GIS-based evaluation and mapping of soil salinization: a case study of Khovos district, Syrdarya province, Uzbekistan

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Abstract. Unsustainable agricultural practices, including excessive irrigation and fertilization, lead to soil salinization in arid and semiarid regions. Understanding the spatial patterns of soil salinization is crucial for implementing effective land management strategies. In this study, we evaluated and mapped soil salinization, shallow groundwater table, and groundwater mineralization. In addition, the impact of groundwater mineralization on soil salinization has been assessed. The results revealed a declining trend in the groundwater table, with the majority of irrigated lands, exhibiting groundwater depths of 2-3 m. The groundwater mineralization has also presented a declining trend; however most irrigated lands have remained within the mineralization of 2–3 and 3–5 g/L. The irrigated lands across the district were slightly saline and moderately saline, although highly and extremely saline areas were present in 2020s. It was found that the slightly and moderately saline areas were driven by groundwater mineralization of 1–2 and 2–3 g/L, respectively, whereas groundwater mineralization of 3–5 g/L also played a major role in moderate soil salinization. The outcomes of this study could be used to reduce soil salinization risks.

1 Introduction

Soil salinization is one of the most pressing agroecological challenges, exerting a profound impact on global agriculture and sustainable development worldwide [1]. Induced by natural factors (i.e., elevation, low-lying and poorly drained topography, arid and semi-arid climate, parent rock material) and human activities (i.e., inefficient irrigation, improper fertilization, deforestation, and the removal of deep-rooted vegetation), salinization poses not only serious threats to crop production and agricultural development, but also to human survival [2]. Affecting soil fertility, soil structure, and plant growth, salinization of irrigated soils leads to land degradation and reduced crop yields, thereby posing a long-term threat to food security [3]. Generally, although soil salinization is viewed as a prevalent issue mostly in arid and semiarid regions, no climatic zone is totally free from this problem, with over 100 countries globally being a victim of land salinization [4]. The Food and Agricultural Organization (FAO) reports for 2021 that 424 million ha of top soil and 833 million ha of sub soil are salt-affected [5]. Moreover, previous studies have highlighted that one billion ha of the terrestrial ecosystem and 20% of the global croplands have become salinized due to human activities [6, 7]. The ongoing salinization is projected to affect up to 50% of the croplands by 2050 under different changing climate scenarios unless proper agricultural practices are implemented [8]. Consequently, it will lead to agricultural land degradation, irrigated land loss and food shortages, necessitating urgent and sustainable management strategies.

Uzbekistan is confronted with complex and multi-faced environmental challenges, stemming from mostly climate change and inefficient agricultural practices [9]. Soil salinization has emerged as a growing threat in the country, affecting more than a half of the irrigated lands, and significantly reducing agricultural production [10]. The problem of soil salinization is largely driven by arid and semi-arid climate, low-quality irrigation water, dysfunctional drainage systems, elevated shallow groundwater table and increased mineralization [11, 12]. On the other hand, high air temperatures, especially during summer, intensify the evaporation of mineralized shallow groundwater, leaving salts behind, thereby leading to salt accumulation in the soil profiles [13].

To better understand the underlying mechanisms of soil salinization, several studies have been conducted in Uzbekistan [11, 12, 13]. For example, Ibrakhimov et al. studied the spatial distribution of groundwater table (GWT) and groundwater mineralization (GWM) and their potential influence on soil salinization (SS) in Khorezm province, a region that exhibits typical arid climate, with an air temperature exceeding 33°C and a precipitation being less than 100 mm/year. By monitoring GWT, GWM and SS at a field scale, they calculated that the annual precipitation is 10 times exceeded by potential evapotranspiration, thereby leading to intensified salt accumulation, and adding 3.5 to 14 t/ha salts [14]. Similarly, Khasanov et al. evaluated the spatiotemporal changes in shallow GWT and GWM, and SS in Syrdarya province. They found that the

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moderate and severe SS types are mainly driven by GWM of 5 to 10 g/L once the GWT is 1 and 1.5 m deep. Furthermore, they revealed that the air temperatures during the summer season accelerate the evaporation and salt accumulation [13]. Kulmatov et al. investigated the SS in Jizzakh province, considering the impact of mineral fertilizers on shallow groundwater and SS. They founded that the irrigated lands in the province are largely threatened by increasing mineralization and chloride concentrations in groundwater [15].

