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The Modern Problems of Sustainable Use and Management of Irrigated Lands on the Example of the Bukhara Region (Uzbekistan)

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Abstract

The Central Asian lowlands are characterized by an arid and continental climate. At the same time, the large streams and rivers have been providing water for the development of flourishing oases and extensive irrigated farming areas. Bukhara is one of those oases. The population of 1.7 mln. and especially the agricultural sector (with an irrigated area of 275,000 ha) use a considerable amount of water. But as the flat topography does not provide sufficient natural drainage, water logging and raising groundwater tables have become serious problems for the agricultural productivity. The combination of the high salinity of the irrigation water and the generous application of fertilizers leads to a widespread soil salinization. Excessive leaching is supposed to reduce the top soil salinity, but as the drainage system is only covering a small portion of the irrigated areas and is in need of maintenance, this process only contributes to the ongoing salinization and the reduction of soil fertility and crop yields. The data presented here for the years 2000 to 2013 indicate that the groundwater table is rising throughout the region while the groundwater salinity is decreasing. The soil salinity on the other hand is, after an improvement during the first half of the study period, slightly increasing since 2009, which also is reflected in the slight worsening of the condition of the reclaimed land during the same period.

Keywords

Water Resources, Water Quality, Irrigation Farming, Groundwater, Soil Salinization, Uzbekistan, Central Asia

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1. Introduction

Most of the plains in the Aral Sea basin are characterized by a high natural soil salinity. In the floodplains the salinity is increased by the accumulation of salty minerals eroded in the upstream mountainous regions. Due to the arid climate and the intensive irrigation farming the floodplains are also prone to the hazardous development of secondary soil salinization [1] [2]. Furthermore, the Aral Sea Basin countries, especially Uzbekistan and Turkmenistan, are heavily impacted by the climate change because of the high sensitivity of the arable lands in the arid lowlands [3]-[9] as well as a strong population and economic growth and increasing demands for the food safety [10] [11]. The climate change (increase of the air temperature and the evapotranspiration), long-term reduced runoff from the Central Asian glaciers and more frequent droughts also increase the water consumption for irrigation. As a consequence of this, the soil salinity will further increase and the productivity of the agricultural lands will continue to deteriorate.

The regions that are most sensitive to these anthropogenic and climatic changes are the lower reaches of the Syr Darya, Amu Darya and Zarafshan River, which are all characterized by large scale irrigation schemes of great economic importance [10]-[12]. The agriculture is a key economic sector in Uzbekistan, currently providing about 18% of the GDP with 27% of employment in this sector. Currently 45.3% of all Uzbek agricultural land is used for the grain production (39.5% wheat), followed by cotton (36.2%), fodder crops (8.6%) and vegetables (4.7%), showing an emphasis on food security and the cash crops [13]. The irrigated lands make up only 15% of the total farmland in Uzbekistan, but provide more than 90% of all agricultural products, making the country the sixth largest cotton producer and the second largest cotton exporter in the world [10]. This economy is solely dependent on the water intense irrigation, as without the current (low efficiency) irrigation network only 10% - 20% of the Aral Sea basin population could be sustained in this mostly arid region [14]. Over the course of the last 30 to 50 years the foundation of this economy, the arable land in the arid lowlands has been subject to extensive salinization, water and wind erosion, increasing groundwater mineralization and raising groundwater tables as well as the contamination with various pollutants (heavy metals, fluorides and pesticides) [6] [12] [13] [15]-[20]. 50.1% of all irrigated lands in Uzbekistan were already affected by salinization in 1994 and due to the extensive flood irrigation and leaching more than 30% of the topsoil humus has been washed out since the 1960s [14]. Two-thirds of the arable land in Uzbekistan has today a humus content of less than 1%, which is far below the international average for agricultural land of 3% [21]. Salinization and soil depletion lead to reduced crop yields (−20% - 30% have been observed for cotton on soils with medium salinity [21]). As a result, the agricultural productivity is with 700 USD/ha at present only one-third of what it had been in the 1980s and the annual financial losses are 1 bln. USD for Uzbekistan alone [10] [22]. The loss of soil productivity is combatted by the extensive use of mineral fertilizers [23]. Between 1996 and 2004, 677 tons of fertiliziers have been used annually in Uzbekistan. More than 40% of these have been applied in the three Zarafshan provinces: Samarkand, Navoi and Bukhara. 81% of the fertilizers are N-based (127 kg/ha), 16.5% contain P_2O_5 (26 kg/ha) and 2.5% K_2O (4 kg/ha) [21]. The amount of phosphorus and potassium fertilizers has been decreasing over the recent decades, being replaced by nitrogen, which leads to an additional long-term reduction of the overall soil productivity [23].

These highly complex issues of water availability, water use efficiency, soil quality, socioeconomic growth, administrative challenges and environmental problems in the Uzbek agricultural sector have been discussed by many researchers [10] [12]-[15] [18]-[21] [24]-[31].

In the Bukhara region, however, a world heritage site and important Silk Road oasis, the water and soil resource management and the resulting environmental problems have been studied mainly by local scientists and without a broader dissemination of the results [32]-[35]. They have analyzed the local soils in great detail and worked on the problems of saline soils and the agro-physical properties and salt regime of irrigated soils. This study now focuses on the dynamics of the water resources usage and the ameliorative conditions of the irrigated areas in the Bukhara province between 2000 and 2013. The knowledge about these important aspects is essential for the improvement of the ameliorative conditions, achieving and maintaining an optimal groundwater level and controlling the groundwater salinity.

