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Groundwater table and salinity: Spatial and temporal distribution and influence on soil salinization in Khorezm region (Uzbekistan, Aral Sea Basin)

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Abstract Groundwater (GW) management is an essential element in irrigated agriculture. This paper analyzes the temporal dynamics of GW table and salinity in Khorezm, a region of Uzbekistan which is situated on the lower Amu Darya River in the Aral Sea Basin and suffering from severe soil salinization. We furthermore identify the critical areas for potential soil salinization by examining GW table and salinity measured during 1990–2000 in 1,972 wells, covering the entire region. Additionally, case studies were performed to assess the contribution of the GW to the soil salinization on a field scale. Over the entire area, GW was only moderately saline averaging 1.75±0.99 g l^{-1} However, GW levels were generally very shallow averaging 148±57 cm below the ground surface and thus likely to prompt secondary soil salinization. Three case studies where GW table, soil and GW salinity were closely monitored at the field scale, suggested that the elevated GW levels forced soil salinization by annually adding 3.5–14 t ha^{-1} of salts depending on the position and salinity of the GW table. Maps interpolated from the regional dataset revealed that GW was significantly shallower and more saline in the western and southern parts of Khorezm despite the presence of a drainage network which is rather uniformly distributed throughout the region. The results of the current study will assist the development of an improved drainage management in Khorezm.

Keywords Agriculture · Amu Darya River · Drainage · Secondary soil salinization · Spatial analysis

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Introduction

The Aral Sea, once the world's fourth largest freshwater lake, has experienced a rapid drying out due to many years of mismanagement of land and water resources (Ivanov et al. 1996; UNESCO 2000; Micklin 1996; Glantz 1999). During 1960–1990, large amounts of water from the principal rivers of the Aral Sea Basin (ASB), were diverted to the irrigated lands that, in the same time, have expanded from 4.5 to 7.9 million ha (UNEP 2000); only 5 km^3 $year^{-1}$ of the river water reached the Aral Sea in the 1990s compared to 63 km^3 before the 1960s (UNESCO 2000). Drainage water discharge back to the rivers has resulted in a continuous decrease of the river water quality and caused higher salt load to the downstream irrigated areas. Continued diversion of huge amounts of water combined with low irrigation efficiency resulted in a rise of the groundwater (GW) table and an increase of salinity in soil and GW within the irrigated areas of the basin (Ikramov 2004).

The secondary soil salinization is especially acute in the irrigated lowlands of the ASB, such as the area of Khorezm, located in Northwest Uzbekistan (Tursunov 1981). Virtually all of the irrigated areas in Khorezm are saline, and more than 50% of them were assessed as moderately-to-highly saline (Rhoades et al. 1992) during the 1980s (MAWR 1990–2000). Crop yield losses can be 30–50% in the slightly and moderately saline areas, and reach 80% in the highly saline areas (Ramazanov and Yakubov 1988). In addition to these economic losses, the arable land becomes less usable and more difficult to ameliorate (Hillel 2000), while more and more of the scarce water resource is needed for salinity mitigation through leaching. In addition, constant operation and maintenance of the drainage network is indispensable for controlling favorable salt balance in the irrigated areas.

Among the major sources of secondary soil salinization are the salinity of the applied irrigation water as well as the depth and salinity of the GW. While salts from surface waters are brought directly with that water and accumulate in the soil profile (Ghassemi et al. 1995), salinization from GW occurs when the GW reaches a certain threshold level above which it rises by capillarity (Hillel 2000). This level depends to a large extent on the soil texture, its hydraulic properties, the general hydrogeologic and geochemical conditions and on the crops grown (Schmidt 1985). From studies of soil salinization in Khorezm, Rakhimbaev et al. (1992) concluded that salinization takes place when GW with salinity over 3 g l^{-1} rises above 2.0 m below the ground surface, and thus, should be managed in a way as to not exceed this level. Less saline GW table may not exceed 1.5 m. Similarly, Kats (1976) argued that a GW table with a salinity level of >3 g l^{-1} should preferably be kept below 1.9–2.5 m. In this paper we adopted a threshold value for the GW table of 1.5 m below the ground surface for GW salinity levels of up to 3 g l^{-1}.

Despite years of research on the acceptable levels of GW table and salinity followed by the (re)construction and maintenance of the drainage network and leaching practices on the micro-, meso- and macro scale, the increase in soil salinization could not be arrested (Ramazanov 2004). To manage the GW levels, a network of more than 9,254 km of surface drainage water collectors has been constructed in the region (Vodproject 1997). Due to financial constrains presently experienced by all the ASB countries, the quality of the network deteriorates from year to year (Buknall et al. 2003).

This paper analyzes the temporal dynamics of the GW table and salinity in Khorezm based on historical secondary GW data. Intensive observation of the GW table as well as GW and soil salinity dynamics at a field scale intended to quantify the salt loads resulting from shallow GW which contribute to the notoriously high soil salinization in Khorezm eventually bringing about the degradation of the agricultural land.

Materials and methods

Study area

Khorezm (Fig. 1) is located in the northwestern part of Uzbekistan (40°27′ and 41°06′ N and 58°31′ and 61°24′ N. From the total area of 680,000 ha, about 270,000 ha can be irrigated (Vodproject 1999). The region, bordered by the Karakum and Kyzylkum deserts in the south, southwest and west, has an extremely arid continental climate. The Amu Darya River makes the northeastern border of the region.

Due to its location in the lower reaches of the river, Khorezm is a low-land flat region with elevation points between 112 and 138 m a.s.l. (Kats 1976). Due to the low hydraulic gradients one has to assume that lateral GW flow is quite slow. Soils are coarse-textured along the river banks while finer textures in the lowlands are stratified vertically to the depth from a few centimeters to some decimeters and underlain by sand (Tursunov and Abdullaev 1987; Popov et al. 1992). According to the local soil fertility classification, land characterized by good and very good suitability for crop cultivation constitutes some 66% of the irrigated area, while moderately or poorly suitable lands respectively amount to 19 and 15% (Abdullaev 2003).