Considering the above-mentioned studies, it could be concluded that soil salinization is mainly caused by elevated GWT and increased GWM in Uzbekistan. However, a major limitation of these studies is that they have not considered district-level variations within provinces in soil salinization studies, which play an important role in the agriculture sector of Uzbekistan. In addition, previous studies have rarely used GIS-based approaches for mapping SS, GWT, and GWM, since the province is considered as a homogeneous unit, which makes it difficult to implement effective meliorative measures. Moreover, the impact of GWM on SS dynamics has been insufficiently considered in previous studies. Therefore, this paper aims to evaluate and map the spatio-temporal changes in shallow GWT, GWM, SS, and to analyze how the GWM affects SS. The Khovos district of Syrdarya province function as a case study area.

2 Materials and methods

2.1 Study area

The Syrdarya province is one of the economically and agriculturally important provinces of Uzbekistan. The province comprises eight districts (Oqoltin, Bayavut, Saykhunabad, Gulistan, Sardoba, Mirzaabad, Syrdarya, and Khovos) and five cities (Yangiyer, Bakht, Shirin, Syrdarya, and Gulistan), with a total area of 427,618 ha. Agricultural lands cover 371,19 ha, of which 287,14 ha (77.3% of the total area) are irrigated. The irrigated lands of the province are affected by varying degrees of salinity; 154.7 thousand ha (53.9%) are slightly saline, 89.9 thousand ha (31.3%) moderately saline, 18.4 thousand ha (6.4%) strongly saline, and 7.2 thousand ha (2.5%) very strongly saline. Non-saline lands account for only 16.9 thousand ha (5.9%) [16]. The climate is typically semi-arid continental, characterized by hot and dry summers [12]. Precipitation mainly occurs in winter and spring. The Garmsel wind dominates during the hottest days of the year, accelerating soil moisture evaporation and thereby leading to accelerated soil salinization [13].

Established in 1966, Khovos is one of the major districts within the Syrdarya province. It covers a total area of 61,95 ha and has a population of 104.1 thousand [17].

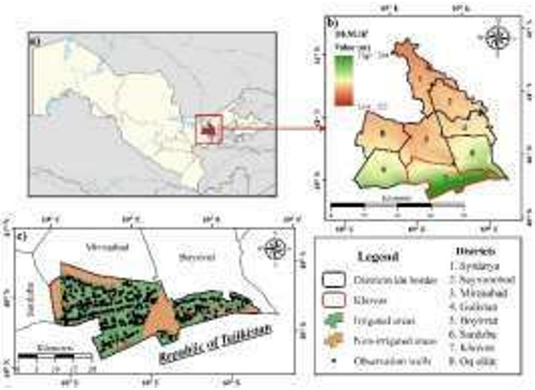

Fig. 1. a) Syrdarya region within Uzbekistan, b) Khovos district within Syrdarya region, and c) observation wells in the irrigated lands of the Khovos district.

The district encompasses 51,984 ha of agricultural land, including 39,952 ha of irrigated croplands, 1,836 ha of perennial plantations, 2,834 ha of fallow land, 1,265 ha of hayfields, and 944 ha of forested areas. Geographically, the district borders Boyovut to the northeast, Bekobod to the southeast, Zomin to the west, and Sardoba and Mirzaabad to the southwest and west, respectively.

2.2 Data collection and mapping

For monitoring GWT and GWM across the district, 308 observation-wells have been installed as shown in Figure 1c. GWT and GWM are measured in April, July, and October each year, while SS is analysed traditionally by collecting soil samples with subsequent laboratory analysis in mid spring and autumn. These monitoring activities are carried out by the Lower Syrdarya Irrigation Systems Basin Authority under the Ministry of Water Resources. The organization performs SS assessments in accordance with FAO requirements [18]. We collected 5-year GWT, GWM and SS data from the local branch of this organization for 2020 and 2024. The collected data were integrated into a GIS and mapped using the Inverse Distance Weighting (IDW) method, which is implemented in many GIS packages. We used this method because several studies conducted in Uzbekistan have shown that IDW is the most suitable method for mapping, owing to its straightforward interpretability, ease of computation, and superior predictive performance relative to Spline and Kriging for generating SS maps [13, 16]. Specifically, Pulatov et al. investigated several techniques for mapping SS in the Mirzaabad district, which borders the Khovos district. They concluded that the IDW with power 2 yielded the most accurate results among the interpolation techniques when cross-validated [19]. The maps depicting the spatio-temporal distributions of GWT, GWM, and SS were generated using ArcGIS 10.8 [20].

