating Water Quality in Irrigation Systems

Quality indicators	Methods and equipment used in laboratory conditions	Units	Extent of Usage Restrictions		
			None	Slight to Moderate	Severe
Total Dissolved Solids (TDS)	Drying and weight measurement (gravimetric method)	mg/l	0-450	450-2000	>2000
Chloride (Cl⁻)	Titration method using silver nitrate ($AgNO_3$) solution	mEq/l	0-4	4-10	>10
pH (power of hydrogen)	Using a pH meter (Electrochemical method)	pH	6.5-8.4	6.5-8.4	6.5-8.4
Nitrate (NO_3^-)	Spectrophotometric method	mg/l	0-5	5-30	>30

Table 3. Ecological groups of plants by degree of the salinity tolerance

Tolerant	Semi-tolerant	Sensitive	Semi-Sensitive
Barley (*Hordeum vulgare*)	Sunflower (*Helianthus annuus*)	Citrus (*Citrus spp.*)	Pea (*Pisum sativum*)
Sugar beet (*Beta vulgaris*)	Wheat, Sorghum (*Triticum aestivum*)	Cowpeas (*Vigna unguiculata*)	Broccoli (*Brassica oleracea var. italica*)
Cotton (*Gossypium spp.*)	Maize (*Zea mays*)	Gram (*Cicer arietinum*)	Cauliflower (*Brassica oleracea var. botrytis*)
Spinach (*Spinacia oleracea*)	Rice (*Oryza sativa*)	Peas (*Pisum sativum*)	Cucumber (*Cucumis sativus*)
Triticale (*Triticosecale*)	Pomegranate (*Punica granatum*)	Guar (*Cyamopsis tetragonoloba*)	Tomato (*Solanum lycopersicum*)
Rye (*Secale cereale*)	Potatoes (*Solanum tuberosum*)	Lentil (*Lens culinaris*)	Corn (*Zea mays*)
Beets (*Beta vulgaris*)	Oats (*Avena sativa*)	Mung (*Vigna radiata*)	Garlic (*Allium sativum*)
	Sorghum (*Sorghum bicolor*)	Rice (*Oryza sativa*)	

	Soybean (*Glycine max*)	Beans (*Phaseolus spp.*)	

Table 4. Classification of observed water based on the WA- WQI model

Water Quality Index Level	Water Quality Status	Grade	Possible usage
0-25	Excellent water quality	A	Drinking, Irrigation and Industrial
26-50	Good water quality	B	Domestic, Irrigation and Industrial
51-75	Poor water quality	C	Irrigation and Industrial
76-100	Very poor water quality	D	Irrigation
>100	Unsuitable for drinking and fish culture	E	Restricted use for irrigation

Table 5. Water quality classification by the CCME WQI model

QI range	Ranking of water quality	Remarks
95-100	Excellent	Water quality is protected with a virtual absence of threat or impairment; conditions very close to natural or pristine levels.
80-94	Good	Water quality is protected with only a minor degree of threat or impairment; conditions rarely depart from natural or desirable levels.
65-79	Fair	Water quality is usually protected but occasionally threatened or impaired; conditions sometimes depart from natural or desirable levels.
45-64	Marginal	Water quality is frequently threatened or impaired; conditions often depart from natural or desirable levels.
0-44	Poor	Water quality is almost always threatened or impaired; conditions usually depart from natural or desirable levels.