From the geohydrological viewpoint three zones can be distinguished in the region. First zone expands along the Amu Darya River, and is characterized by the 1.5–2.0 m thick upper fine-textured soil layer which is underlain by water-bearing fine-grained sand with a thickness of 30–40 m. The hydraulic conductivity and transmissivity of the soils in this zone respectively range 28–34 and 900–1,200 m^2 day^{-1}. The second zone, located in the central part of the region, is characterized by soil transmissivity of 530–800 m^2 day^{-1} and the thickness of the upper soil layer averaging 10–12 m. The third zone covers the southern part of the region, where the hydraulic conductivity and transmissivity respectively range 5–7 and 66–300 m^2 day^{-1}. These peculiar geohydrological conditions have their influence on lateral and vertical GW movement.

High temperatures exceeding 33°C and low relative humidity occur between May and August. Long-term average precipitation of ca. 100 mm is 10 times exceeded by the potential evaporation and does not have a significant influence on surface- and groundwaters (Mukhammadiev 1982). The evaporation rises as early as in April, reaching its maximum in July.

Upland cotton (*Gossypium hirsutum*), winter wheat (*Triticum aestivum*) and rice (*Oryza sativa*) are the dominant crops in the region (Table 1). The peak irrigation period for all crops is June–August whereas irrigation of winter wheat starts in November. The crops are irrigated with surface furrow and flood methods. Water is supplied through a complex-hierarchy irrigation network of which only 11% are lined (as of 1997; Vodproject 1999). The irrigation of these water-intensive crops and seepage from the canal network are the primary causes of the GW rise in Khorezm (Nurmanov 1966; Jabbarov 1990). Copious leaching is practiced throughout the region mainly in March to cope with soil salinity. Fields with slightly saline soils receive ca. 400 mm while highly saline areas are supplied with up to 600 mm (Ramazanov and Yakubov 1988; Forkutsa 2006). An open horizontal drainage network is used to remove excess surface- and groundwater.

Measurements of groundwater table and salinity on a regional scale

Long-term observation data on GW table and salinity were obtained from the Khorezmian Hydrogeological Melioration Expedition (GME) of the Ministry of Agriculture and Water

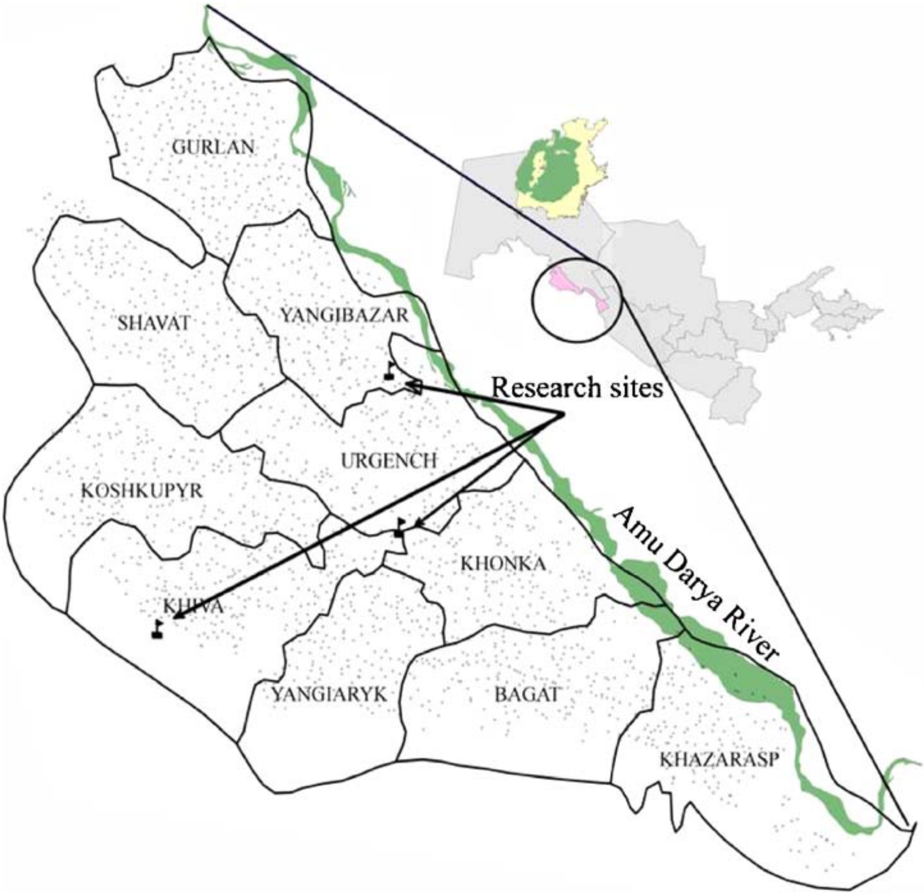

Fig. 1 Khorezm region with its administrative districts, the Amu Darya River, location of research sites and the distribution of the groundwater monitoring wells used in this study

Management (MAWR). GME conducts measurements at over 2,000 monitoring wells that are more or less evenly distributed over the area (Fig. 1). GW salinity is analyzed for total dissolved solids (TDS).

The GW salinity measurements are conducted annually in April, July and October. The measurements in April allow assessing the influence of leaching practices on desalinization of the upper GW layer, which highly determines salt exchange between GW and soil. The salt accumulation in GW can be assessed during the intensive irrigations in July and, outside the growing period, in October. GW table measurements are conducted every 5 days during the growing period and every 10 days upon its cessation.

For the present study, the datasets of GW table and salinity for April, July and October were obtained from 1,972 wells and monthly averaged for the period from 1990 to 2000.

Basic characteristics of observation fields

Three locations were selected for observations of GW table and salinity and their influence on the soil salinization on the field scale. These fields were located in the northern, central

Table 1 Major crops grown in the Khorezm region in the Khorezm region, area covered and recommended irrigation rates

Crops	Area, %	Water requirements, mm
Cotton	40.6	550–610
Wheat	18.3	240–320
Rice	7.1	2,620–2,640
Vegetables	3.7	610–790
Fruits	3.1	310–410
Maize	2.3	470–600
Alfalfa	0.3	660–710

Source: Djanibekov, N., (forthcoming). A Micro-economic Analysis of Farm Restructuring in Khorezm Region, Uzbekistan. ZEF, Bonn University, Germany.

and southern parts of Khorezm (Fig. 1) and exemplified major land use systems in the region. Two fields selected in (1) Khiva and (2) Khonka districts, represented agricultural land use systems with cotton winter–wheat rotation. The sites were classified as having good and very good suitability for crop cultivation with soil salinity maintained at the levels, adequate for plant growth (Abrol et al. 1988). An additional location was selected in (3) Yangibazar district and represented a degraded agricultural land. This site was set aside from cropping due to high soil salinization and used for afforestation experiment with salt tolerant tree species (Khamzina 2006). The selected fields were characterized by sandy- and silty-loamy textures predominant in Khorezm (Table 2).