2. The Characteristics of the Investigated Region

The Bukhara region is located on the southwest of the Republic of Uzbekistan, bordered by the Kashkadarya, Navoi and Khorezm regions of Uzbekistan as well as by the autonomous republic of Karakalpakstan and the

Republic of Turkmenistan (**Figure 1**). This region covers 40,320 km^2 and has a population of 1.7 mln. people. The majority of the population lives in rural areas (68%) with Bukhara (0.24 mln. inhabitants) itself being the only major city in the region. The climate is continental, with cold winters (monthly average: 1.6˚C in January) and hot summers (monthly average: 29.4˚C in July). The annual average air temperature is 15.6˚C and the annual precipitation is 142 mm. Most of the rainfall occurs during the winter months and in early spring (20.7 mm in December, 19.5 mm in January, 18.3 mm in February 28.8 mm in March) while the summer months are very dry (1.4 mm in June, 1.1 mm in July, 0.3 mm in August). Bukhara is a Silk Road oasis with a long history of cultivation. That is why only 23% of the area is unused, even though large areas of the Bukhara region are covered by the Kyzyl Kum desert, due to the arid climate with annual evaporation rates of approximately 2000 mm [11] [12]. 64% of the area is used for pastures, 4.7% for agriculture and 2.4% are covered by artificial drainage water lakes. And while the percentage of agricultural land is low, it is of great importance for the regional economy. A total of 274,900 ha are intensively irrigated to allow the production of cotton and wheat [36]. The main industries are textile, silk and cotton ginning. A second important part of the Bukhara economy is the mining and processing of oil, natural gas and precious metals. The region is one of the largest industrialized areas specializing on fuel and energy in Central Asia.

Soil Characteristics of the Bukhara Region

All of the soils found in the Bukhara region are characterized by a very low humus content (1% - 2%) [37]. The soil atlas of Uzbekistan [37] shows 11 different major soil types for this region, which can be sorted into four different categories (**Figure 2**):

- Sand and desert sand soils (**Figure 2**, No. 1 - 3; FAO-types: Dunes/Shifting Sand (DS), Cambic Arenosols (Qc) [38] [39]): These soil types dominate the western part of the Bukhara region, where the Kyzyl-Kum is located, but also the southern part, near the Uzbek-Turkmen border. These soils have a humus content of about 0.5% and nitrogen contents between 0.04% and 0.05%. Lacking both humus and nutrition elements, these soils are usually free of vegetation and thus are exposed to increased degradation and deflation.

Figure 1. The map of Bukhara region (Cartography: M. Groll, Base map: commons.wikimedia.org).

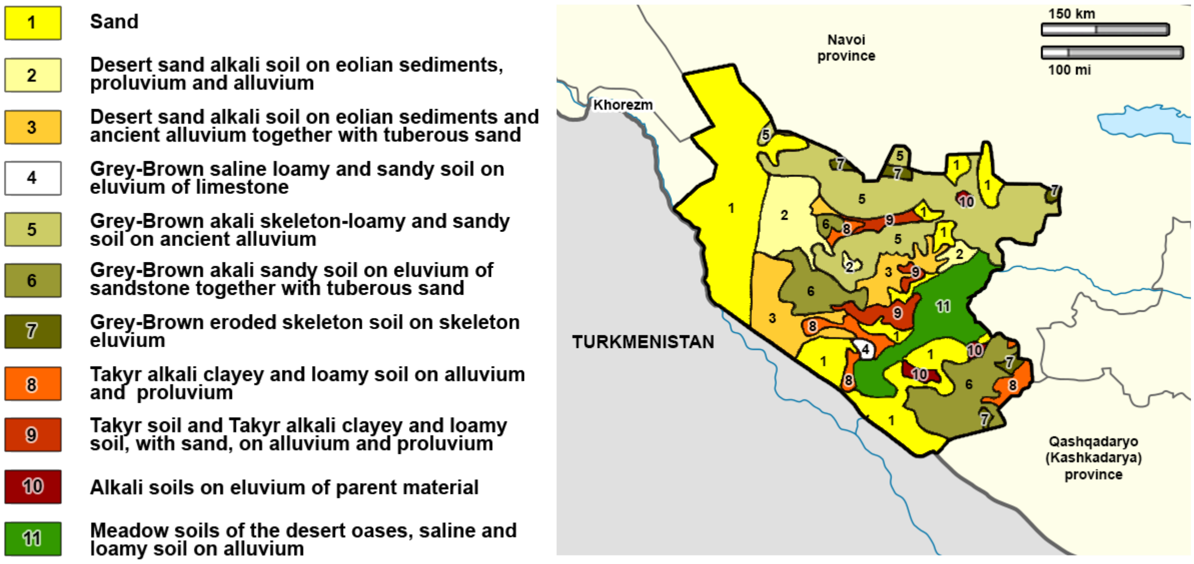


Figure 2. Soil map of the Bukhara region (Cartography: M. Groll, Base map: commons.wikimedia.org, Data: [37]).