Table 6. General physico - chemical indicators of underground water

Samples	Data	pH	NO_3^-	TDS	Cl^-	Samples	Data	pH	NO_3^-	TDS	Cl^-
Well 1	2020-02	7.9	9.3	1386.4	5.93	Well 2	2020-02	7.7	9.1	950	6.41
	2020-05	7.9	9.9	1589.2	7.75		2020-05	7.8	10.3	1567	10.68
	2020-08	7.7	9.6	1522.8	7.39		2020-08	7.5	9.7	1480	9.01
	2020-11	8.3	9.5	1569.9	7.61		2020-11	7.7	9.6	1540	7.39
	2021-02	7.6	9.7	1022.3	6.22		2021-02	6.8	9.1	1180	8.73
	2021-05	7.8	9.8	1580.1	7.49		2021-05	7.9	8.4	1830	5.3
	2021-08	7.7	9.8	1428.7	8.37		2021-08	7.9	10.2	1400	6.84
	2021-11	8.7	9.6	1479.2	8.3		2021-11	7.4	9.5	1180	8.73
	2022-02	7.4	10.8	1590	8.38		2022-02	7.6	10.8	1590	8.38
	2022-05	8.2	12.5	1543.2	1.28		2022-05	8.5	12.6	1580	7.44
	2022-08	7.6	14.2	1560	10.03		2022-08	7.9	8.6	1524.6	7.39
	2022-11	6.9	10.3	1548.4	7.32		2022-11	7.8	9.6	1080.7	8.73
	2023-02	7.5	9.9	1510.3	5.8		2023-02	7.2	10.1	1250	5.72
	2023-05	7.8	13.2	1545	5.91		2023-05	7.6	13.5	1680	9.23
	2023-08	7.7	13.6	1570	4.04		2023-08	6.9	15.7	1570	6.76
	2023-11	7.9	12.4	1690	3.96		2023-11	6.9	14.5	1280	9.01
	2024-02	7.3	10.1	1433.1	6.49		2024-02	7.5	9.1	1820.3	13.11
	2024-05	7.6	9.8	1536.1	7.78		2024-05	7.5	11.6	2370	21
	2024-08	7.8	9.6	1522.1	10.9		2024-08	8.1	8.6	1878.1	18.51
	2024-11	7.2	6.8	940	6.41		2024-11	7.3	9.4	1210.0	8.28
Well 3	2020-02	7.8	9.1	1030	5.91	Well 4	2020-02	7.9	8.8	1420.4	7.79
	2020-05	8.5	9.8	1610	6.41		2020-05	8.8	9.7	1566.7	9.47
	2020-08	8.9	9.4	1578	7.77		2020-08	7.8	9.9	1710.5	10.35
	2020-11	7.6	9.2	1060	8.34		2020-11	7.5	9.4	1360.4	8.4
	2021-02	7.6	9.7	1490	6.2		2021-02	7.7	9.7	1426	6.21
	2021-05	8.6	9.5	1568	8.06		2021-05	7.8	9.9	1600	8.7
	2021-08	8.7	9.9	1530	5.01		2021-08	8.3	9.4	1595	10.04

