



Assessment of the Space-Time Dynamics of Soil Salinity in Irrigated Areas Under Climate Change: a Case Study in Sirdarya Province, Uzbekistan

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Abstract Saline areas are progressively increasing in irrigated lands of the Aral Sea Basin and this obstructs intensive agricultural development and food security in this region. Such circumstances, leading to the expansion of salt-affected areas, are assumed to become climate change, rising of groundwater levels and its mineralizations, poor functioning of the collector-drainage system, and insufficient compliance with agro-technical requirements. These drivers, in turn, lead to the withdrawal of arable land for agricultural purposes and a significant drop in crop yields. Regarding Uzbekistan, this research on soil salinity assessment was conducted in the irrigated areas of the Sirdarya province by analyzing raw data derived from traditional methods from 2000 to 2015, as well as from 2016 to 2019, using the integrated traditional and geographic information systems (GIS)-based methods. Soil salinity maps of the Sirdarya province were created to investigate spatial and temporal changes in soil salinity using the inverse distance weighting (IDW) interpolation

method based on the results of field survey and laboratory studies. The results of this research revealed that the IDW interpolation method had a great potential and accuracy to map longitudinal changes in salt-affected irrigated areas. Moreover, it was determined that soil salinity highly depends on local terrain conditions and there is a weak dependence on climatic factors. The main findings of this research advocate agricultural specialists and local farmers to get distinctly encouraged to take the following measures to address the actual soil salinity state in the irrigated areas of the province: targeted and economic use of irrigation water; existing drainage networks are in perfect working condition and monitoring their full effective operation; and, lastly, accelerating the integration of innovative GIS technologies into traditional methods.

Keywords Soil salinity · Climate change · GIS · Interpolation · IDW · Irrigation · Statistical analysis · Sirdarya province · Uzbekistan

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1 Introduction

Today, salinization of irrigated agricultural lands is a global environmental problem that negatively affects the sustainable use of land resources, agricultural production, and food security. Salinization processes in irrigated soils lead to reduced crop yields and cause food shortages for countries in the arid zone (Gorji et al. 2015; Mingliang et al. 2016; Zewdu et al. 2017). Also, soil salinity (SS) increases due to the influence of anthropogenic factors as well as strong economic and demographic growth, which leads to a decrease in soil fertility in arid lowlands sensitive to climate change (Chub and Ososkova 2008; Dukhovny and de Schutter 2011; Sokolov 2015; Groll et al. 2015).

SS has become a serious environmental and socio-economic problem worldwide. Globally, one-third of all agricultural land is increasingly saline, covering more than 100 countries and all climatic conditions. Specifically, 1 billion ha of land are saline, including 77 million ha as a result of human activities. Salinity has a particularly negative impact on the economy of arid and semi-arid regions (Sidike et al. 2014; Squires and Glenn 2011). According to the United Nations, about 6 million ha of agricultural land are currently degraded annually by SS. More than 40% of arable land is degraded due to deficiencies in irrigation and land reclamation, heralding arable land unsuitable for cultivation (Abdullaev 2019; Pankova and Konyushkova 2013).

The plains of Central Asia are mainly naturally saline and are considered a potential threat to the development of secondary salinization of the soil (Shirokova and Morozov 2020). Salinization of irrigated lands is causing great damage to agricultural production in the semi-desert and arid regions of this region. In particular, 11.5% of 1.08 million ha of irrigated land in Kyrgyzstan, 16.0% of 719,200 ha in Tajikistan, 33.0% of 2.31 million ha in Kazakhstan, 95.9% of 1.74 million ha in Turkmenistan, and around 50% of 4.28 million ha in Uzbekistan are prone to soil salinization at different levels (Bucknall et al. 2011; Shirokova et al. 2000). On the other hand, climate change and arid climates also naturally increase soil salinity levels in arid and semi-arid regions because of a high evaporation rate of mineralized groundwater (Akcura et al. 2008). Besides, due to intensive irrigation farming, there is secondary soil salinization of irrigated lands in the countries located in the lower Aral Sea Basin, especially in Turkmenistan, Uzbekistan, and southern Kazakhstan (Hbirkou et al.

2011; Kitamura et al. 2006). In Uzbekistan, saline soils account for 50% of irrigated land: weakly saline soils 30%, moderately saline soils 16%, and heavily saline soils 4%. Nowadays, 77% of irrigated lands in the Republic of Karakalpakstan, 100% in Khorezm province, 87% in Bukhara province, 79% in Jizakh province, and 87% in Navoi province are saline at different degrees (Kulmatov 2018; MoA (Ministry of Agriculture) 2020; MWR (Ministry of Water Resources) 2020).