The GW and soil observations at the selected sites were conducted during growing seasons 2002–2005. The agricultural fields were irrigated with locally practiced watering rates via surface furrow method. The tree plantation site received deficit irrigation during first 2 years of development and afterwards relied solely on the GW table and precipitation (Table 2).

Table 2 Basic characteristics of the observation sites

Site location/ characteristics	Khiva	Khonka	Yangibazar
Size, ha	3.5	3	2
Crop grown	Cotton–winter wheat	Cotton–winter wheat	Russian olive (*Elaeagnus angustifolia* L.), Euphrates poplar (*Populus euphratica* Oliv.), Siberian elm (*Ulmus pumila* L.)
Suitability for crop cultivation	Good and very good	Good and very good	Poor
Soil texture	Sandy loam	Silt loam	Silt loam
Distance to nearest irrigation canal	Next to the field	Next to the field	Next to the field
Distance to nearest drain	Next to the field	Next to the field	>150 m
Irrigation quantity, mm	236 and 370 mm respectively, in 2002 and 2003	401 and 628 mm in 2004 and 2005	80–160 mm year^{-1} in 2003 and 2004
EC of irrigation water, dS m^{-1}	1.16	1.19	1.62

Groundwater table and salinity monitoring on a field level

The afforestation site in Yangibazar with the plantation density of 5,714 trees ha^{-1} included 60 GW observation wells distributed throughout the site. GW table and electrical conductivity (EC) were recorded every 10 days throughout growing seasons in 2003–2005. Samples for soil EC analysis were collected next to the observation wells in 0.2 m layers down to 1 m depth. In Khiva site six monitoring wells were installed. Two wells were located close to the irrigation canal in the western part of the field; two other wells were placed in the eastern part, close to the drain. The remaining two wells were in the northern and southern parts of the field. GW table and salinity readings were performed every 5–6 days during growing seasons 2002–2003. At the same time, soil samples were collected to measure EC. Khonka field was equipped with 20 monitoring wells recording dynamics of the GW table and soil and GW salinity every 5 days from June through August in 2004–2005.

The wells used for observation were polyethylene pipes (∅=4 cm) closed at the bottom, perforated, protected from clogging with a fine synthetic filter and installed down to a depth of about 2 m. Soil and groundwater EC was measured with a portable EC meter (Shirokova et al. 2000). The soil:water $EC_{1:1}$ values were converted into EC_e using the relationship [$EC_e=EC_{1:1}*3.6$] developed by Shirokova et al. (2000) for Khorezm soils. The factor used for conversion of EC values onto g l^{-1} basis was 0.7 according to Shirokova et al. (2000).

The salt loads originating from irrigation and groundwater in Yangibazar and Khonka fields were estimated with simple water–salt balance calculations. For Khiva site HYDRUS 1D was used to obtain more precise estimates of the salt water balance (cf. Forkutsa 2006 for details).

Statistical and geostatistical analyses

Prior to temporal analyses, the regional data were checked for the distributional assumptions, which revealed skewness and outliers. GW table outliers were mostly associated with rice fields where values ranged few centimeters below the surface due to constant flooding. Thus, readings from the rice fields representing less than 15% of the overall land use in Khorezm were excluded from the analyses.

All statistical analyses were performed using SPSS 13.0. Logarithmic transformation resulted in a reasonable approximation to a normal distribution. Distributions were calculated using BestFit 4.5. Geostatistical kriging interpolation method was used to estimate GW values at unvisited places (Journel and Huijbregts 1978; Cressie 1992).

Results

Temporal dynamics of groundwater table and salinity at a regional level

The GW table was generally shallow throughout the region, averaging 1.48±0.57 m over the observation period of 11 years. Monthly means in April and July amounted to 1.4 and 1.2 m respectively, thus exceeding the defined threshold of 1.5 m, while values in October averaged 1.9 m below the ground surface (Table 3). The minimum and maximum values of the GW table for these three observation periods were similar. The minimum values of 0.3–0.5 m clearly indicated that in some areas the threshold level was highly exceeded even in

Table 3 Descriptive statistics of the average groundwater table and salinity for April, July and October in the period 1990–2000 in Khorezm

Parameter	Groundwater table, m			Groundwater salinity, g l^{-1}		
	April	July	October	April	July	October
Mean	1.4	1.2	1.9	1.83	1.78	1.70
Std. dev.	0.43	0.44	0.52	1.08	1.04	1.06
Minimum	0.4	0.3	0.5	0.49	0.50	0.50
Maximum	3.6	3.5	4.0	13.72	13.99	15.01
N	1,896	1,751	1,881	1,972	1,972	1,972

October. In the mean time, the maximum observed values of 3 m implied no threat of soil salinization at these few locations.

The analysis of the probability distribution of the 1990, 1994 and 2000 datasets showed that about two thirds of the April and July data (on average 62 and 67%, respectively) had GW tables above the threshold level, versus only 19.7% of the October data (Fig. 2 shows the distribution functions for 1990 as an example).

The analysis of temporal changes of the GW table in Khorezm revealed that the April and July levels did not significantly fluctuate over the years (Fig. 3). In contrast, the GW table in October rose from ca. 2.3 m in 1990 to 1.5 m in 1996 and remained at that level until 1999, indicating a trend to higher GW tables.

According to the FAO classification, the overall average GW salinity value of 1.75± 0.99 g l^{-1} observed, falls into the category of moderately saline waters (Rhoades et al. 1992). Locally, high GW salinity was recorded, reaching as much as 14–15 g l^{-1} (Table 3). At some locations marginally non- to slightly saline GW water of 0.5 g l^{-1} could have been re-used for irrigation through pumping.

The average values of GW salinity in the October, April and July measurement periods did not differ significantly. The spread of the salinity values was generally skewed towards the lower ranges, and 50–60% of the values in each period indicated moderately saline GW (Fig. 4 shows the example for October 1994). Less than 1% of the values in each period exceeded 7 g l^{-1}, the threshold for high salinity defined by Rhoades et al. (1992). The temporal changes of the GW salinity during the study period were also insignificant (P>0.05) ranging from 1.6 g l^{-1} to 2.0 g l^{-1} in all three measurement periods (Fig. 3).