Well	Date					Well	Date				
	2021-11	8.3	9.5	1166	8.06		2021-11	7.9	7.8	1470	8.36
	2022-02	6.9	8	1010.6	4.1		2022-02	7.3	9.4	1479.5	5.76
	2022-05	7.8	8.7	1460.4	5.91		2022-05	8.7	8.3	1890.7	9.73
	2022-08	7.6	8.4	1480.4	4.03		2022-08	8.8	7.8	1010.7	9.75
	2022-11	7.8	10	1307.5	8.34		2022-11	7.7	10.6	1312.4	6.7
	2023-02	7.2	10.5	1250.6	6.65		2023-02	7.4	10.2	1540	5.68
	2023-05	7.9	10.7	1550.5	5.03		2023-05	7.8	11.3	1505.2	5.03
	2023-08	8.4	9.8	1590.7	4.84		2023-08	7.7	12.4	1546.7	4.04
	2023-11	7.7	10.2	1420.5	5.75		2023-11	7	8.5	1496.4	5.03
	2024-02	7.4	10.3	1376.1	9.47		2024-02	7.8	10.3	1556.1	6.57
	2024-05	8.1	12.1	1487.1	7.64		2024-05	7.7	11.5	1587.3	5.03
	2024-08	7.6	14.1	1334.1	7.97		2024-08	7.1	10.3	1433.1	5
	2024-11	7.4	8.6	780	4.04		2024-11	7.4	12.9	1780	13.9
Well 5	2020-02	7.9	13.7	1720	4.97	Well 6	2020-02	7.8	10.1	1430.5	5.91
	2020-05	8.5	13.6	1976	9.3		2020-05	8.6	13.5	1620.6	7.75
	2020-08	8.8	12.5	1710	9.91		2020-08	8.8	14.7	1671.3	9.89
	2020-11	8.2	10.3	1569.8	9.19		2020-11	8.5	13.4	1560.1	8.4
	2021-02	7.6	15.6	1522.6	6.23		2021-02	7.9	10.6	1540.4	7.76
	2021-05	8.6	17.9	1567.9	8.69		2021-05	7.3	13.9	1430.6	8.61
	2021-08	8.2	15.6	1578.5	11.2		2021-08	8.5	14.3	1527.1	9.3
	2021-11	7.6	16.3	1446.6	6.61		2021-11	8.7	11.4	1585.3	9.74
	2022-02	7.7	10.7	1488	5.24		2022-02	7.5	11.5	1450.6	5.8
	2022-05	7.8	11.6	1980.6	5.03		2022-05	8.4	13.5	1550.3	5.03
	2022-08	8.7	13.7	1510.6	6.2		2022-08	8.6	14.6	1567.6	10.21
	2022-11	7.8	12.8	1515.7	8.34		2022-11	7.6	12.5	1470.7	8.31
	2023-02	7.5	8.7	1581.1	7.84		2023-02	8.1	10.2	1510	7.39
	2023-05	8.6	10.4	1526.6	8.24		2023-05	8.6	13.5	1580.4	9.13
	2023-08	8.8	11.6	1586.6	9.2		2023-08	8.3	14.6	1567.3	10.66
	2023-11	8.4	13.6	1561.5	7.96		2023-11	8.4	13.5	1456.3	8.15
	2024-02	7.6	10.3	918.9	7.23		2024-02	7.6	10.1	1564.5	6.8
	2024-05	7.7	11.5	1100.3	6.11		2024-05	7.4	7.6	1566.5	7.22
	2024-08	7.8	11.3	1000.1	6.42		2024-08	7.7	9.1	1000	6.7
	2024-11	7.3	10.7	1490.0	10.55		2024-11	7.5	9.1	1460.0	10.25
Well 7	2020-02	7.8	9.1	1516.2	6.41	Well 8	2020-02	8.3	10.2	1460.4	5.53
	2020-05	8.6	10.7	1576.5	7.56		2020-05	8.8	13.2	1576.5	6.48