3 Results and discussion

3.1 Descriptive statistics

Table 1 presents descriptive statistics of soil salinity (EC), groundwater table (GWT) and groundwater mineralization (GWM). The mean soil EC is 3.93 dS/m. This value shows that the irrigated lands in the study area are slightly saline. The minimum and maximum values range from 1.92 to 10.57 dS/m, with a difference of 8.64 dS/m, indicating a substantial spatial variability in soil salinization. The standard deviation of 1.18 confirms the heterogeneous salinity distribution across the district.

Table 1. Descriptive statistics (2247 samples) of Soil Salinity, Groundwater Table, and Groundwater Mineralization.

	Soil EC	GWT (m)	GWM (g/L)
Mean	3.929	2.88	3.087
Minimum	1.923	1.49	1.898
Maximum	10.567	6.57	5.010
Range	8.644	5.08	3.112
Standard Error	0.025	0.05	0.026
Standard Deviation	1.177	0.81	0.454
Median	3.609	2.67	3.039
Sample variance	1.384	0.65	0.206

The GWT is 2.88 m, varying from 1.49 to 6.57 m, with a range of 5.08 m. This result indicates generally shallow groundwater conditions in large parts of the study area. This depth of groundwater can be seen shallow, yet could enhance capillary rise and promote salt accumulation in the root zone, thereby increasing the risk of secondary soil salinization.

The GWM exhibits a mean value of 3.09 g/L, with minimum and maximum values being 1.90 and 5.01 g/L, respectively. The observed range of 3.11 g/L indicates high variability in mineralization levels, suggesting high potential for soil salinization in most areas.

The standard deviations of Soil EC (1.18), GWM (0.45), and GWT (0.81) demonstrate noticeable variability around their mean values. In addition, the relatively small standard errors indicate high precision in estimating the average values. The median values were close to the corresponding means, suggesting relatively balanced data distributions, although the presence of extreme values influenced overall variability.

3.2 Groundwater table dynamics

Identifying the spatial and temporal variations in GWT in irrigated areas is essential for developing effective strategies to mitigate soil salinization [15]. Figure 2 illustrates the changes in GWT across the irrigated lands of Khovos district over five years (2020–2024). The maps highlight that the irrigated areas with a very shallow GWT of 0 – 1 m was observed only in small areas for the observed period. Similarly, the areas with GWT of 1 – 1.5 m can be detected in small patches. This could be explained by the fact that in October agricultural practices, especially irrigation, is not performed, thus leading to a decline in GWT.

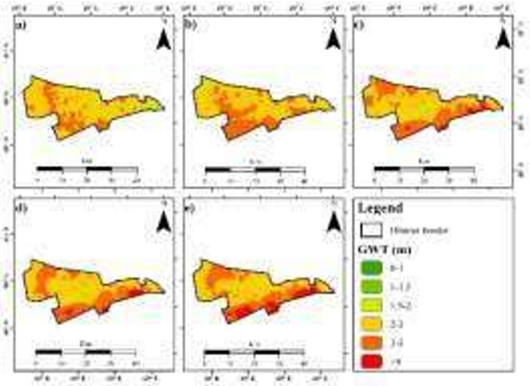

Fig. 2. Spatio-temporal variations of the groundwater table (GWT) by years: a) 2020, b) 2021, c) 2022, d) 2023, e) 2024.

During the study years, the GWT was predominantly within the ranges of 2–3 m and 3–5 m across the district. However, in the later years, 2023 and 2024, the GWT in the areas bordering Tajikistan has experienced a decline to a depth of 5 m. This is explained by the fact that the elevation in these areas is relatively high compared to other parts of the district, being as high as 394 m. Thus, the shallow groundwater in irrigated soils is quickly evaporated, leading to its quick decline. During the study period, overall, the GWT was predominantly observed at depths of 2–3 m and 3 – 5 m.

Table 2 shows the GWT dynamics in hectare. According to the table, the areas with a very shallow GWT (0–1 m) were observed only rarely, which is highlighted in the Figure 2.

Table 2. Dynamic changes in the groundwater table (in ha).