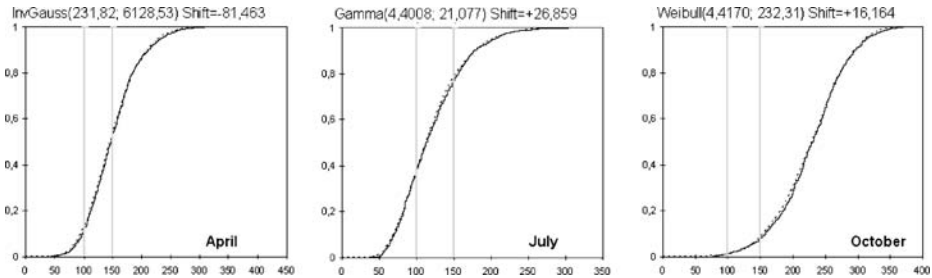

Fig. 2 Probability distribution functions for the groundwater data sets of April, July, and October 1990, respectively. *Y*-axis = probability; *X*-axis = GW table in cm; *grey vertical lines* mark the 100 and 150 cm lines, respectively

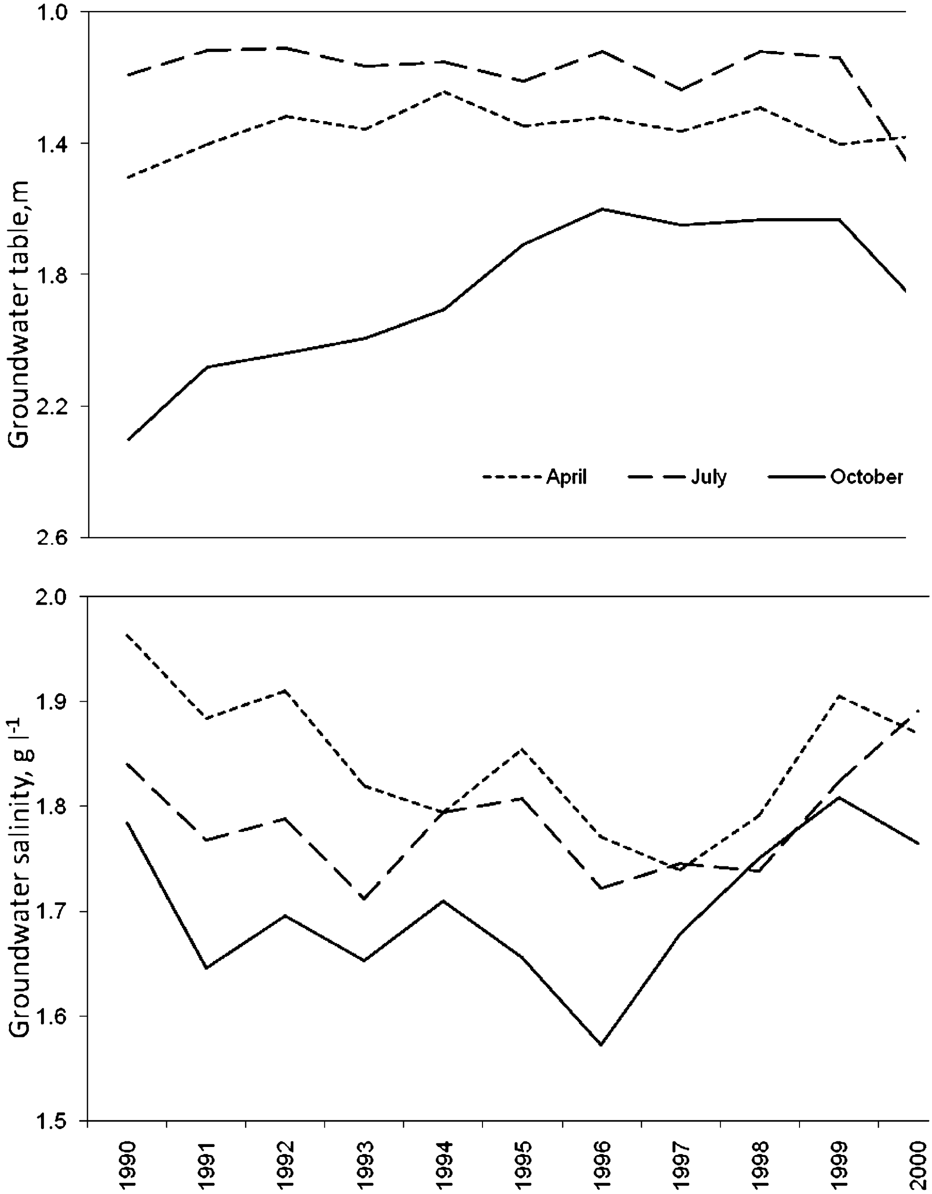

Fig. 3 Temporal changes of average groundwater table and salinity in Khorezm in April, July and October during 1990–2000

Case study: soil salinization factors on a field scale

GW table, soil and GW salinity

The critically shallow GW tables observed and the presence of salts in the GW require quantification of their input to the soil salinization in Khorezm. The close monitoring of GW table fluctuations at the selected observation sites showed a seasonal pattern similar to

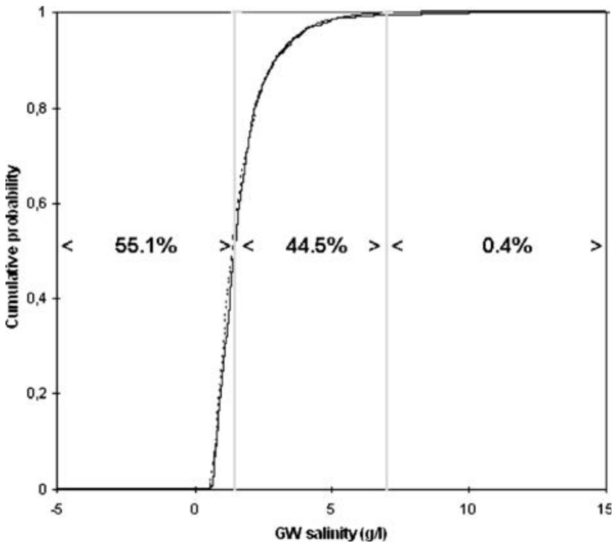

Fig. 4 The cumulative probability distribution for GW salinity in October 1994 shows that 44.5% of the wells had moderately saline GW, and only 0.4% had highly saline GW. *Straight line* = data distribution. *Dotted line*: Fitted Inverse Gauss distribution function

that resulted from the monitoring on the regional scale. Particularly at the afforestation site where low watering amounts did not affect the GW table fluctuations ($P>0.10$), the GW rise from about 2 m in winter time to 1 m and higher during growing periods must be attributed solely to the influence of irrigation activities in the surrounding fields and infiltration from the inter-farm irrigation canal. A drastic rise in the GW level in April marked the beginning of the growing season, which in the region is typically started with leaching. After cessation of irrigation the GW table dropped (Fig. 5a).