Especially in recent years, there has been deterioration in the reclamation of irrigated lands near the Aral Sea and the geography of saline irrigated lands is expanding from year to year. In Bukhara, Navoi, and Jizakh provinces, Kulmatov et al. (2015, 2018) and Mirzaev et al. (2018) conducted many investigations with traditional methods on the efficient use of water and irrigated land resources, assessment of groundwater level and mineralization of irrigated lands, and improving the reclamation status of arable land. According to these studies, over the past 20–25 years, extensive use of irrigated land in these provinces, deficiencies in irrigation and drainage networks, rising groundwater levels, increasing its mineralization, and climate change have led to salinization of irrigated lands. In determining the salinity level of irrigated lands, mainly traditional methods were used and served as the fair basis for obtaining satisfactory data (Kulmatov et al. 2015; Vargas et al. 2018; Mirzaev et al. 2018).

Subsequent studies have proven that the integration of traditional methods and GIS technologies is an effective tool in studying SS (Krishnamurthy et al. 2019; Solomon and Quiel 2018). In line with GIS technologies, remote sensing data provide accurate spatial data and allow for faster and more efficient detection and assessment of large-scale salt-affected areas than common traditional methods Mingliang et al. (2016). GIS technologies facilitate the integration and analysis of large amounts of data. But, supplementary field research enables to justify and verify the accuracy of GIS-based results (Nayak et al. 2015; Solomon and Quiel 2013). GIS technologies are currently widely used in determining and assessing the salinity level of irrigated areas. GIS technologies in investigating SS also support obtaining exceptional results, playing an important role in the accurate assessment of SS (Nayak et al. 2015; Sadat-Noori et al. 2014).

Many scientists and experts in developed and developing countries have studied the relationship between the salinity levels of irrigated areas and groundwater

level and its mineralization, and other anthropogenic influences using and comparing GIS-based methods (interpolation, vegetation, and hydrological indices) (Kulmatov et al. 2018; Solomon and Quiel 2018). As a result, the acceleration of the soil salinization process in irrigated lands under the impact of climate change on groundwater levels and its mineralization has been largely studied and scientifically satisfactory results have been obtained and validated. Moreover, it was noted that the GIS-based methods used in these studies were more likely to give the expected results if they were iterated in other areas similar to the geomorphology of studied areas.

Akramkhanov et al. (2008), Amézketa Lizárraga (2007), Kulmatov (2014), Pankova et al. (2018), and Sadiev et al. (2019) primarily conducted their research depending on the traditional approach of studying the distribution of SS in experimental fields of such study sites, similar to the nature of Uzbekistan. This led to obtaining favorable results without integrating GIS technologies. Platonov et al. (2015) and Khasanov (2019) estimated the widespread of SS in Uzbekistan using the normalized difference vegetation index (NDVI), a tool of remote sensing. The results obtained have been proven to be statistically accurate, despite having a lack of in-field research. Thermography, another innovative method of remote sensing, was applied to probe SS by estimating canopy temperature and was proposed in Uzbekistan by Ivushkin et al. (2017). This method was used for only one experimental year and was compared with other SS assessment methods, thus requiring further research involving perennial analyzes.

Ibrakhimov et al. (2020), Pulatov et al. (2020), and Sultanov et al. (2018) applied three different GIS-based methods to determine the latitudinal distribution of SS: (1) inverse distance weighting (IDW), (2) kriging, and (3) spline. Kriging and IDW methods were compared with the spline method in estimating groundwater mineralization, which is a factor influencing soil salinization processes. The kriging method showed favorable results in determining groundwater mineralization, while the IDW method rendered satisfactory results in determining the distribution of SS. According to the results of these studies, the error of the spline method was high and it was not encouraged to use in the determination of SS in the context of Uzbekistan, and instead used the IDW method.

The literature review above pinpoints that the analysis of perennial data on salinity of irrigated lands was

undertaken by mainly relying on traditional methods. Besides that, GIS-based methods to assess SS were applied under a restricted period of time. However, in such areas where the groundwater table is close, there is a lack of scientifically based data and maps using GIS-based methods, tracing the salinity of irrigated land over time as groundwater levels rise.

With this in mind, this study aims to determine the dynamic changes in SS levels under the influence of climatic factors during 2000 to 2015, combining traditional research methods and GIS technologies at the example of irrigated lands of the Sirdarya province, as well as to verify the accuracy of GIS-based approach results.

2 Study Area

Sirdarya province is one of the main economic areas of agriculture in Uzbekistan, located in the center of the country on the left bank of the Syr Darya River. The province borders Kazakhstan, Tajikistan, Tashkent, and Jizakh provinces of Uzbekistan. Sirdarya province covers an area of 4300 km² and the Mirzachul Steppe occupies a large part of this province. The average altitude of Sirdarya province is 300 m above sea level. The province is divided into eight administrative districts: Sirdarya, Saykhunabad, Gulistan, Boyout, Khovost, Mirzaabad, Akaltin, and Sardoba districts [SCSRU 2020]. The total irrigated area of Sirdarya province, according to 2019's data, is 287,900 ha (Fig. 1) (Chernishov and Shirokova 2019).