GWT classes depth (m)	2020	2021	2022	2023	2024
0 – 1	7.2	15.48	54.81	20.61	27
1 – 1.5	351.18	19.44	134.1	83.88	78.84
1.5 – 2	4,977.6	2,463.5	2841.8	2,951.5	1769.7
2 – 3	44,628.5	39,503.2	34,817.6	35,028.9	33,699.4
3 – 5	14,192.64	22,211.01	24,634.98	23,723.19	22,260.96
>5	193.41	137.61	1,867.2	2,542.5	6,514.6

For example, in 2020, such areas accounted for 7.2 ha (or 0.02%), while by 2024 these areas increased slightly to 27 ha (0.04%), followed by 54.81 ha (or 0.08%) in 2022. The irrigated fields with a GWT of 1 – 1.5 m were somewhat more widespread compared to very shallow depths, but still occupied only a small portion of the irrigated lands. Specifically, such areas covered 351.18 ha (0.54%) in 2020, declining steadily to 78.84 ha (or 0.11%) by 2024. This small extent of very shallow GWT (0 – 1 m) and shallow groundwater levels can be considered an unsatisfactory indicator, since the closer groundwater lies near to the soil surface, leads to the higher evaporation with an increased risk of soil salinization.

The irrigated areas with GWT of 1.5–2 m were 4977.6 ha (or 7.74%) in 2020, but these areas declined to 1,769.7 ha (or 2.75%) by 2024, indicating a reduction of 3,207.9 ha or 5%. Likewise, GWT of 2–3 m and 3–5 m holds the largest share of the irrigated areas in the district in 2020, covering 44628.6 ha (69.35%) and 14,192.64 ha (22.05%), respectively. By 2024, however, those areas also decreased to 33,699.42 ha (52.35%), while 3–5 m depth areas expanded to 22,260.96 ha (34.6%). Also, significant alterations were detected in the GWT >5.0 m. Initially, these areas covered only 193.41 ha (or 0.3%), but by 2024 they expanded markedly to 6514.65 ha (10.13%). These dynamic changes in GWT over last years present a general declining trend. Although this trend appears to be a satisfactory indicator for land conditions, as its impact on salt accumulation in the upper soil layer is relatively weak, it might reduce soil moisture, thereby leading to desertification [12].

3.3 Groundwater mineralization dynamics

Figure 3 shows the spatio-temporal variations in GWM across the irrigated lands in the Khovos district. It can be seen that the shallow groundwater was highly mineralized, with the mineral content being around 2 – 3 g/L and 3 – 5 g/L.

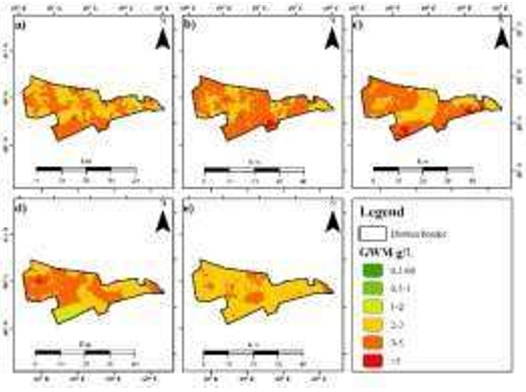

Fig. 3. Spatio-temporal variations in groundwater mineralization (GWM) by years: a) 2020, b) 2021, c) 2022, d) 2023, e) 2024.

In almost all years, except 2024, the majority of the irrigated lands had a GWM of 3 – 5 g/L, indicating that these lands had a high risk of salinization. Irrigated fields with a GWM of 1–2 g/L were observed only in limited areas, while the irrigated fields with low (0.6–1.0 g/l) and very low (0.4–0.5 g/l) mineralization were detected only in 2023. Several studies in Uzbekistan have revealed that GWM increases while GWT decreases, particularly in October after agricultural practices are completed [14, 15, 16]. This finding is consistent with the results obtained in our study area.

For the same study period, the irrigated areas with differently classified GWM were calculated in hectare as given in Table 3. The irrigated areas with very low GWM (0.4–0.5 g/L) engage only 9.72 ha (0.01%) in 2020, followed by a decline of 1.17 ha in 2024. Similarly, the areas with a GWM of 0.6–1 g/L engage 73.62 ha (or just 0.11%) in 2020, and these areas also decreased to 7.65 ha (or 0.01%) in 2024, indicating a downward trend. The irrigated lands with a moderate mineralization (1–2 g/L) covered 1,722.42 ha (or 2.68%) in 2020, followed by a decrease to 641.7 ha (1%) in 2024, indicating a decline of nearly 1,000 ha in the last 4 years. Nevertheless, this category peaked in 2023, reaching 4,970.97 ha (or 7.73%), while in 2021 it was at its lowest, covering only 435.96 ha (or 0.68%).