- Grey-Brown soils (**Figure 2**, No. 4 - 7; FAO-types: Yermosols (Y)) [38]-[39]): These soil types dominate the northern and eastern parts of the region which are characterized by intensive irrigation farming on aridic soils. These soils have a varying texture (from sandy-loamy to medium-loamy) and a below average humus contents (0.6% - 0.9% in the arable layer). In the older parts of the irrigated land the amount of humus is higher and ranges from 1.2% to 1.8%. The nitrogen content in the irrigated grey-brown soils is between 0.05% and 0.16% while the total concentration of phosphor ranges from 0.09% to 0.11% [37].
- Takyr soils (**Figure 2**, No. 8 - 10; FAO-types: Takyric Yermosol (Yt), Calcic Xerosols (Xk)) [38] [39]): Not very common, these soil types can be found mainly in the central part of the Bukhara region, interlocked with grey-brown and sandy soils. They are formed in shallow depressions with high clay contents, which collect water and form salt crusts after the water evaporates.
- Meadow soils (**Figure 2**, No. 11; FAO-types: Calcaric and Eutric Gleysols (Gc, Ge)) [38] [39]): These soil types of the desert oases are located along the Zarafshan river and its former riverbed, reaching out to the Amudarya. Compared to other types of desert soils, the meadow soils have a higher humus (1.1% - 1.4%) and nitrogen (0.08% - 0.12%) content.

The humus in the soil determines its physical, physical-mechanical, hydrological, thermal, agronomic and biological properties as well as the soil productivity. In this respect, the soils in the Bukhara region are below average [14] [23] [37].

3. Materials and Methods

This article uses data from regional Hydro-Geological Reclamation Expeditions (HGRE), carried out by the Uzbek Basin Irrigation System Administration of the Ministry of Agriculture and Water Resources. The HGRE monitors the groundwater levels, mineralization and soil salinity [21]. This extensive database is complemented by results collected during 2 field studies in 2005 and 2010. During these field surveys additional data about the soil characteristics, soil salinity and cropping patterns have been gathered using soil science field methods and questionnaires.

The groundwater mineralization was determined based on the Priklonsky classification ([40], **Table 1**) and the degree of salinization of the irrigated areas was assessed using the Salinity classification developed by Bazilevich and Pankova ([41], **Table 2**).

The groundwater samples for the hydro-chemical analysis were collected three times per year (April, July and October, 2000-2013) from 1870 observation wells (metallic tubes with an inner diameter of 90 - 110 mm and a length of 3 - 6 m, filled with sand-gravel filters), operated by the Hydro-Geological Melioration Expedition of the Department of Agriculture and Water Resources in Bukhara (HGME). The samples were taken by the on-farm

Table 1. The classification of the groundwater mineralization [40].

No.	Category	Total Dissolved Solids (TDS) (g/l)
1.	Fresh	0 - 1
2.	Low mineralization	1 - 3
3.	Medium mineralization	3 - 10
4.	High mineralization	10 - 50

Table 2. The classification of the soil salinity, based on the total dissolved solids (TDS) and Clorine (Cl) [41].

No.	The Level of Salinization	Sulfate	Chloride-Sulfate		Sulfate-Chloride		Chloride
		TDS (g/l)	TDS (g/l)	Cl (g/l)	TDS (g/l)	C1 (g/l)	C1 (g/l)
1.	Non saline	<0.3	<0.1	<0.01	<0.01	<0.01	<0.01
2.	Slightly saline	0.3 - 1.0	0.1 - 0.3	0.01 - 0.05	0.1 - 0.3	0.01 - 0.04	0.01 - 0.03
3.	Moderately saline	1.0 - 2.0	0.3 - 1.0	0.05 - 0.2	0.3 - 0.6	0.04 - 0.2	0.03 - 0.1
4.	Highly saline	2.0 - 3.0	1.0 - 2.0	0.2 - 0.3	0.6 - 1.0	0.2 - 0.3	0.1 - 0.2
5.	Very highly saline	>3.0	>2.0	>0.3	>1.0	>0.3	>0.2

technicians (each responsible for a single farm with an average size of 1000 - 2000 ha), allowing the swift collection and analysis of more than 5600 groundwater samples per year. During the first sampling period (April), the effects of the extensive salt leaching, which are conducted just before the irrigation season starts, can be monitored. The second sampling period (July) covers the peak irrigation activity and the third sampling period (October) takes place immediately after the end of the growing season. This allows the analysis of the lowering of the phreatic surface without groundwater recharge. Furthermore, the analysis of the groundwater table dynamic outside the growing season is important, as a seasonal salinity restoration might occur when the upward flux prevails over the lateral outflow.

15,000 soil samples were taken by the HGME after the end of the growing season in November of each year (2000-2013) in 0 - 30 cm, 30 - 70 cm and 70 - 100 cm depth. Each sample is considered to be representative for 10 - 20 ha, resulting in a much denser grid of soil data than groundwater data. For each soil sample the electric conductivity was measured at the four corners of a 1.5 × 2.0 m^2 area surrounding the soil sampling site. The determination of the soil salinity was carried out applying two different methods. First through the extraction and assessment of the soluble salt contents and second through a SM-138 conductivity sensor applied to a 1:1 mixture of soil sample and water [42]. The measured soil salinity was then categorized as low (0.02 - 0.06 mg equivalent per liter), moderate (0.06 - 0.12 mg equivalent per liter) and high (>0.12 mg equivalent per liter). This classification was then assigned to the area represented by each soil sample in order to gain the spatial information about the soil salinity distribution and dynamic.