The climatic conditions of the study site are sharply continental, characterized by dry and hot summers. Precipitation is mainly observed in winter and spring. Often a hot wind (*garmsel*) blows and dries the soil, adversely affecting plant development (Uzhydromet 2020). According to Uzhydromet (2020), in 2009–2019, the average annual temperature was 14.8°C, followed by the highest average annual temperature of 15.8 °C and the lowest of 13.72 °C in 2014.

The largest amount of precipitation in the province falls in the winter and spring months. The largest and smallest amounts of precipitation were 447 mm in 2018 and 236 mm in 2014. The rainiest year was 2012 and the least rainy happened to be in 2014. The main reason why we pay more attention to the climate of this province is that the hydro-meteorological data of the area have a direct impact on the level and mineralization of



Fig. 1 Location of Sirdarya province

groundwater, thus causing secondary salinization of soils in irrigated areas.

3 Methodology

Determining the SS level and its occupying area is important in preventing salinization of irrigated areas. There are various methods for determining SS, one of which is straightforward and suitable for field use to determine the soil electrical conductivity (EC). Assessment of SS for irrigated lands of the Sirdarya province has been carried out since 1992 by the Hydro-Technical Land Reclamation Expedition under the Regional Basin Irrigation Systems Administration under the Ministry of Water Resources, as well as the State Committee for Land Resources, Geodesy, Cartography, and State Cadaster (2018).

To constantly monitor SS, the reclamation expedition conducts field surveillance in the spring and autumn of the year. It is important to note that we also participated in the research work of the field expedition in 2019–2020 (Fig. 2). As of October 2016–2019, soil samples were taken for analysis from an average of 3800 points per year from about 287,600 ha of irrigated areas in Sirdarya province. Samples were taken from depths of

0–30, 30–70, and 70–100 cm of the soil layer, with a total average of 11,400 soil samples taken each year to determine soil salinity. For analysis, soil samples taken out of 0–30 cm and 30–70 cm depths are considered. Regarding soil samples from 70 to 100 cm layer, they are in many cases omitted. This is because the analysis results of these samples do not influence the overall analysis results of a sampling point.

In the field, the SS was determined using the digital conductometer-thermometer “PROGRESS 1T” (Fig. 2). This device is easy to use in fieldwork due to its lightweight structure, and convenient location of electronic components. In on-site studies, a mechanical drill was used for sampling in such circumstances where the soil was hard to sample.

Data for 2000–2015 years were deeply and statistically analyzed, and data taken out for 2016–2019 years served to compare and verify the advances of GIS technologies in contrast to the in-field results (LSBAIS 2020). As long as these studies aim at providing an insight into the distribution of differently classified values of SS levels in the “PROGRESS 1T” device on the irrigated lands of the province, it is necessary to analyze the classified values of SS. SS depends on many factors: soil properties, groundwater level and its mineralization, irrigation methods and agronomic practices,



Fig. 2 Process of determining soil salinity using the digital conductometer-thermometer “PROGRESS 1T”

critical depth, drainage system efficiency, and type of crops planted (Rhoades et al. 1999). Rhoades et al. (1999) pointed out that, for irrigated lands based on the electric conductivity (EC) data, values of SS identified by an EC meter were used to classify SS as follows to determine the extent to which the amount of salts does not affect crop yields (growth) during the entire growing season (Table 1).

For the spatial analysis of SS distribution, four satellite images taken in the 2016–2019 years were used for this research. The sensor of the satellite images was Landsat (for more information about Landsat, see CRISP), downloaded from the Earth Explorer database, for analysis of primary raw data. Date of downloaded Landsat images was selected according to the collected primary data for April 2016, 2017, 2018, and 2019, respectively. These satellite images were then used to assess the various levels of SS present in the irrigated lands of Sirdarya province to track the spatial and temporal changes in SS patterns. The COST model was used to improve the satellite image quality and filtering was performed using Erdas Imagine 2015 (ERDAS 2015; Wu et al. 2005). Although the satellite images were automatically coordinated, they were geometrically corrected again to accurately fit the local coordinate system. With the help of ArcGIS 10.6 (ESRI 2018), SS maps for the irrigated areas of the Sirdarya province were created using the IDW interpolation method through considering and entering primary raw field data on SS derived in April of 2016–2019 years.