	2020-08	8.8	11.3	1710.3	9.89		2020-08	8.6	15.3	1710.2	9.89
	2020-11	7.7	10.1	1564.7	5.42		2020-11	8.5	12.3	1460.3	8.4
	2021-02	7.7	10.3	1440.4	4.95		2021-02	7.7	10.3	1442.4	7.76
	2021-05	7.3	12.5	1540.4	5.76		2021-05	8.4	12.5	1520.3	6.9
	2021-08	7.4	13.4	1588.7	5.28		2021-08	7.6	13.6	1580.2	8.74
	2021-11	7.8	11.6	1597.3	6.01		2021-11	7.5	14.7	1420.3	7.56
	2022-02	7.4	9.6	1490.3	5.04		2022-02	8.5	10.4	1100.6	5.27
	2022-05	8.6	10.3	1534.2	7.84		2022-05	7.9	12.6	1491.5	6.09
	2022-08	8.7	12.4	1642.5	6.93		2022-08	7.8	13.7	1567.3	6.04
	2022-11	8.5	10.2	1578.3	5.46		2022-11	6.9	13.3	1567.8	8.4
	2023-02	8.3	10.3	1467.3	6.6		2023-02	7.7	10.4	1550.5	6.43
	2023-05	8.5	11.4	1589.3	7.45		2023-05	8.7	11.1	1545.7	6.33
	2023-08	8.8	13.5	1554.3	7.87		2023-08	8.6	12.5	1567.2	5.03
	2023-11	8.2	12.7	1458.2	6.6		2023-11	7.7	13.5	1547.3	4.16
	2024-02	7.8	6.5	1100	5.13		2024-02	7.8	11.3	730	6.6
	2024-05	7.5	9.1	1300	5.86		2024-05	6.1	8.3	1270	8.08
	2024-08	7.1	8.6	1560	7.42		2024-08	7.3	9.3	1456.1	7.78
	2024-11	7.6	7.6	970.0	5.42		2024-11	7.8	8.0	1020.0	8.1
Well 9	2020-02	8	8.8	1760.8	5.54	Well 10	2020-02	8.7	8.8	1460.3	5.52
	2020-05	7.8	9.7	1676.6	6.49		2020-05	8.8	9.7	1576.3	6.48
	2020-08	7.8	12.6	2140.4	10.66		2020-08	7.8	9.9	1710.7	9.89
	2020-11	7.6	8.8	1254.7	8.08		2020-11	7.7	9.3	1540.8	7.39
	2021-02	7.5	10.2	1443	8.68		2021-02	7.7	10.3	1569.2	6.25
	2021-05	8.3	11.3	1580.3	7.24		2021-05	7.5	10.6	1550.5	6.21
	2021-08	7.4	10.2	1650.5	7.63		2021-08	6.4	11.3	1580.4	8.74
	2021-11	7.7	11.5	1480.6	7.22		2021-11	7.6	11.6	1570.3	6.64
	2022-02	6.9	11.6	1410.5	4.1		2022-02	6.9	10.2	1810.5	4.1
	2022-05	8.9	12.7	1460.6	5.13		2022-05	7.6	11.4	1560.4	5.22
	2022-08	7.8	14.6	1565.3	6.07		2022-08	7.6	12.6	1561.4	7
	2022-11	7.9	13.8	1445.7	8.08		2022-11	7.6	11.5	1546.1	7.22
	2023-02	7.7	9.9	1450.5	6.42		2023-02	8.4	9.9	1405.7	5.29
	2023-05	7.8	10.7	1590.5	5.91		2023-05	6.9	10.2	1567.2	4.46
	2023-08	7.6	10.4	1530.1	5.03		2023-08	7.7	11.3	1567.2	4.04
	2023-11	7.9	11.5	1420.5	4.43		2023-11	7.9	10.3	1456.2	4.43
	2024-02	8.3	10.3	1456.1	8.03		2024-02	8.4	10.3	1533.1	4.4