4. Results and Discussion

4.1. Development of the Irrigated Area and the Application of Fertilizers

Between 1991 and 2014, the population of the Bukhara province has grown by 47% (from 1.195 mln to 1.756 mln) [42], resulting in a strong economic growth and increasing food demand. In order to meet the growing demand the irrigated area increased as well-but at a slower rate (+12.7% since 1991; +0.4% between 2000 (273,800 ha) and 2013 (274,900 ha) while the population grew by 21.9% during the same period) [36]. This ongoing expansion of the irrigated land takes place on marginal lands with lower soil fertility and higher degrees of salinization. Thus, not only did the amount or irrigated land per capita decrease from 0.2 ha in 1991 to 0.16 ha in 2013 (−22%), but the productivity of that land also decreased, so that the crop yields in the Bukhara region (Wheat: 2.4 t/ha and year; Cotton: 2.1 t/ha and year; Vegetables and fruits: 10.6 t/ha and year) are now below the national average (Wheat: 2.5 t/ha and year; Cotton: 2.2 t/ha and year; Vegetables and fruits: 11.0 t/ha and year).

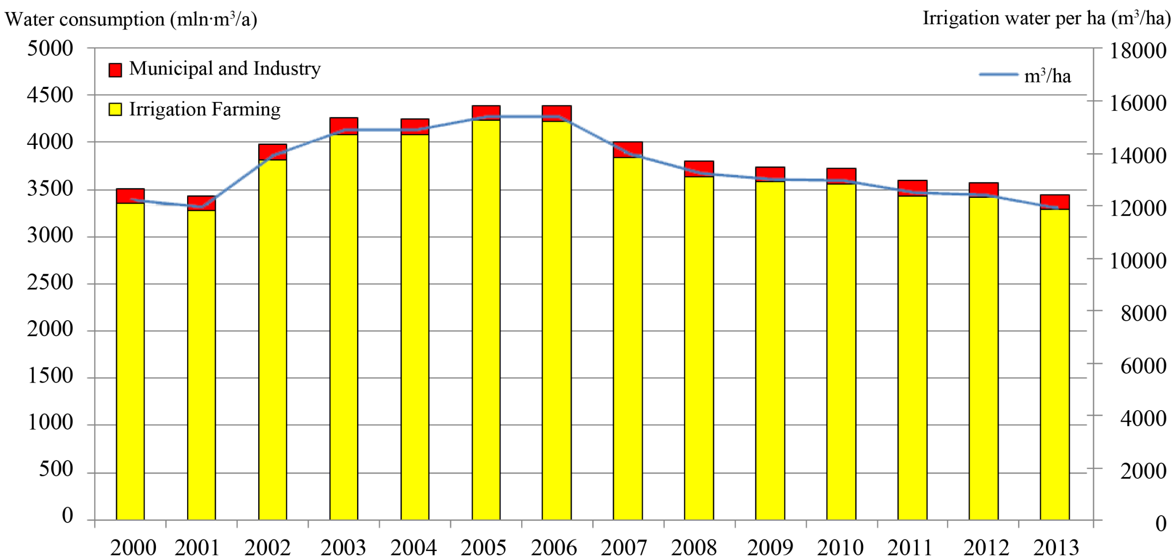
In order to increase the crop yield on the unproductive soils, mineral and organic fertilizers are applied in large quantities. **Table 3** shows a similar composition of the fertilizers in the Bukhara region and nation-wide (95% - 96% organic fertilizer), but also that on average 41.5% more fertilizers are applied in the Bukhara province (8646.7 kg/ha and year) than throughout the country (6110 kg/ha and year) and that the amount of fertilizers applied in the Bukhara region increased from 7510 kg/ha in 2011 to 9330 kg/ha in 2013 (+24.2%). And even though this increase will in the short-term stabilize the crop yields and secure the food and revenue generation of the region, in the long-term the extensive usage of (mineral) fertilizers will reduce the soil productivity and lead to more salinization [14] [21] [23].

4.2. Usage of the Water Resources

The irrigation farming is not only the most important part of the economy (90% of all crops are grown on irrigated areas) in the Bukhara region, it is also the largest water user (between 2000 and 2013 on average 95.8% of the annual water consumption has been allocated to the agricultural sector, **Figure 3**) [43]. Until the 1950s this water had been provided by the Zarafshan River, which crossed the Bukhara province and flowed into the Amu-Darya near Türkmenabat in Turkmenistan. But due to the extensive water withdrawal in the middle reaches of the Zarafshan the river since then officially "ends" 40 km northeast of Bukhara near Gijduvon, all its remaining water being distributed into the irrigation network [6]. Only during spring the Zarafshan River water is still used

Table 3. Application of mineral and organic fertilizer (in kg/ha) in the Bukhara region in comparison to the Uzbek average.