During the growing seasons, the GW table was constantly above the threshold depth of 1.5 m at the degraded site as well at the agricultural field in Khonka. The GW table in Khiva was relatively deeper than at the other two sites, particularly if measured near the drain (Fig. 5b and c).

The agricultural fields were characterized by moderate degree of GW salinity although in Khiva, GW was at the upper margin of the 'moderately saline' class (4–6 dS m^{-1}, Fig. 6) while in Khonka an average value of 3.5±1 dS m^{-1} (≈2.54 g l^{-1}) was observed. The GW salinity at the afforestation site declined from 3.2±0.9 dS m^{-1} in 2003 to 2.2±0.7 and 1.5±0.5 dS m^{-1} in 2004, respectively (Fig. 6a) thus changing from moderately to slightly saline.

The highest soil salinity was observed at the tree plantation site where soil EC ranged within 4.1–14.6 dS m^{-1} during the growing seasons (Fig. 7a) which corresponds to moderate-to-strong salinity (Abrol et al. 1988). In cropped fields of Khiva and Khonka, soil salinity was slight-to-moderate averaging 2.5–4.0 dS m^{-1} (Fig. 7b and c).

Salt contribution from irrigation and groundwater

Since the quantity of salts added with water is the product of amount and salt concentration of that water, water–salt balance showed the input of salts to the soil profile from irrigation and groundwater. Given deficit irrigation quantities used for watering the trees, the salt contribution with irrigation did not exceed 2.6 t ha^{-1} at this site (Table 4). In the irrigated agricultural fields, larger surface water supply (Table 2) resulted in somewhat larger amounts of salts added (Table 4).

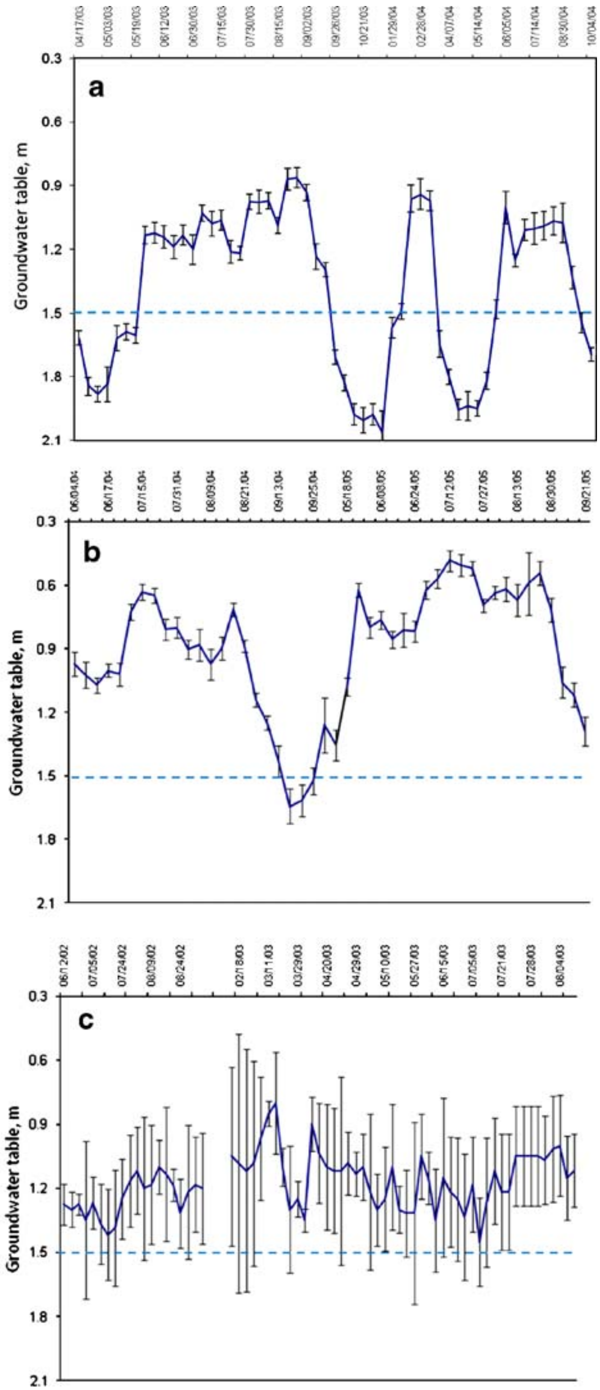

Fig. 5 Means, standard deviations and threshold lines of groundwater table in research fields in Yangibazar (**a**), Khonka (**b**) and Khiva (**c**). *Dashed line* indicates the threshold level recommended for the GW management