Table 3. Dynamic changes in the groundwater mineralization (GWM) (in ha).

GWM classes (g/L)	2020	2021	2022	2023	2024
0.4 –0.5	9.72	1.44	2.61	0.63	1.17
0.6 – 1	73.62	19.71	26.28	8.01	7.65
1 – 2	1722.42	435.96	1668.78	4970.97	641.7
2 – 3	32946.12	20477.88	22416.93	26450.28	36843.39
3 – 5	29598.75	43415.64	40236.03	32920.74	26856.72

In 2020, the irrigated areas with a GWM of 2–3 g/L and 3–5 g/L were accounted for 32,946.12 ha (or 51.2%) and 29,598.7 ha (or 46, 0 %), respectively. In 2024, the area with a GWM of 2–3 g/L had increased by 6% to 36,843.4 ha (57.25%). In comparison, the irrigated fields with a GWM of 3–5 g/L decreased to 26,856.7 ha (41.74%), representing a 5.2% reduction. Overall, the irrigated areas with a GWM of 0.4–0.5 g/L, 0.6 –1 g/L, and 1–2 g/L declined, while the areas, having a GWM of 2–3 g/L increased correspondingly.

3.4 Soil salinization dynamics

Figure 4 shows the spatio-temporal changes in SS. The majority of irrigated lands in the studied district were slightly saline (2-4 dS/m), followed by moderately saline (4-8 dS/m). Between 2020 and 2022, moderately saline (4-8 dS/m), along with slightly saline (2-4 dS/m) areas, were dominant, covering a large portion of the district. However, from 2023 onwards, the irrigated areas in the district were dominated by the slightly saline (2-4 dS/m) areas. This trend could be interpreted as a relatively positive indicator, since most agricultural crops cultivated in Uzbekistan are relatively adapted to slightly saline soils [9].

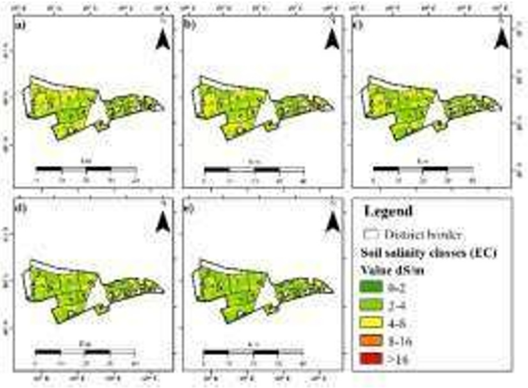

Fig. 4. Spatio-temporal variations in soil salinization (SS) by years: a) 2020, b) 2021, c) 2022, d) 2023, e) 2024.

The extent of each class calculated in hectares is given in Table 4. According to this table, non-saline (0-2 dS/m) areas have significantly decreased over the years. For example, in 2020, this class had 87.66 ha (0.19%), whereas in 2024, it had reduced to 31.95 ha (0.07%), experiencing a decrease of nearly 0.12%, indicating intensified salt accumulation.

Table 4. Dynamic changes of soil salinization (SS) (in ha).

SS classes	2020	2021	2022	2023	2024
Non-saline	87.66	48.15	61.65	66.87	31.95
Slightly saline	24173.01	24131.34	26529.57	30519.99	33796.35
Moderately saline	21430.35	21951.63	19533.78	15562.08	12366.45
Highly saline	502.02	98.46	104.58	80.64	34.83
Extremely saline	36.54	0	0	0	0

The areas with slight salinization (2-4 dS/m), showed a noticeable increase during the observation period. In 2020, these areas covered 24,173.0 hectares, whereas in 2024 their area has expanded to 33,796.3 hectares, representing a nearly 20% increase of 9,600 hectares. Moderately saline (4-8 dS/m) areas initially increased by 500 ha (1%) between 2020 and 2021. However, from 2021 to 2024, these areas continued to decline, reaching 12,366.4 hectares or 26.75% of the total irrigated area in 2024, approximately 20% less than in the first year of the observation. The areas of highly and extremely saline lands also showed a declining trend between 2020 and 2024. In 2020, the highly saline lands accounted for 502 ha (1.08%) and extremely saline lands for 36.54 ha (0.08%), whereas in 2024 these values had decreased to 34.83 ha (0.08%) and 0 ha, respectively. The reduction in highly and extremely saline areas can be considered as a positive indicator. However, the relatively high proportion of slightly saline lands may reflect declining soil fertility and a potential for further salinization. Therefore, it is necessary to take meliorative measures aiming to reducing the water-soluble salts in soil.