The main reason for choosing the IDW method is that this method uses a simple mathematical algorithm built upon statistical modeling Ibrakhimov et al. (2020). In this method, the square root value of the errors is minimized. According to Pulatov et al. (2020), Sultanov et al. (2018), and Ibrakhimov et al. (2020), negligible errors in mapping SS were detected by the IDW method. Results of these studies have shown that the IDW method has proven to render satisfactory results in determining the spatial distribution of SS when there was sufficient information (Eshchanov 2008; Ibrakhimov 2004). It should be noted that IDW interpolation also does not provide a 100% result. Considering this aspect, the overall accuracy level (ACC_{overall}) of the SS maps over the irrigated area was determined using the following equation based on Woodcock and Gopal’s method (Woodcock and Gopal 2000):

$$ACC_{\text{overall}} = \frac{D_{\text{maps}}}{D_{\text{reference}}} \cdot 100\%$$

where D_{maps} is the data from a particular map, and $D_{\text{reference}}$ is the primary data.

After determining the accuracy of GIS-based interpolated SS maps by comparing with primary SS data, a statistical analysis to prove the extent to which climatic factors (perennial average air temperature and perennial precipitation) affect spatial distribution dynamics of SS is of great importance. From the statistical analysis, a simple Pearson correlation was performed showing the

Table 1 Classification of SS determined for irrigated lands in relation to water-soluble salts and EC values

Soil–water salt concentration		EC values (dS/m)	Cl ions	SS classes	Impacts on agricultural crops
g/l	siemens/cm				
0–3	0–4.5	0–2	>0.01	No salinity	Weak
3–6	4.5–9	2–4	0.01–0.03	Weak salinity	Decreased yield of sensitive crops
6–12	9–18	4–8	0.031–0.07	Moderate salinity	Decreased yield of majority crops
>12	>18	>8	>0.071	Severe salinity	Yield only from halophyte crops

dependence. This analysis was performed using the R studio program (RStudio Team 2017).

4 Results and Discussion

5 Dynamics of Changes in the Salinity Level of Irrigated Lands in Sirdarya Province Within 2000–2015

Data on the SS level determined for irrigated areas of the province were obtained on the administrative districts of Sirdarya province scale and combined to analyze for the entire study area. The results of SS data analysis depending on the primary data for 2000–2015 years are displayed in Fig. 3.

Referring to Fig. 3, during the study years, about 60% of the irrigated area of the province was mainly weak saline areas, and the significance of the growth rate (R^2) over the years was noted as almost 0.7. While non-saline areas were less than about 4000 ha (1%) in 2000, followed by doubling to 7500 ha (2%) in 2015, this increase was considered statistically insignificant ($R^2 = 0.002$). Irrigated soils with moderate salinity occupied 70,000 ha (24%) in 2000, and after having experienced a steep decrease by around 50,000 ha (17%), this decrease that indicates a strong effect size ($R^2 = \sim 0.7$) is an affirmative indicator. At the beginning of the study years, the strongly saline areas were 23,000 ha (8%) and suffered a significant decrease over the past 15 years to 5000 ha (1.5%) in 2015. The rate of decline, unlike other levels of SS, had a statistically significant coefficient of the maximum value ($R^2 = \sim 0.76$), which in turn is deemed a palatable phenomenon.

Regarding such studies dedicated to the SS research, these similar phenomena are mainly caused by rising

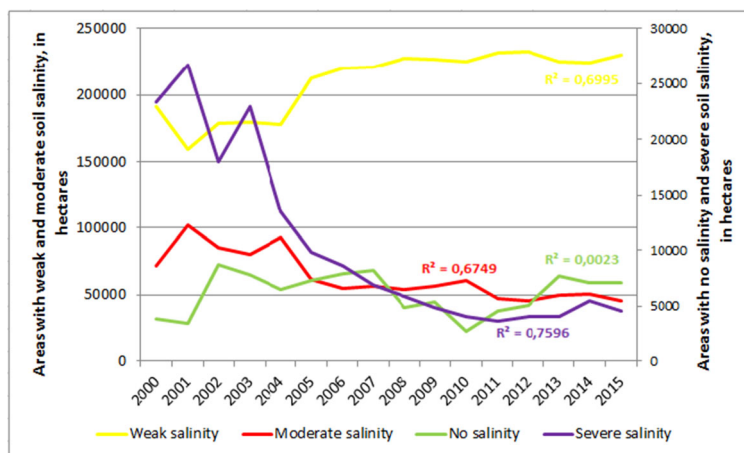
mineralized groundwater table due to natural changes in precipitation between seasons and years, and anthropogenic factors (Dasgupta et al. 2015; Ivushkin et al. 2017; Ivushkin et al. 2018; Peng et al. 2021). Throughout late winter and spring, when snow melts and precipitation is potentially high, the GWT rises. Soil salinity, on the other hand, commonly occurs where unsustainable furrow irrigation with waters rich in salts is predominantly applied, excessive filtration comes from unlined canals and reservoirs, and mineral and inorganic fertilizers are immoderately used. According to our results, salt in affected areas are potentially high concerning the massive application of furrow irrigation with mineralized waters despite having a high evaporation rate and poor drainage system. Thus, the gap between the saline and non-saline areas is considerably inflated.