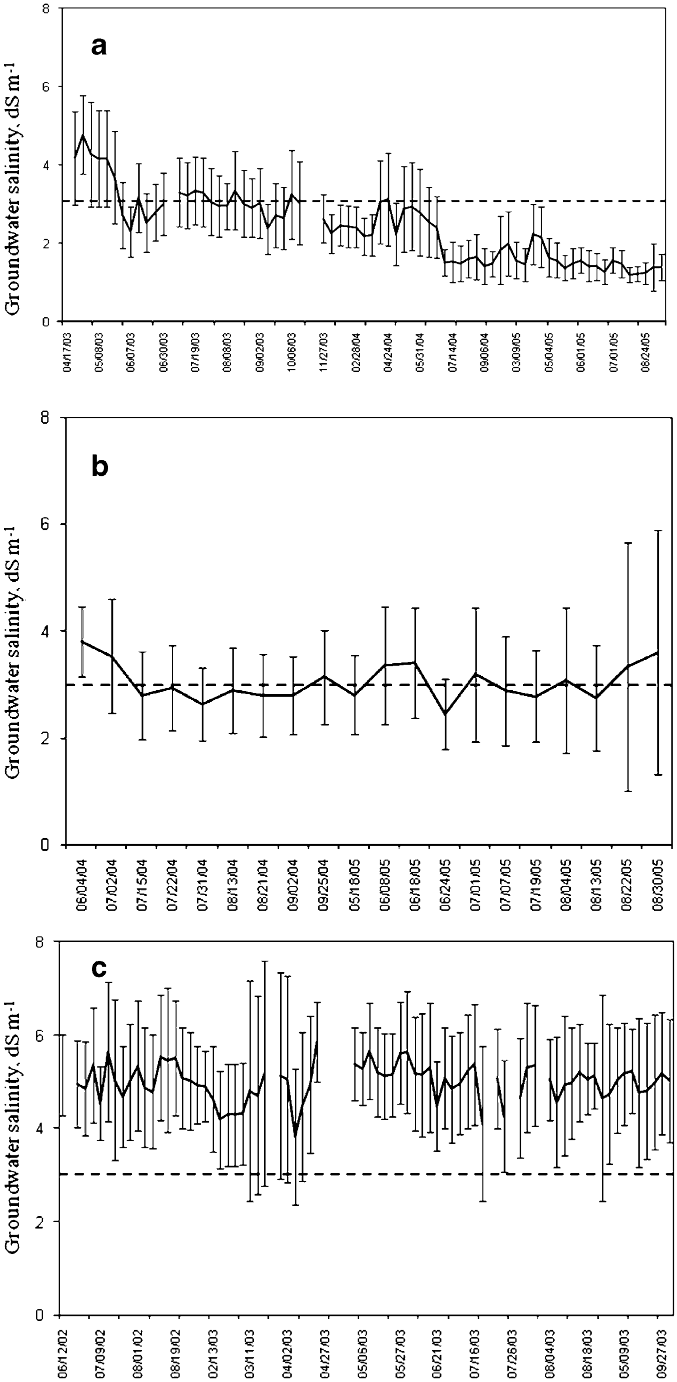

Fig. 6 Means and standard deviations of groundwater salinity in research fields in Yangibazar (**a**), Khonka (**b**) and Khiva (**c**). *Dashed line* indicates the threshold level for moderate groundwater salinity

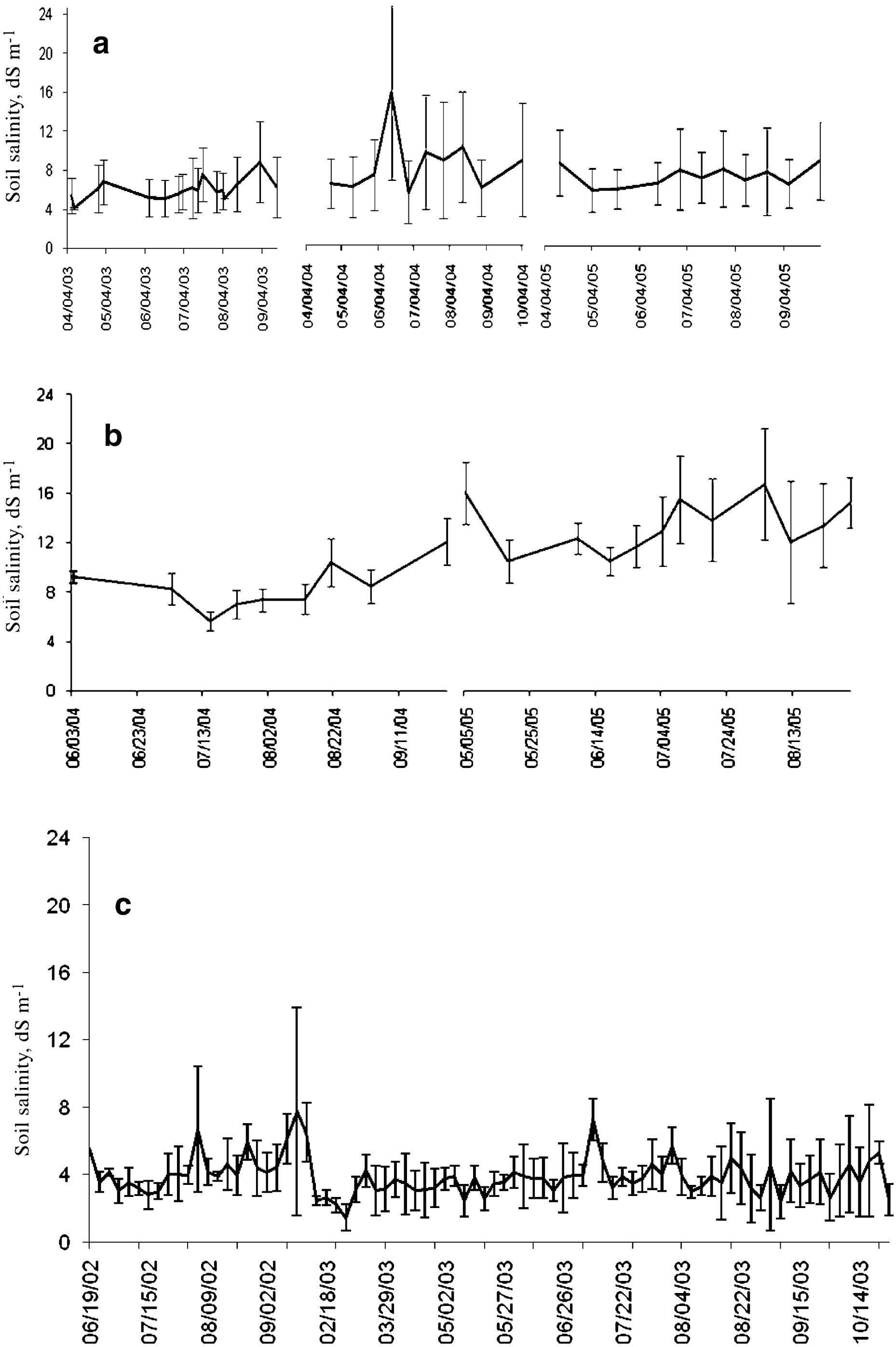

Fig. 7 Means and standard deviations of soil salinity in research fields in Yangibazar (**a**), Khonka (**b**) and Khiva (**c**)