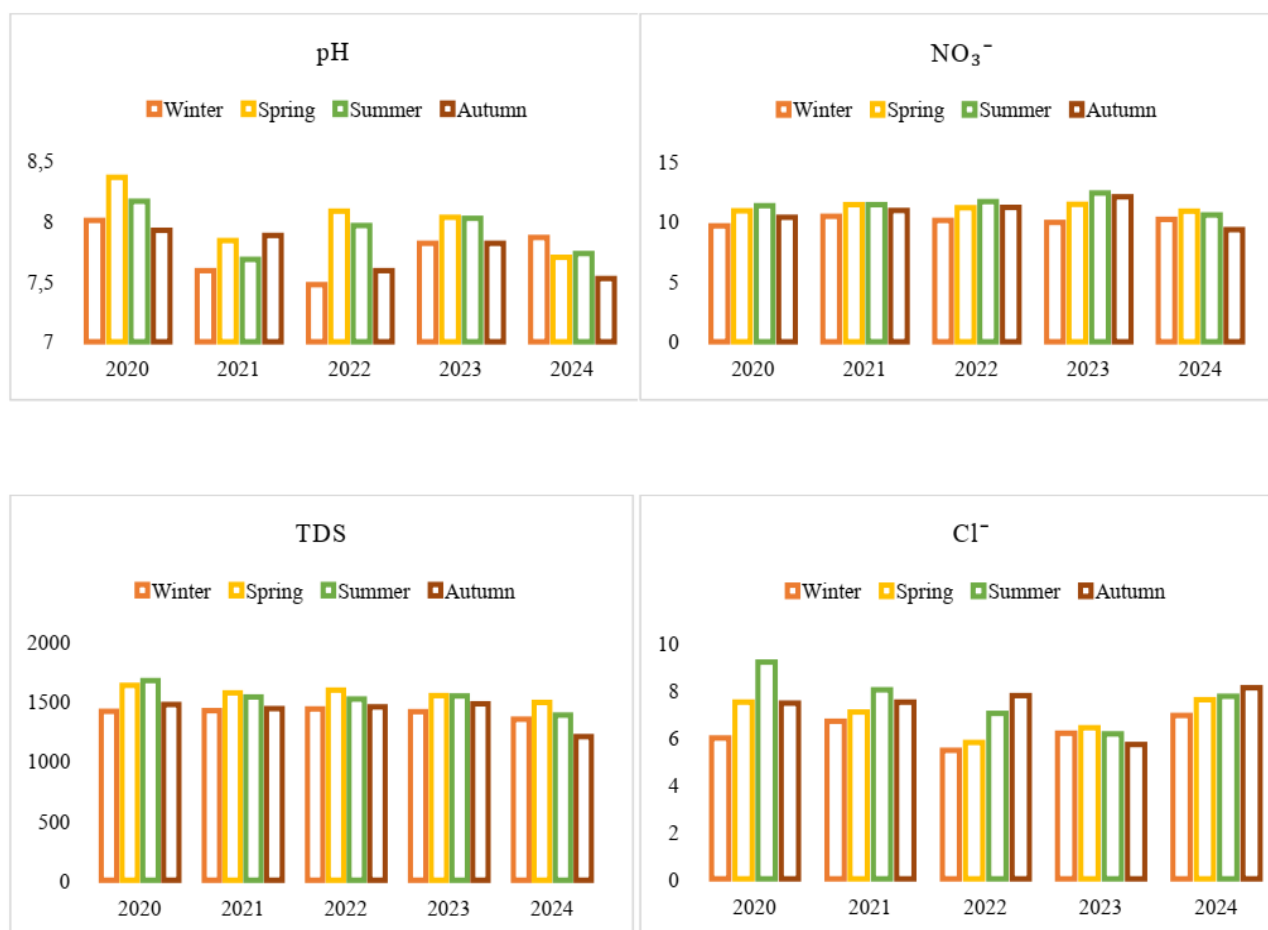|	Date	pH	NO$_3^-$	TDS	Cl$^-$		Date	pH	NO$_3^-$	TDS	Cl$^-$
	2024-05	7.9	11.4	1387.1	7.78		2024-05	8.3	13.5	1487.1	4.15
	2024-08	7.5	11.6	1478.1	6.59		2024-08	8.6	11.2	1327.1	4.66
	2024-11	7.7	14.5	1910.0	13.5		2024-11	7.5	8.9	1150.0	7.39
Well 11	2020-02	8.7	8.8	1460.4	5.52	Well 12	2020-02	7.6	10.2	1450.4	6.33
	2020-05	8.5	9.2	1568.7	5.12		2020-05	7.8	11.7	1776.7	6.48
	2020-08	7.7	9.5	1513.4	5.75		2020-08	7.8	11.8	1710.5	9.89
	2020-11	7.9	8.9	1650.3	4.99		2020-11	7.9	13.5	1630.6	5.8
	2021-02	7.6	10.3	1605.1	6.22		2021-02	7.7	9.6	1440.3	4.95
	2021-05	7.7	11.3	1566.3	5.75		2021-05	6.9	9.4	1590.4	6.31
	2021-08	7.7	10.2	1478.4	6.37		2021-08	6.4	9.1	1580.4	8.75
	2021-11	7.7	9.2	1478.3	5.53		2021-11	7.7	8.7	1450.8	7.22
	2022-02	8	9.6	1458.3	4.2		2022-02	7.6	8.7	1408.3	5.1
	2022-05	7.7	10.6	1580.6	4.95		2022-05	6.9	9.3	1568.6	5.75
	2022-08	7.6	11.5	1547.6	6.13		2022-08	6.9	8.2	1770.5	4.41
	2022-11	6.9	10.7	1591.6	8.4		2022-11	7.7	9.2	1550.9	8.02
	2023-02	8.3	9.2	1420.5	4.7		2023-02	8.5	9.9	1100.4	5.58
	2023-05	8.6	10.2	1536.5	5.03		2023-05	7.6	11.3	1427.2	5.22
	2023-08	8.2	10.6	1530.6	5.59		2023-08	7.6	12.6	1430.6	6.71
	2023-11	8.1	11.6	1540.4	4.83		2023-11	7.7	12.8	1490.2	4.16
	2024-02	8.4	10.3	1533.1	4.4		2024-02	8.5	13.5	1233.1	5.02
	2024-05	8.3	13.5	1487.1	4.15		2024-05	8.3	10.6	1387.1	6.32
	2024-08	8.6	11.2	1327.1	4.66		2024-08	7.6	11.8	1356.1	6.4
	2024-11	7.7	6.8	800	4.34		2024-11	7.9	8.7	990.0	5.13
FAO		8.4	5	450	4	FAO		8.4	5	450	4
Units		pH	mg/l	mg/l	mEq/l	Units		pH	mg/l	mg/l	mEq/l