3.5 The impact of groundwater mineralization on soil salinization

SS is mainly driven by a combination of both natural factors and human activities. In dryland areas, intensive agricultural irrigation leads to an increase in shallow GWT and GWM. High temperatures evaporate the soil water, leaving water-soluble salts behind. As a consequence, intensifying salt accumulation in the upper soil profile takes place [13]. Arable land in Uzbekistan is predominantly irrigated, making crop production only possible through irrigation [21]. In addition, the drainage infrastructures remain outdated, with majority being dysfunctional, causing a seasonal formation of increased GWT and GWM [22]. Figure 5 presents the correlative relationship between SS and GWM. In this study, groundwater with a mineralization of 0 – 1 g/L was excluded from the analysis, as this level does not significantly contribute to soil salinization. In addition, the irrigated areas with no salinization were also removed. A weak correlation was detected between the GWM of 1 – 2 g/L and slightly saline areas, indicating the role of GWM in SS is slightly minor. Weak negative correlations with moderately and strongly saline areas were also detected, with corresponding values of -0.24 and -0.03. These values indicate that less mineralized groundwaters could not transform soil into moderately and strongly saline areas.

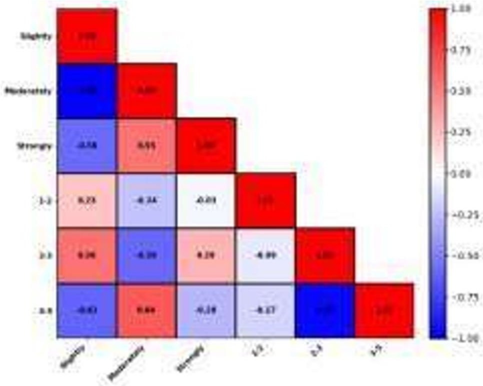

Fig. 5. A correlative relationship between SS and GWM.

The GWM of 2–3 g/L shows moderate and weak correlations with slightly and strongly saline areas, with corresponding correlation coefficients of 0.56 and 0.29, respectively. This indicates that once mineralization in shallow groundwater exceeds 2 g/L and reaches 3 g/L, slightly saline areas begin to emerge and expand, thereby leading to soil salinization. Meanwhile, the GWM of 3–5 g/L showed a moderate correlation (r = 0.64) with moderately saline areas, suggesting that higher groundwater mineralization is associated with stronger correlations with soil salinity. In addition, it revealed moderate-to-weak negative correlations with slightly saline and strongly saline areas, with corresponding coefficients of -0.61 and -0.28, respectively. These negative correlations suggest that the slightly saline areas occur when a GWM is 2 – 3 g/L while strongly saline areas develop with a GWM of >5 g/L or other underlying factors.

4 Conclusion

Soil salinization is presenting a major constraint for irrigated agriculture by significantly affecting sustainable development and crop production in arid regions. Spatio-temporal changes of the groundwater table, groundwater mineralization, and soil salinization were evaluated and mapped, using the Inverse Distance Weighting method. In addition, the influence of groundwater mineralization on soil salinization was analysed. Our main findings are:
(1) The groundwater table shows a declining trend across the Khovos district, with the majority of irrigated areas having 2 – 3 m and 3 – 5 m deep shallow groundwater.
(2) The groundwater mineralization in irrigated lands also presented a downward trend (2 – 3 g/L), although initially being highly mineralized (3 – 5 g/L).
(3) The irrigated areas were found to be slightly saline, although moderately saline areas were initially dominant.
(4) The correlative analysis between soil salinization and groundwater mineralization showed that the groundwater mineralization of 1 – 2 and 2 – 3 g/L leads to slightly saline areas, while moderately saline areas are caused by groundwater mineralization of 3 – 5 g/L.
It is recommended that groundwater mineralization must be reduced to approximately 1 g/L in order to minimize the risk of further moderate and slight salinization. These findings indicate the need for effective meliorative measures aiming to reduce groundwater mineralization.

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