Year	Bukhara Region (kg/ha)		Uzbekistan Average (kg/ha)	
	Mineral Fertilizer	Organic Fertilizer	Mineral Fertilizer	Organic Fertilizer
2011	370	7140	260	5470
2012	380	8720	290	5850
2013	330	9000	310	6150
Average	**360**	**8286.7**	**286.7**	**5823.3**
Total	**8646.7**		**6110**	
%	**4.2**	**95.8**	**4.7**	**95.3**



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
% Irrigation	95.6%	95.6%	96.0%	95.8%	96.2%	96.3%	96.4%	96.0%	95.8%	95.7%	95.7%	95.5%	95.5%	95.4%
% Temp.	100%	102.4%	100.0%	97.8%	104.3%	100.7%	100.7%	101.7%	103.4%	100.7%	102.9%			
% Precip	100%	96.9%	169.9%	168.8%	143.7%	121.1%	91.5%	120.3%	85.9%	156.2%	103.2%			

Figure 3. Water consumption in the Bukhara province between 2000 and 2013.

for the leaching of the irrigated areas. The main source of water is nowadays the Amu-Darya. Water is withdrawn and delivered to the Bukhara oasis by a series of pumping stations, overcoming a height-difference of 68 m and a distance of 194 km. The hydrographic infrastructure of the Amu-Bukhara irrigation canal network includes the II-Amu-Bukhara Machine Station, the Amu-Karakul canal as well as the Kuyi-Mazar, Tudakul and Shurkul reservoirs, which are used for the irrigation water management. This irrigation network is complemented by an extensive drainage system with six major Drainage Water Collectors (DWC)-Central, North, Parallel, Tashkuduk, Parsankul and Ogitma.

Figure 3 shows the water consumption in the Bukhara province between 2000 and 2013. The municipal and industrial water use has been consistently low throughout this period, ranging from 150.3 mln·m^3 (2001) to 177.4 mln·m^3 (2003). The irrigation water on the other hand was subject to a strong interannual dynamic (min: 3.28 km^3 in 2001, max: 4.23 km^3 in 2006, average: 3.7 km^3) (**Figure 3**). The highest water consumption in 2006 (total: 4.4 km^3) coincides with a below average precipitation (91.5% of the reference year 2000), which might have influenced the agricultural water consumption. This total high also represents the year with the highest percentage of water used for the irrigation farming (96.4%), though this percentage has been very consistent throughout the whole period (average: 95.8%). The amount of water used for irrigation per hectare or irrigated land ranged between 15,425 m^3/ha in 2005 and 11,950 m^3/ha in 2013, with an average of 13,495 m^3/ha [12] [13]. To contrast these values, in the neighboring and equally arid Navoi province 18,754 m^3/ha are consumed. In Khorezm the amount of water used for the irrigation is also higher than in the Bukhara province (15,500 m^3/ha) while in Karakalpakstan the water consumption is comparable (13,200 m^3/ha) and in the Samarkand province, which is located further upstream along the Zarafshan River and is characterized by a higher annual rainfall (339 mm) only 6504 m^3 of water are used per hectare [6] [12] [13]. But the additional rainfall is not the main reason for the much lower water consumption in the Samarkand province, but the need for extensive leaching in the more arid provinces which are more heavily affected by salinization [12] [13]. On top of that the irrigation efficiency is very low in Central Asia. Significant losses are caused by the open irrigation canals (evaporation and infiltration due to lack of maintenance), large scale reservoirs (evaporation) and by the inefficient furrow irrigation [10] [15] [21] [44]. Dukhovny and de Schutter [10] have stated that the efficiency within the Amu-Darya catchment was as low as 50% in 1965 and that in the Zarafshan River catchment this low efficiency was already undercut in 1936. A higher efficiency of up to 82% was possible in the Golodnaya Steppe through the use of modern drip irrigation methods in the 1970s, but unfortunately these modern approaches were not implemented area-wide. The performance of the irrigation and drainage networks in Central Asia further decreased considerably since the disintegration of the Soviet Union as infrastructure maintenance is no longer coordinated and the financial means are no longer available. In the Uzbek part of the Zarafshan catchment 540,000 ha of arable land are irrigated by a main irrigation system with a length of 3140 km (41% of the canal length is lined) and an interfarm irrigation system with a length of 17,400 km (11% of which are lined)- and most of this network is in dire need of rehabilitation [14].

The water consumption and meteorological data (**Figure 3**) furthermore show that in years with an above average precipitation the water consumption for the irrigation farming is also above average (100% - 125% precipitation = 116% irrigation water consumption; >160% precipitation = 118% irrigation water consumption; base year: 2000). This means that the water availability in the irrigation network (rivers, canals and reservoirs) is already today the limiting parameter for the agricultural activities in this region and that a decrease of the water availability (e.g. by climate change induced droughts) cannot be buffered by the existing reservoir capacities and will directly affect the agricultural productivity.

Besides the very high water losses because of unsuitable irrigation methods and the overall lack of maintenance of the water infrastructure, the irrigation farming is still seen as the best economic option for the arid lowlands of the Aral Sea basin. There are however, other problems related to the irrigation besides the considerable water losses. In the Bukhara region these include excessive waterlogging, soil salinization, water depletion and water quality degradation.

The drainage of the irrigated and leached fields started in 1932. Drainage water collectors (DWC) were constructed throughout the Bukhara oasis, especially between 1956 and 1979. The main collectors in the region are the West Romitan, North Bukhara, Dengizkul, Main Karakul, Parallel and Central Bukhara collectors. The drainage not only removes the surplus water from the irrigated fields but also the leached salts, fertilizers and pesticides. As a result the mineralization of collector-drainage water is very high in the Bukhara region and ranges from 3.8 g/l to 4.2 g/l. These values are way above the national threshold of 1 g/l and indicate the severe impairment of the water quality in the lower Zarafshan River catchment [6]. But the CDW quality is not uniform throughout the Bukhara province as it also reflects the groundwater and soil salinity, which show a strong spatial varibility [45].