6 Dynamics of Changes in the SS Levels for 2016–2019 Using Geographic Information Systems

GIS technologies are currently one of the most advanced methods of assessing the ecological condition of our environment (Ibrakhimov 2004). Taking into account the advantages of the GIS, the assessment results of SS level and its spatial distribution across administrative districts of the province for 2016–2019 are illustrated in Fig. 4.

According to the data obtained through the IDW interpolation, only the non-saline areas in the 2018 data can be easily and virtually distinguished from other salinity levels in the rest of the years (Fig. 4). Between 2016 and 2019, weakly saline areas accounted for larger areas than other levels of saline soils, whereas the areas with moderate to severe SS have decreased relatively, and this is a satisfactory indicator.

Fig. 3. Dynamics of changes in the SS level of irrigated areas in Sirdarya province



The accuracy of the results obtained by IDW was examined according to the method proposed by Woodcock and Gopal (2000). In this case, the value of the primary field data, which corresponds to the data obtained by IDW, was compared with each other. As a result of the comparison, the IDW maps derived an accuracy of 76.8% ($p = 0.0007$) and besides that, the root mean square error (RMSE) of IDW maps with power 2 was 0.0631. This provided a basis for the widespread use of the IDW method in the subsequent assessment of SS through GIS technologies.

This similarity can be observed in the results of a study conducted in the Mirzaabad administrative district of this province (Pulatov et al. 2020). As we know, RMSE of interpolation methods pinpoints the absolute fit of the used interpolation output to the data—how close the observed data points are to the predicted values of interpolation (Chen and Liu 2012). In our case, RMSE is an affirmative measure of how accurately the IDW output predicts the SS mapping. Here, we derived as lower value of RMSE as in many other studies (Ibrakhimov et al. 2020; Nouri et al. 2018; Sultanov et al. 2018; Zhao et al. 2019). This indicates that, the lower the RMSE, the greater the fit of the IDW interpolation. Therefore, based on our findings, we confirm that the IDW interpolation effectively runs on SS mapping.

The areas classified for each level of SS obtained by the IDW method in Sirdarya province were calculated in the form of histograms at the district level in hectare (Fig. 5). The territory of non-saline areas reached its maximum only in 2018, and in other years, it was observed to become insignificant among the areas occupied by different levels of saline soils. This is a relatively poor indicator (Fig. 5A).

The distribution of weakly saline areas during the research years did not differ much, with the largest irrigated area in the Akaltin district which in 2019 was 37,000 ha (94% of the total irrigated area of the district, hereinafter TIAD). In Sirdarya and Boyout districts, weakly saline areas have changed negligibly over the 4-year period and averaged 32,000 ha per annum (91% of TIAD). A similar pattern as Sirdarya and Boyout districts was observed in the irrigated areas of Gulistan, Khovost, and Sardoba districts, averaging 23,000 ha per annum (72% of TIAD). Such areas with the lowest inter-district weakly salt-affected soils were in the Mirzaabad district, which remained unchanged during 2016–2019 with 17,000 ha per annum (42% of TIAD) (Fig. 5B).

Irrigated areas with moderate SS expanded in two districts of the province and simultaneously decreased in two districts. Moderately saline areas increased in Khovost and Sardoba districts, with an average increasing rate of 5000 ha in 4 years (16% of TIAD), while in Mirzaabad and Akaltin districts, these areas declined from 19,500 ha (48% of TIAD) to 17,000 ha (43% of TIAD), and from 5000 to 1700 ha, respectively. On the other hand, changes in moderately salt-affected irrigated areas in Sirdarya, Saykhunabad, and Gulistan districts were almost undetectable; however, in the Boyout district, these areas remained stable with 4200 ha (12% of TIAD) during the experimental years (Fig. 5C).

Within 4 years, severely saline irrigated areas of the province were detected in only three districts. Of these, the Mirzaabad district is notably the most prone to severe soil salinity. In 2016, the severely saline areas of this district were 3400 ha (8% of TIAD); by 2019, this area has expanded, occupying 5700 ha (14% of TIAD) of irrigated lands (Fig. 5D).