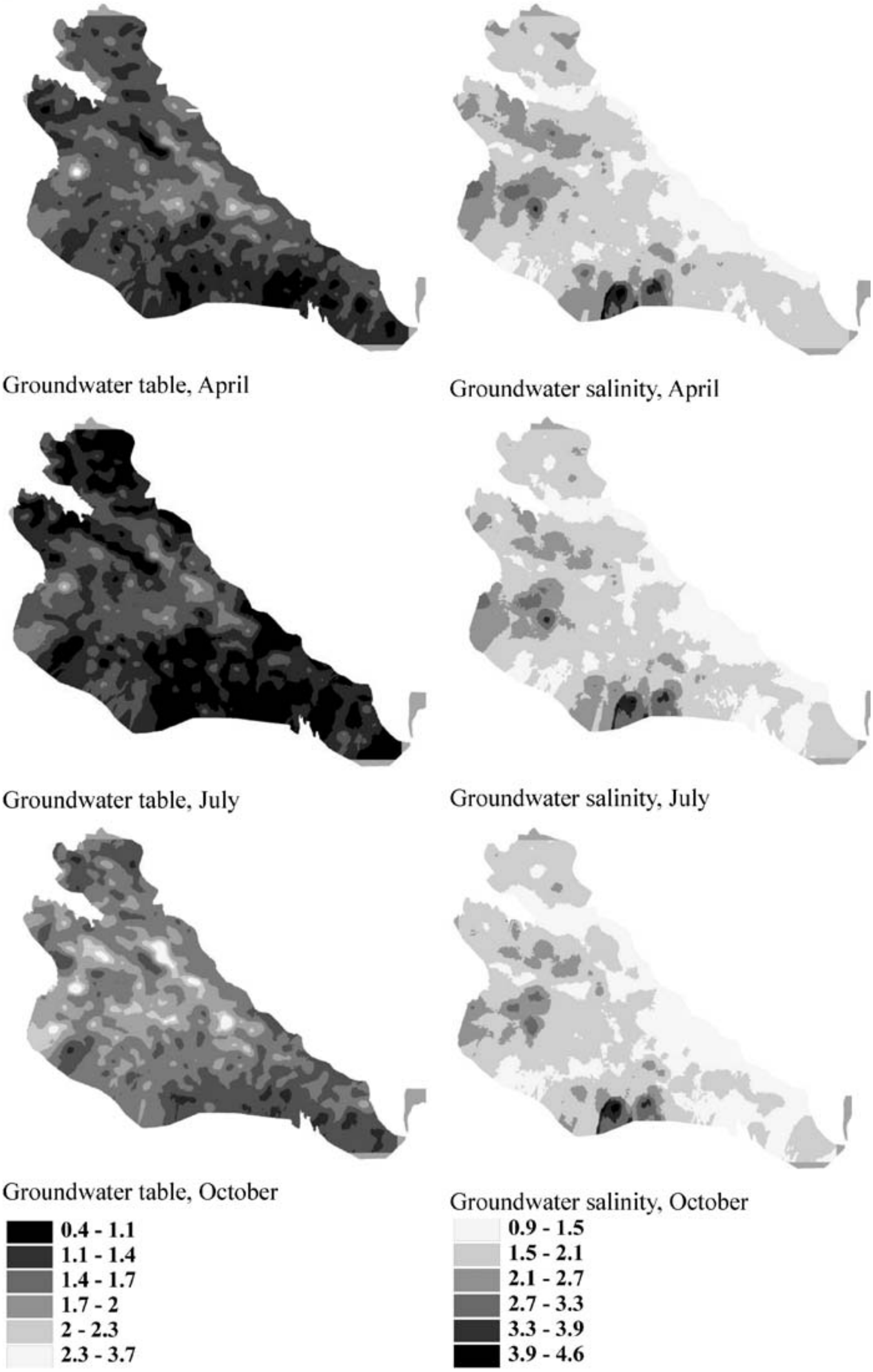

Fig. 8 Maps of average April, July and October measurements of groundwater table cm and salinity g l^{-1} in Khorezm during 1990–2000

Table 4 Salt inputs in the 1 m soil column by the irrigation and groundwater at the observation fields

Observation field	Year	Salt load, t ha^{-1}	
		From irrigation	From groundwater
Khiva	2002	1.93	5.01
	2003	3.52	4.80
Khonka	2004	1.25	5.84
	2005	2.46	7.96
Yangibazar	2003	1.31	14.0
	2004	2.62	10.4

For quantification of salt loads originating from the GW in Yangibazar we assumed that the amount of applied surface water was totally used for evapotranspiration estimated as 704 mm in 2003 and 835 mm in 2004 according to Allen et al. (1998). Thus, the moisture deficit of 624 and 675 mm respectively in 2003 and in 2004 was covered by the GW. Given the observed GW table and salinity, the salt load of 10.1–14.4 t ha^{-1} was estimated in the 1 m soil column as the result of the GW contribution (Table 4).

The agricultural fields experienced considerably lower salt loads originating from the GW table. In Khiva, where GW table was located near its optimal depth, the average moisture contribution from the GW was estimated to be 1,180–1,230 m^3. With an average GW salinity of 5 dS m^{-1} (≈3.6 g l^{-1}), this contribution amounted to 4.8–5.1 t of salts added. Due to resemblance of environmental conditions in the two agricultural fields, we assumed similar upward GW flux in the field in Khonka, being approx. 2,300 m^3 (minimum, as the GW flux was estimated in a part of the Khiva field which had the shallowest GW). With the average GW salinity of 2.54–3.06 g l^{-1}, the contribution of salts from the GW into the upper 1 m soil column constituted 5.8–7.9 t ha^{-1} (Table 4).

GIS analysis and spatial distribution of GW table and salinity

Due to the essential contribution of the GW tables to the soil salinization, it is important to identify those areas in the region where GW is particularly shallow and saline.

The geostatistical semivariogram analysis of the GW table measurements revealed the absence of a trend (global change) in the data, but a presence of anisotropy (local change) in the east–west direction. The variogram in that direction had a clearer structure with a longer range (distance of autocorrelation) and thus was chosen for further interpolation. There was a relatively large nugget variance of the GW table and salinity for all the measurement periods. The ranges were similar among the measurement periods despite the differences in irrigation intensity between April, July and especially October (Table 5). The geostatistical analysis also exposed the existence of a global trend, in the north-east to south-west direction, for GW salinity which was removed from the dataset prior to interpolation.