The collected drainage water is mostly dumped into natural depressions outside of the irrigated zone. These include the Shurkul Lake (filled with water from the West Romitan, Mahankul, Gurdyush and Main Karakul collectors), the Karakyr depression (served by the Severobuhra collector) and the Agitma depression (filled by the Agitma collector).

4.3. The Groundwater Table and Its Influence on the Characteristics of the Irrigated Area

The fertility of the irrigated lands in arid regions is largely dependent on the groundwater table and its salinity. Maintaining an adequate groundwater level is therefore a critical factor in creating the best ameliorative conditions for the irrigated lands. The groundwater table (GWT) itself is mainly determined by the terrain, the drainage depth, the distance from the drains and from the infiltration and percolation of irrigation water and precipitation [24]. High water tables of saline groundwater lead to a capillary rise of the salts into the upper soil layers and to water logging in the root zone, resulting in a reduction of the crop yields. In order to secure sufficiently high yields and regain the sustainability of the agriculture a better understanding of the groundwater dynamics and the spatial distribution of salinized areas, water logging and the salinization risk. Based on such results localized measures can be taken in order to prevent any further worsening of the status quo.

The data collected from the 1870 groundwater monitoring stations shows that the majority of the irrigated areas (63.7%) in the Bukhara region have a groundwater table depth of 2.0 - 3.0 m, followed by areas with a groundwater table depth of 1.5 - 2.0 m (20.8%). On the other hand, areas with a very high water table and areas with a very low water table only made up a very small percentage of the total irrigated area (**Figure 4**). From 2000 to 2013, areas with a groundwater table depth of higher than 3 m increased their coverage from 80.1% to 94.9%. On average the groundwater table rose by 38 cm from 2.66 m (2000) to 2.28 m (2013). This means that the irrigated area with a shallow groundwater table of 3 m or less (and thus a high potential for water logging and salinization) increased from 219,300 ha in 2000 to 260,900 ha in 2013.

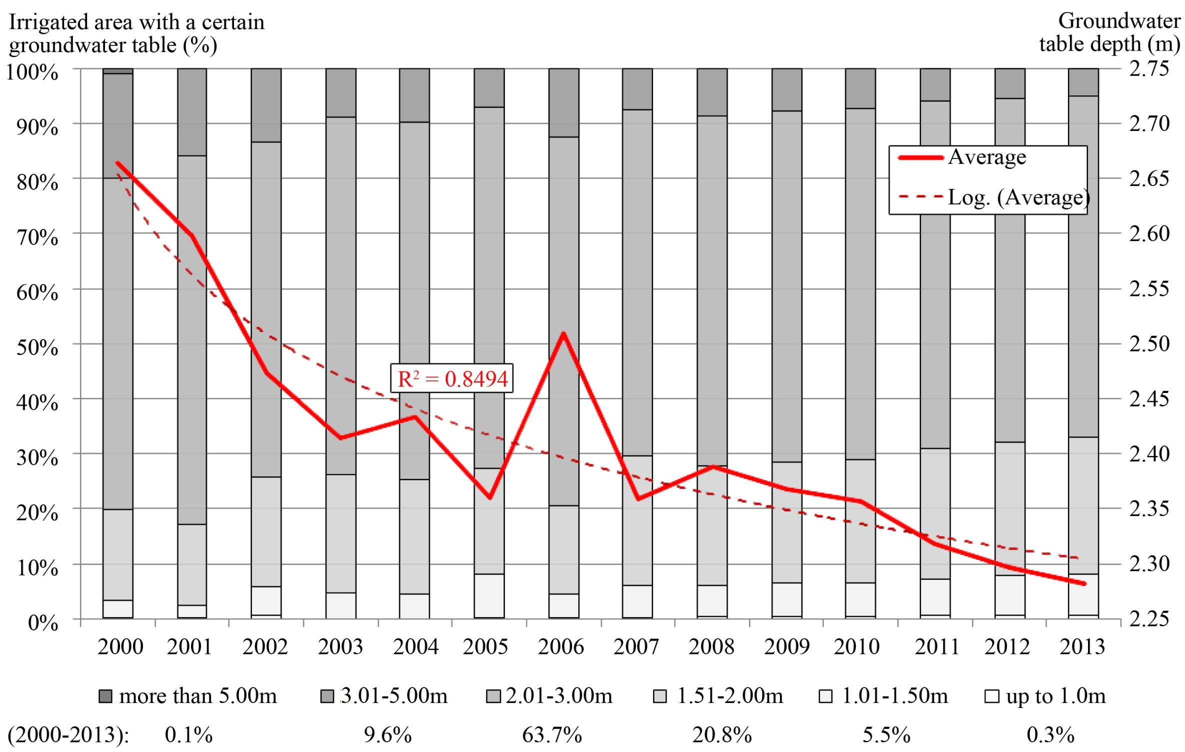


Figure 4. Temporal dynamic of the groundwater table depth in the irrigated areas (in % and average depth in m).