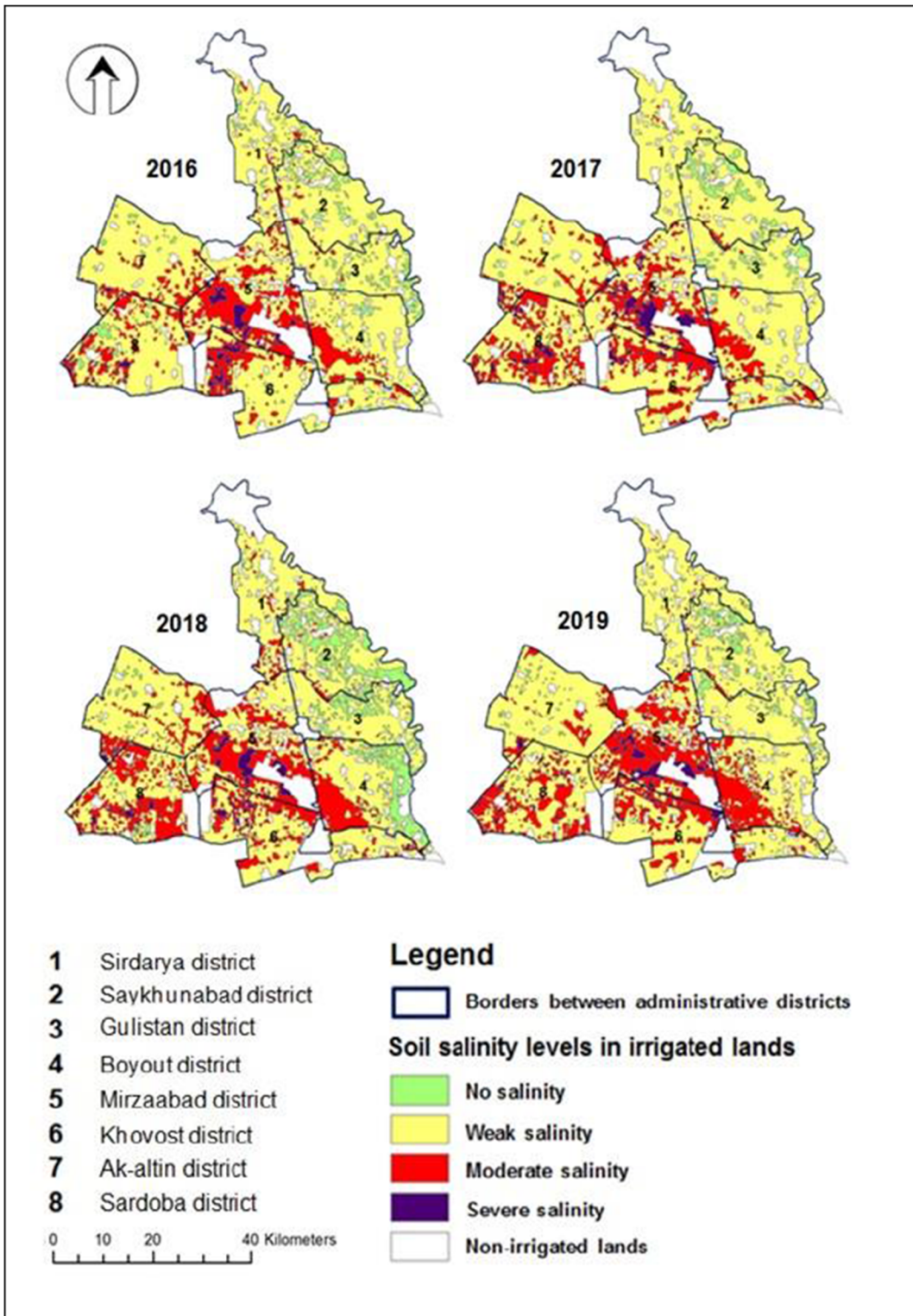


Fig. 4 Distribution of irrigated areas in the districts of the region according to the level of salinity during 2016–2019