Figure 2: Quantitative changes in water quality indicators (pH, NO$_3^-$, TDS, Cl$^-$) during the seasons

Table 7. Overall Water Quality Index for sensitive crops

| Data	Samples	WA-WQI		Grade	CCME WQI	
		Index	Water quality		Index	Water quality
2020	S1	238.51	Unsuitable for drinking and fish culture	E	**32.17**	**Poor**
	S2	**229.76**	Unsuitable for drinking and fish culture	E	32.13	Poor
	S3	214.59	Unsuitable for drinking and fish culture	E	18.54	**Poor**
	S4	246.74	Unsuitable for drinking and fish culture	E	19.55	Poor
	S5	281.51	Unsuitable for drinking and fish culture	E	16.33	Poor
	S6	262.89	Unsuitable for drinking and fish culture	E	14.50	Poor
	S7	250.58	Unsuitable for drinking and fish culture	E	17.48	Poor
	S8	258.32	Unsuitable for drinking and fish culture	E	14.69	Poor
	S9	265.53	Unsuitable for drinking and fish culture	E	31.25	Poor
	S10	245.04	Unsuitable for drinking and fish culture	E	17.74	Poor
	S11	236.20	Unsuitable for drinking and fish culture	E	18.54	Poor
	S12	262.90	Unsuitable for drinking and fish culture	E	31.15	Poor
2021	S1	224.86	Unsuitable for drinking and fish culture	E	**26.18**	**Poor**
	S2	224.73	Unsuitable for drinking and fish culture	E	32.58	Poor
	S3	228.01	Unsuitable for drinking and fish culture	E	18.22	**Poor**
	S4	243.18	Unsuitable for drinking and fish culture	E	31.83	Poor
	S5	282.73	Unsuitable for drinking and fish culture	E	18.21	Poor
	S6	259.73	Unsuitable for drinking and fish culture	E	16.72	Poor
	S7	249.05	Unsuitable for drinking and fish culture	E	32.00	Poor
	S8	253.21	Unsuitable for drinking and fish culture	E	31.13	Poor
	S9	248.16	Unsuitable for drinking and fish culture	E	31.55	Poor
	S10	250.09	Unsuitable for drinking and fish culture	E	31.68	Poor
	S11	239.86	Unsuitable for drinking and fish culture	E	32.38	Poor
	S12	236.39	Unsuitable for drinking and fish culture	E	32.43	Poor
2022	S1	253.37	Unsuitable for drinking and fish culture	E	**33.46**	**Poor**
	S2	236.92	Unsuitable for drinking and fish culture	E	19.83	Poor
	S3	206.20	Unsuitable for drinking and fish culture	E	33.81	**Poor**
	S4	229.24	Unsuitable for drinking and fish culture	E	18.04	Poor
	S5	260.60	Unsuitable for drinking and fish culture	E	19.44	Poor