Figure 4 furthermore shows a drop of the average groundwater table by 15 cm in 2006, the year with the highest amount of irrigation water but a very low precipitation (comp. **Figure 3**). This indicates that the precipitation—even in this arid region—has a considerable influence on the groundwater recharge and that this influence might be greater than that of the irrigation farming. This is also supported by the fact that in the years after 2006 the amount of irrigation water decreased continuously, while the groundwater level kept rising. A third important parameter influencing the groundwater table in the Bukhara region is the inflow of groundwater from deeper aquifers, which pushes towards the surface [24].

4.4. The Groundwater Salinity and Its Impact on the Irrigated Areas

The groundwater table is only one driver of the salinization. The salinity of the groundwater is another equally important one. On average the groundwater in the Bukhara region has a salinity between 3.53 g/l (in 2001) and 2.83 g/l (in 2013) (**Figure 5**), which are extremely high values. The Amu-Darya for instance has a mineralization of 0.2 - 0.3 g/l in its middle reach and up to 1.0 g/l in the lower reach [46]. The same salinity (0.98 - 1.09 g/l) has been reported for the lower Zarafshan River near Navoi [6]. The majority of the irrigated areas in the Bukhara region showed a salinity of 1.1 - 3.0 g/l (61.1%, 168,000 ha) while the percentage of areas with a low salinity of lower than 1.0 g/l was with 0.2% (421 ha) negligible.

Between 2000 and 2013 the groundwater salinity decreased from more than 3.1 g/l to below 2.9 g/l. But just as for the water consumption for irrigation, the precipitation and the groundwater table, the groundwater salinity shows an anomaly in the year 2006. The salinity peak in the shallow groundwater was probably caused by a dry year (see **Figure 3**), where the lower amount of infiltrating water not only led to a drop of the groundwater table (see **Figure 4**), but also to higher concentrations of the applied fertilizers in the soils as the thinning effect of the rainfall has been much less pronounced than in previous years.

The contribution of the groundwater to the evaporation in the Bukhara province is between 60% and 80% and on average up to 5000 m^3 of groundwater per hectare rises up into the root zone and evaporates each year [47] [48].

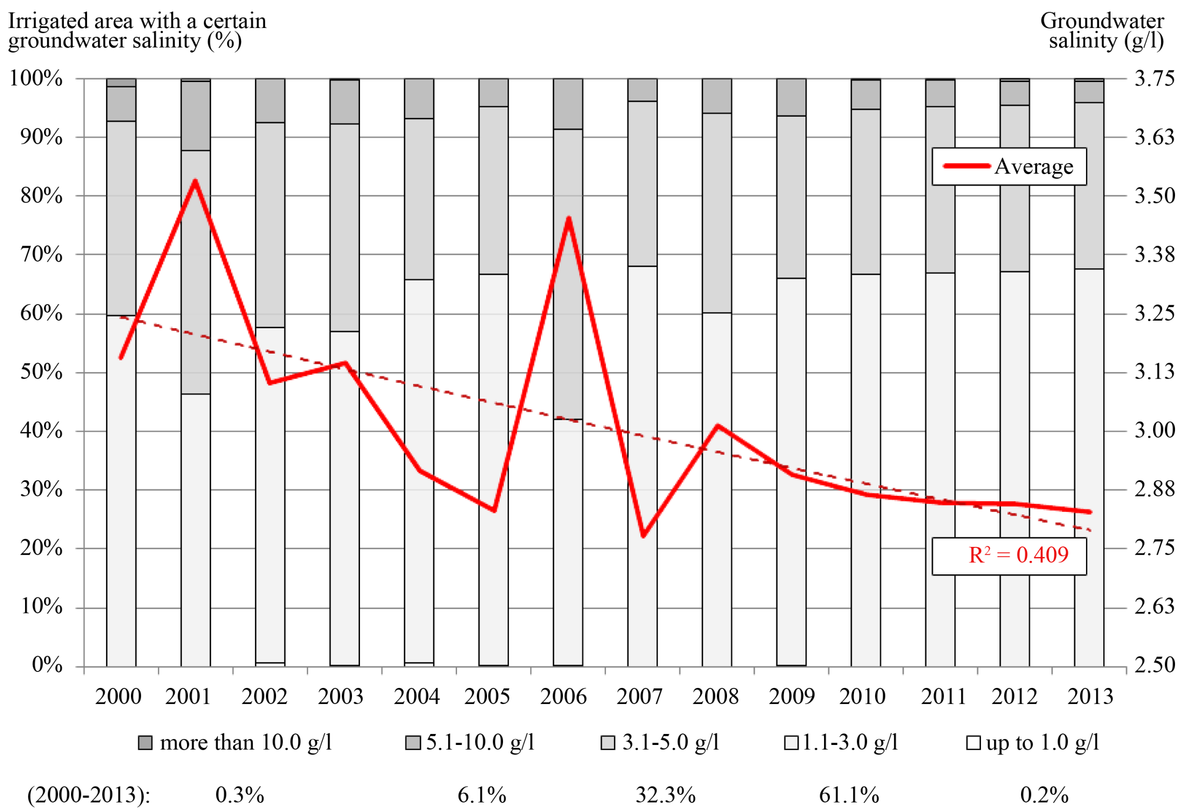


Figure 5. Temporal dynamic of the groundwater salinity in the irrigated areas (in % and average salinity in g/l).