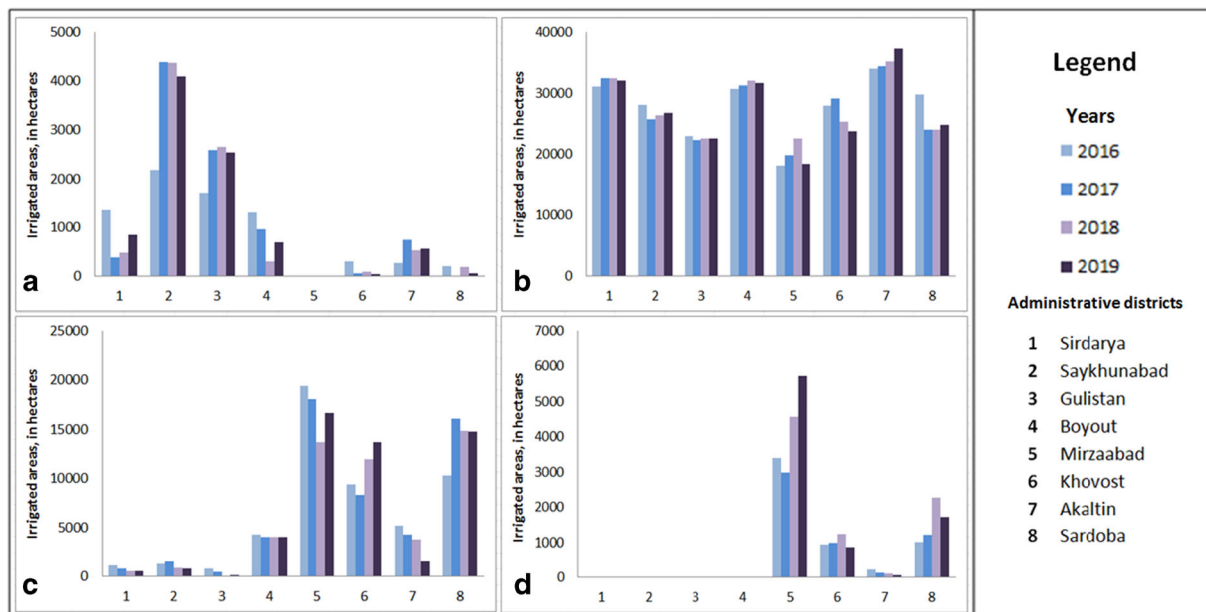


Fig. 5 Area corresponding to the classified SS levels by districts of Sirdarya province, ha. **A.** Non-saline areas. **B** Weakly saline areas. **C** Moderately saline areas. **D** Severely saline areas

Moreover, changes in severely saline areas in the Khovost district stabilized (about 1000 ha) in the entire 4-year period, while in Sardoba district, such areas occupied 1000 ha in 2016, increasing by about 800 ha, and expanded to 1800 ha in 2019 (4% of TIAD). The non-existence of severely saline irrigated areas in the rest of the districts is a remarkable indicator (Fig. 5D).

Quantified results obtained for 2016–2019 in the province are shown in the graph as a logical continuation of Fig. 4 above (Fig. 6). While the trend lines indicating non-saline and severely saline areas up to the post-2015 threshold (solid line) were relatively stable, at the end of the period these lines representing these areas increased slightly and amounted to about 9000 ha (3% of the province’s total irrigated area, hereinafter PTIA). The rapidly growing areas with weak SS slowly reduced, while such areas with moderately SS remained almost unchanged from the threshold until 2019, occupying approximately 220,000 ha (77% of PTIA) and 50,000 ha (17% of PTIA), respectively (Fig. 6).

Based on the results of this research, changes in irrigated areas of the districts regarding SS maps, when quantified data from salinity maps and compared with the data obtained by the traditional method, the overall accuracy was 77%. This, in turn, shows that the results

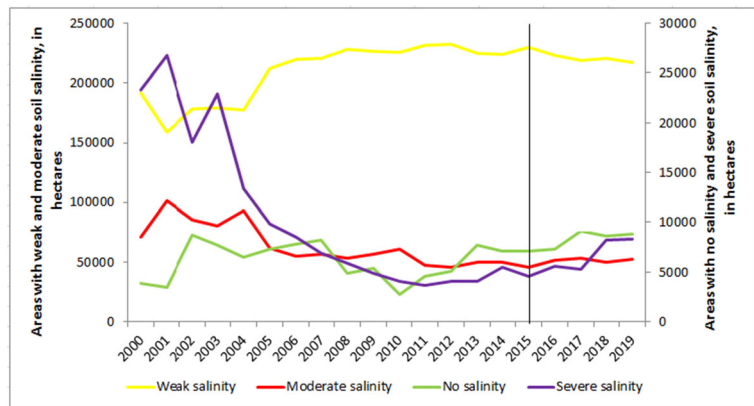
obtained through GIS tools have scientific and practical significance. Summarizing the results of the research, the following conclusion can be drawn.

According to the results of detection and investigation of irrigated lands in the province through conventional and GIS-based methods, the following work should be addressed to ameliorate the current situation related to soil salinization: determining the level of water mineralization used for irrigation and their economic use; ensuring that existing drainage systems are functional and monitoring their effective operation; annual inspection of the technical condition of existing collector drainage system and cleaning out unsatisfactory functional collector drainages; and based on the results of GIS technologies, it is recommended to take into account the existing 23% of error in the application of the IDW method in practice.

7 Climate Change and Soil Salinization

The impact of climate change on provincial SS levels was assessed using correlation coefficients (Table 2). The average perennial (2000–2019) seasonal air temperature and the amount of perennial seasonal precipitation were selected as climatic factors. For seasonal

Fig. 6 Dynamics of changes in the SS level of irrigated areas in Sirdarya province after 2015 (solid line threshold) assessed by GIS tools



average air temperature and the sum of precipitation, the months of January, February, and December as for winter, and June, July, and August as for summer were chosen. This is because, as the air temperature rises within the critical months selected, the mineralized groundwater evaporates, and the salt contents in groundwater could remain and accumulate in the topsoil (Moussa et al. 2009; Santoni et al. 2016). Besides, the amount of precipitation also has a direct effect on changes (decreases) in SS levels. The increase in precipitation also contributes to leaching the salts in the topsoil of the irrigated area (Santoni et al. 2016). This can lead to a decrease in irrigated areas with a certain amount of severe salt contents.