The maps of the average April, July and October measurements of the GW table (Fig. 8) revealed areas with significantly shallower GW (P=0.05) in the southern, western and north-western districts of the region. Striking in these maps is the similarity of the spatial patterns of the GW table in each measurement period: GW table was shallower in the southern and deeper in the central parts of the region even in October when no or rare irrigations occur. Interpolation and comparison of the GW table maps in each individual

Table 5 Parameters of kriging interpolation for the average groundwater table and salinity in Khorezm in April, July and October 1990–2000

Season		Range (m)	Nugget	Sill
April	Salinity	5,926.6	0.412	0.103
	Depth	3,448.4	0.054	0.034
July	Salinity	5,926.6	0.375	0.078
	Depth	3,422.4	0.054	0.035
October	Salinity	5,926.6	0.357	0.074
	Depth	4,246.1	0.065	0.055

A spherical kriging model was used in all cases.

measurement period showed that the spatial distribution of the GW tables was very similar to those of the averaged April, July and October measurements. Similar to the spatial distribution pattern of the GW table, salinity was more pronounced in the southern and western parts of the region ($P<0.05$, Fig. 8) and spatially did not differ across the measurement periods.

Maps in Fig. 8 show that the majority of the areas experienced shallow GW tables (0.4–1.1 m, above threshold levels), which have salinity ranging between 1.5 and 4.6 g l^{-1}. It is clear that a substantial soil salinization has probably taken place in these areas.

Discussion

GW studies are important to understand one of the principal sources of secondary soil salinization which is a major cause of degradation of irrigated lands worldwide. Here we examined the spatio-temporal dynamics of the GW table and salinity in the Khorezm region, where the entire irrigated area is suffering from various degrees of soil salinization while about 15% of it are severely degraded. Several case studies exemplified the contribution of the shallow saline GW tables to the soil salinization.

Temporal dynamics of the groundwater table and salinity

The observed temporal dynamics of the GW table in Khorezm region revealed that during the growing period about two thirds of the areas were at risk of secondary soil salinization due to unacceptably shallow GW levels. The GW level rises beyond the critical level of 1.5 m already in April, which limits the efficiency of leaching (Hillel 2000) performed throughout the region in early spring to flush salts from the soil profile before cropping. A shallow GW table in July (the peak growing period) implies a continuous salt up-rise into the soil root-zone, which may be counterbalanced by irrigation events. The relatively shallow, but since 1996 gradually rising GW tables in October are associated with introduction of winter wheat which requires late-season irrigation leading to an 0.7 m increase in the GW table outside the growing season (Ibrakhimov et al. 2004). The shallowness of the GW table is an indicator of a creeping problem: a danger of salt build-up in the soil outside downward irrigations exists particularly in moderately and heavily textured soils, where the capillary rise is high (Tursunov 1981).

On the other hand, shallow GW contributes to soil moisture and thus can be available to crops (Kiseliova and Jumaniyazov 1975) depending on the salinity levels. The Khorezmian farmers whose fields are remote from the irrigation canals, widely use a method of sub-irrigation (artificially raising GW levels for short time periods) to cope with frequent water shortages. Clearly, considerable amounts of salts are then added into the soil root-zone, and larger water applications are necessary to leach them.

The observations at the selected fields showed that even moderately saline GW appears an important contributor of salts to the soil profile. Despite that the quantity of the applied irrigation water was two to three times higher than the amount of GW used for evapotranspiration, the salt load through irrigation was largely exceeded by that resulting from the GW. Besides, it is likely that part of the salts that were added into the soil profile with the irrigation water was removed with the percolating water hence the actual salt load from surface was probably lower (Forkutsa 2006).

Even cropped fields, characterized by good suitability for agricultural practices experienced considerable salt input from the elevated GW table thus requiring large amounts of water for leaching and adequate functionality of drainage network to cope with soil salinization. As expected, the highest salt load was observed at the degraded agricultural site, re-used for afforestation which thus allowed alternative utilization of the land, no longer suitable for cropping.

Spatial dynamics of the groundwater table and salinity

Clearly, those areas characterized by the most shallow and saline GW tables are particularly susceptible to soil salinization and require improved drainage conditions. Spatial analysis utilizing the geostatistical interpolation method of kriging revealed such areas in the southern and western parts of the region. Apart from accurate interpolation, kriging offers estimation of the parameters and an assessment of the uncertainty of estimates and thus, comprehensive analysis (Cressie 1992). The observed nugget variance signifies high variation of the readings between the closest monitoring wells, which implies distant location of neighboring monitoring wells and possible measurement errors. Thus the present grid of observation wells allows only a regional, but not a site-specific groundwater management.

A spatial distribution of the GW table and salinity can be related to the spatial distribution and functionality of the drainage network in the region, which is one of the main management measures to cope with excessive and saline GW. The density of the drainage network in Khorezm, calculated as magnitude per unit area (38 m ha^{-1}), generally appeared to be uniformly distributed. Yet, despite the similar design and uniform coverage of the drainage network the shallower and more saline GW was observed at the particular areas. Previously, Khodzhibaev (1979) suggested that heavier soil texture found in the southern part of Khorezm might negatively influence the drainage performance in this area of the region and thus, affect the GW dynamics there. An alternative explanation is that the higher GW tables in southern and western parts of Khorezm could be caused by an outlet problem—the region is very shallow and the drainage network, the more in its present unattended state, may just not be able to carry away all the drainage water in short time. The fact that the GW table falls after cessation of irrigation period supports this view, but clearly, more detailed studies are needed here. Overall, the saline GW tables typically exceeding the critical levels during the growing periods, point to immediate need of improving the conditions of the drainage network to mitigate the soil salinization in Khorezm.

Conclusions

In the present study we analyzed the temporal and spatial dynamics of the GW table and salinity in Khorezm region over a period of 11 years. The GW table regularly becomes shallow beyond the critical level of 1.5 m widely accepted as a threshold for GW management purposes.

Case study analyses indicated that even with predominantly moderate salinity, the shallow GW contributed to a rise in soil salinization.

Spatial analysis revealed that GW was especially shallow and more saline in the western and southern parts of the region, which indicates a limited capacity of the drainage network in this part of the region.

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