	S6	255.09	Unsuitable for drinking and fish culture	E	19.21	Poor
	S7	245.33	Unsuitable for drinking and fish culture	E	15.52	Poor
	S8	468.51	Unsuitable for drinking and fish culture	E	19.82	Poor
	S9	248.58	Unsuitable for drinking and fish culture	E	19.72	Poor
	S10	256.34	Unsuitable for drinking and fish culture	E	31.76	Poor
	S11	243.00	Unsuitable for drinking and fish culture	E	32.24	Poor
	S12	240.35	Unsuitable for drinking and fish culture	E	48.21	Poor
2023	S1	255.08	Unsuitable for drinking and fish culture	E	**34.23**	**Poor**
	S2	253.19	Unsuitable for drinking and fish culture	E	31.10	Poor
	S3	229.58	Unsuitable for drinking and fish culture	E	32.80	**Poor**
	S4	448.40	Unsuitable for drinking and fish culture	E	32.70	Poor
	S5	254.40	Unsuitable for drinking and fish culture	E	17.08	Poor
	S6	262.37	Unsuitable for drinking and fish culture	E	18.76	Poor
	S7	248.89	Unsuitable for drinking and fish culture	E	17.34	Poor
	S8	249.37	Unsuitable for drinking and fish culture	E	17.76	Poor
	S9	236.51	Unsuitable for drinking and fish culture	E	32.58	Poor
	S10	235.28	Unsuitable for drinking and fish culture	E	33.00	Poor
	S11	235.83	Unsuitable for drinking and fish culture	E	20.61	Poor
	S12	226.25	Unsuitable for drinking and fish culture	E	17.05	Poor
2024	S1	192.66	Unsuitable for drinking and fish culture	E	**32.60**	**Poor**
	S2	305.16	Unsuitable for drinking and fish culture	E	28.79	Poor
	S3	188.36	Unsuitable for drinking and fish culture	E	28.74	**Poor**
	S4	195.15	Unsuitable for drinking and fish culture	E	31.29	Poor
	S5	162.55	Unsuitable for drinking and fish culture	E	32.94	Poor
	S6	180.36	Unsuitable for drinking and fish culture	E	32.55	Poor
	S7	161.09	Unsuitable for drinking and fish culture	E	34.27	Poor
	S8	166.28	Unsuitable for drinking and fish culture	E	33.53	Poor
	S9	200.54	Unsuitable for drinking and fish culture	E	30.74	Poor
	S10	179.19	Unsuitable for drinking and fish culture	E	20.81	Poor
	S11	201.40	Unsuitable for drinking and fish culture	E	19.34	Poor
	S12	173.26	Unsuitable for drinking and fish culture	E	20.98	Poor
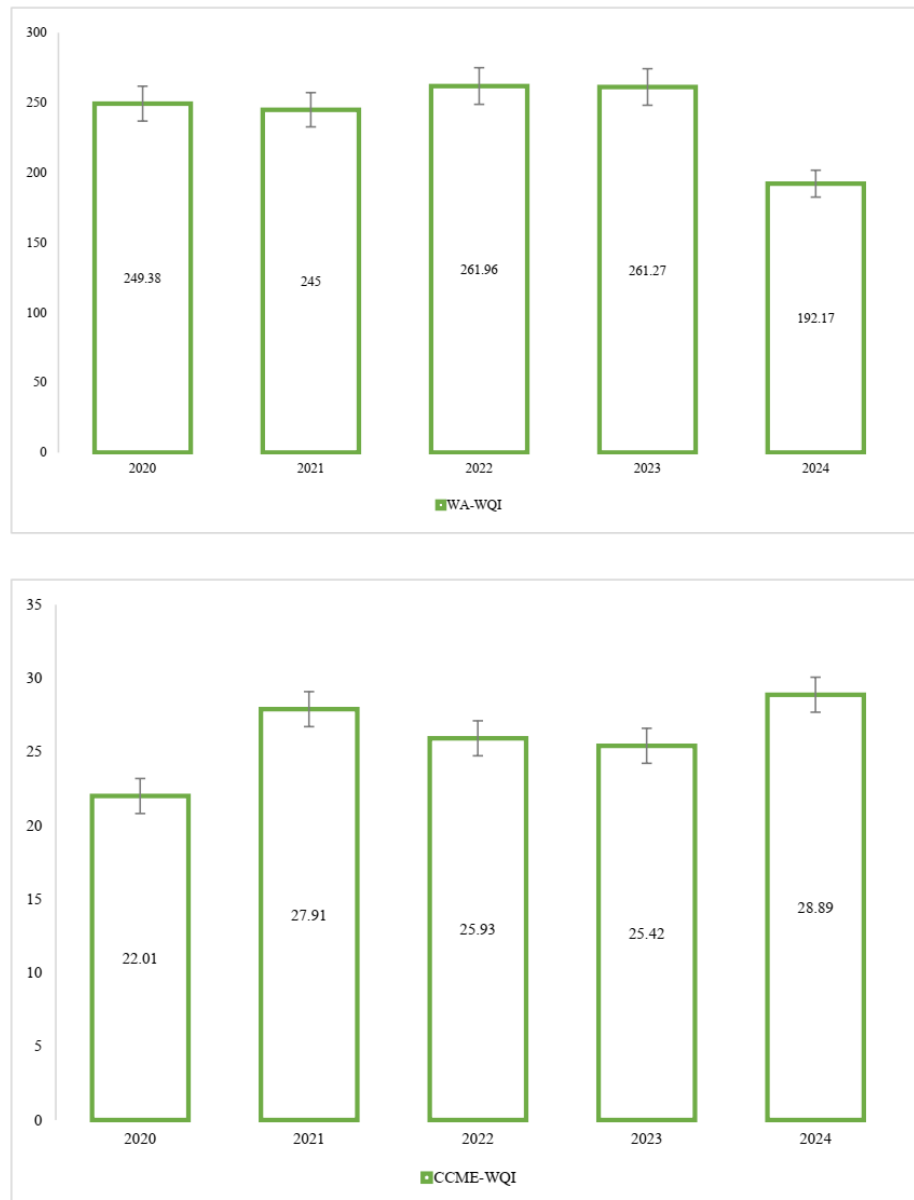
Figure 3: Water Quality Indices of Water Samples Taken from a Total of Twelve Wells