Similar correlation analyses were performed by Kulmatov (2014) to investigate the effect of climatic parameters on salinization of irrigated lands in the Navoi province of Uzbekistan. In this study, the average annual air temperature and precipitation were considered climatic factors, and the correlation coefficients of many external global and regional factors were also determined. The results of this research showed a weak dependence of climatic factors on SS (< 15%).

The correlation data (Table 2) revealed that the change in non-saline irrigated areas insignificantly depends on the amount of precipitation and the seasonal average air temperature (correlation coefficients 0.283 and 0.25). The dynamics of change in weakly, moderately, and severely saline irrigated areas showed only a frail dependence on the average summer air temperature (0.59, 0.53, and 0.56), as well as insignificant (0.2, 0.28, and 0.03) on the amount of precipitation. According to the table, almost no serious correlation was found for air temperature in winter months and precipitation in all seasons. Moderately saline irrigated areas also change

proportionally as the average seasonal air temperatures rise under the influence of climatic factors. Besides that, the change in the average salinity areas was also partially related to the amount of precipitation. Within the correlation analysis, it was found that the dynamics of changes in the severely saline soils also depend on air temperature (0.56). However, such areas are not dependent on atmospheric precipitation at all.

Uzbekistan is considered one of the countries that are vastly vulnerable to climate change and groundwater rise due to its geographical location. However, climate-related increases in salinity from saltwater intrusion in soils because of traditional irrigation have been highlighted as a serious problem. Systematic studies of long-term spatiotemporal impacts are restricted in Uzbekistan. This research has attempted to fill the gap between the salt-affected areas' expansion and climate variability. Based on the results of the correlation analysis, we found that the impact of climate change was weakly correlated with the saline areas' expansion in the study area. While an increase in air temperature in

Table 2 Correlation coefficients indicating the dependence degree of climatic factors on SS level of irrigated lands

Climatic factors	Salinity level of irrigated lands			
	No salinity	Weak	Moderate	Severe
Air temperature, °C (summer)	0.250	0.589	0.532	0.562
Precipitation, mm (summer)	0.063	0.086	0.126	0.010
Air temperature, °C (winter)	0.083	0.356	0.418	0.227
Precipitation, mm (winter)	0.283	0.206	0.279	0.027

summer months infirmly leads to a positive change in saline irrigated areas due to the evaporation of mineralized groundwater, the effect of increased precipitation on soil salinization has not been observed.

8 Conclusion

Soil salinization as a threat of land degradation is a global environmental problem that adversely affects the sustainable use of land resources, agricultural production, and food security. The establishment of a proper and scientifically valid methodology as an asset to the governmental approach towards tackling SS issues is nowadays a salient case in sustainable development. Therefore, this present study examined the potential of the IDW interpolation method as one of the GIS-based approaches at the provincial level, compared the performance of this interpolation method with the governmental results, and assessed the impact of climate change on the provincial extension of salt-affected areas.

We concluded that the IDW interpolation gives a clear illustration of salt-affected areas in the Sirdarya province. Our approach clearly distinguished between soil salinity classes, producing an enhanced accuracy of salinity maps with lower root mean square error. Besides that, visual examination of soil salinity maps showed that actual salinity patterns were more similar to the reference data generated by the responsible governmental institutions. The IDW interpolation method thus appears to harbor the substantial potential for salinity monitoring on agricultural areas of the Sirdarya province. As designating the important points of our findings, non-saline irrigated areas in the province have increased negligibly over the years, accounting for 3% of the total irrigated area of the province today. The variation level of weakly and moderately saline irrigated areas should be maintained in such a critical state; otherwise, this indicator may lead to the formation of weakly saline areas to become moderately saline. Considering these variations, the policy-based attention should mainly be paid to the Mirzaabad, Khovost, Sardoba, and Boyout districts of the province since there are almost no such areas without salinity. Moreover, we found that there is no correlation between salinity classes, air temperature in winter months, and precipitation. However, only a weak correlation between salinity classes and air temperature in summer is observed. This is because, as we assume, the higher air temperature leads

to the higher evapo(-transpi-)ration rate of mineralized ground and soil water, thus accelerating the salinization processes.

The used IDW approach is recommended for use in monitoring the SS status of the province, selection and placement of crop species, and developing scientific and practical conclusions on improving the ameliorative condition of soils. A promising path of future research is the evaluation of the general applicability of the proposed approach in terms of other arid regions.

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Declarations

Competing Interests The authors declare no competing interests.

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