According to results from WA-WQI and CCME WQI models, the potential for irrigating low-tolerance plants is nearly 100 % restricted. The major parameters negatively affecting water quality are TDS, NO_3^-, and Cl^-, with values significantly exceeding FAO standards. Groundwater typically has high mineral content, with its qualitative variations potentially attributable to agricultural activities and geological rock formations (Ojukwu *et al.*, 2021; Alexakis *et al.*, 2022; Uddin *et al.*, 2023; Mohseni *et al.*, 2024). Figure 3 illustrates the mean values obtained from WA-WQI and CCME WQI models. Both models indicate extremely low water quality indices.

However, this water can be used for irrigating highly tolerant crops under limited water availability conditions, as tolerant plants can adapt to various challenging ecological conditions.

CONCLUSIONS

The overall water quality index of groundwater formed in the Amudarya region is very low, limiting its direct use for irrigating low-tolerance crops. According to FAO guidelines, improving water quality requires

managing irrigation and growth conditions while considering each plant's ecological tolerance level. Additionally, agricultural water conservation and ecological sustainability can be achieved by planting salt-tolerant crops. So according to our results we can make following recommendations:

1. To improve groundwater quality in the Amudarya region, it is necessary to enhance irrigation systems, select salt-tolerant plants, and implement optimal water usage in irrigation.

2. Agricultural water conservation, water quality improvement, and agrocenosis sustainability can be achieved through planting salt-tolerant species. Therefore, establishing plantations with high-tolerance crops is essential.

CONFLICTS OF INTEREST

The authors declare that they have no potential conflicts of interest.

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