Based on the average groundwater salinity of 3.02 g/l the annual amount of salts accumulated in the irrigated soils of the Bukhara province is 15.1 t/ha (for a total of 4.14 mln. tons per year). Broken down for the different categories of groundwater salinity this means that in areas with a groundwater salinity of 1 - 3 g/l (61.1% of the irrigated area) approximately 10 tons of salt are accumulated per hectare and year while in areas with a groundwater salinity of 5 - 10 g/l approximately 37.5 t/ha are accumulated. That means that even though the overall groundwater salinity has decreased over the past decade, certain areas within the Bukhara province are still heavily affected by groundwater based salt influx. This secondary salinization is combated by excessive leaching and increased irrigation quotas. But while these measures can help to mitigate the salt stress of the crops in the short term, in the long term this practice only leads to a further rise of the groundwater table, as only 30.2% of the irrigated areas in the Zarafshan River catchment are connected to the drainage system [6], and an increase of the groundwater salinity, especially as the irrigation water itself is characterized by a high mineralization of more than 1 g/l (the threshold for surface water mineralization in Uzbekistan) [35] [47].

4.5. The Soil Salinization in the Irrigated Areas

The soil salinization in the Bukhara province is, due to the salinity of the shallow groundwater and the irrigation water, the extensive use of fertilizers and the high evaporation rates, a widespread problem. 91.6% (251,400 ha) of all irrigated areas are at least slightly saline (**Figure 6**), 35.4% (97,200 ha) are characterized by at least a medium salinization and 7.8% (21,400 ha) are considered fully saline. These data confirm the salinization assessment by the Uzbek state committee for land resources, geodesy, cartography and state cadastre [49], which in 2008 had presented a map of the salinization in parts of the Bukhara oasis (**Figure 7**).

On average, the soil salinization score, which is calculated using the intensity of the salinization (four classes) and the percentage of the irrigated area affected by that salinization intensity and can have a score between 0 (non saline) and 1 (fully saline), is with 0.45 on a moderate level. The temporal development of this score shows a peak in 2001 (0.524), followed by a steady reduction of the soil salinization until 2009 (0.417). Since then the salinization again slightly increased. This trend does not correlate statistically with the average air temperature

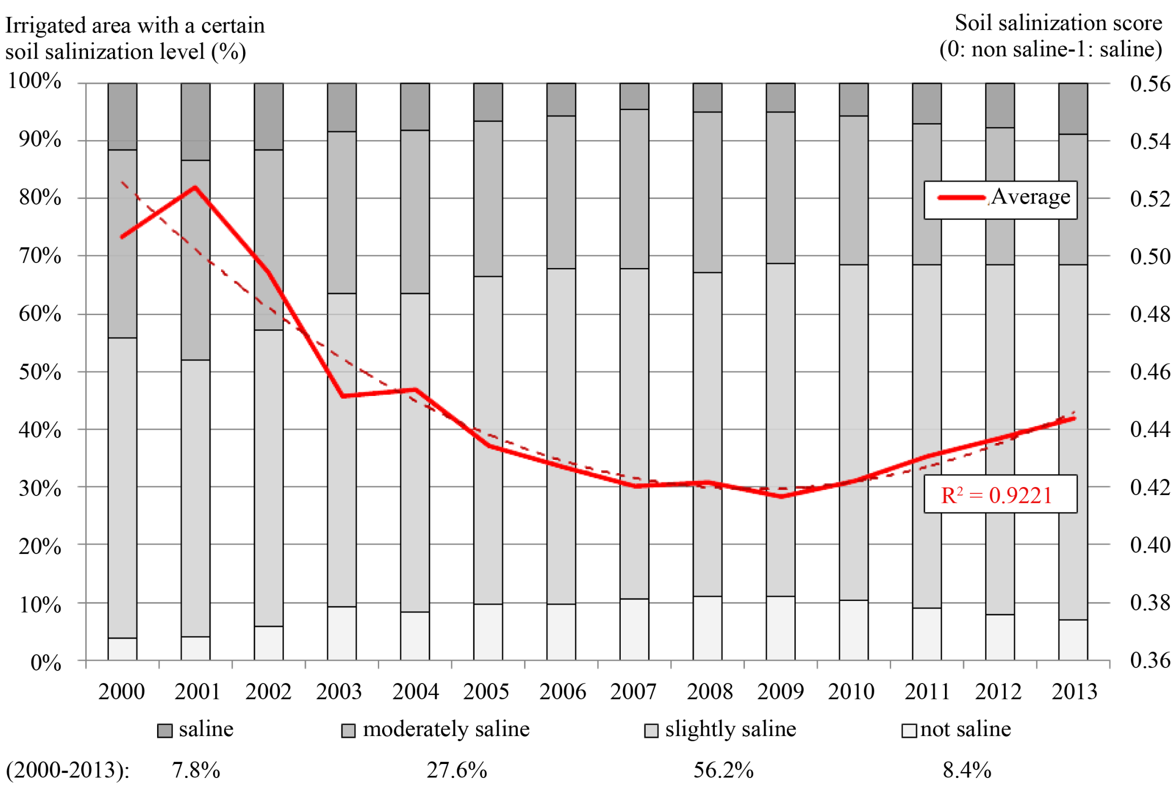


Figure 6. Temporal dynamic of the soil salinization in the irrigated areas (in % and soil salinization score between 0 (non saline) and 1 (saline)).

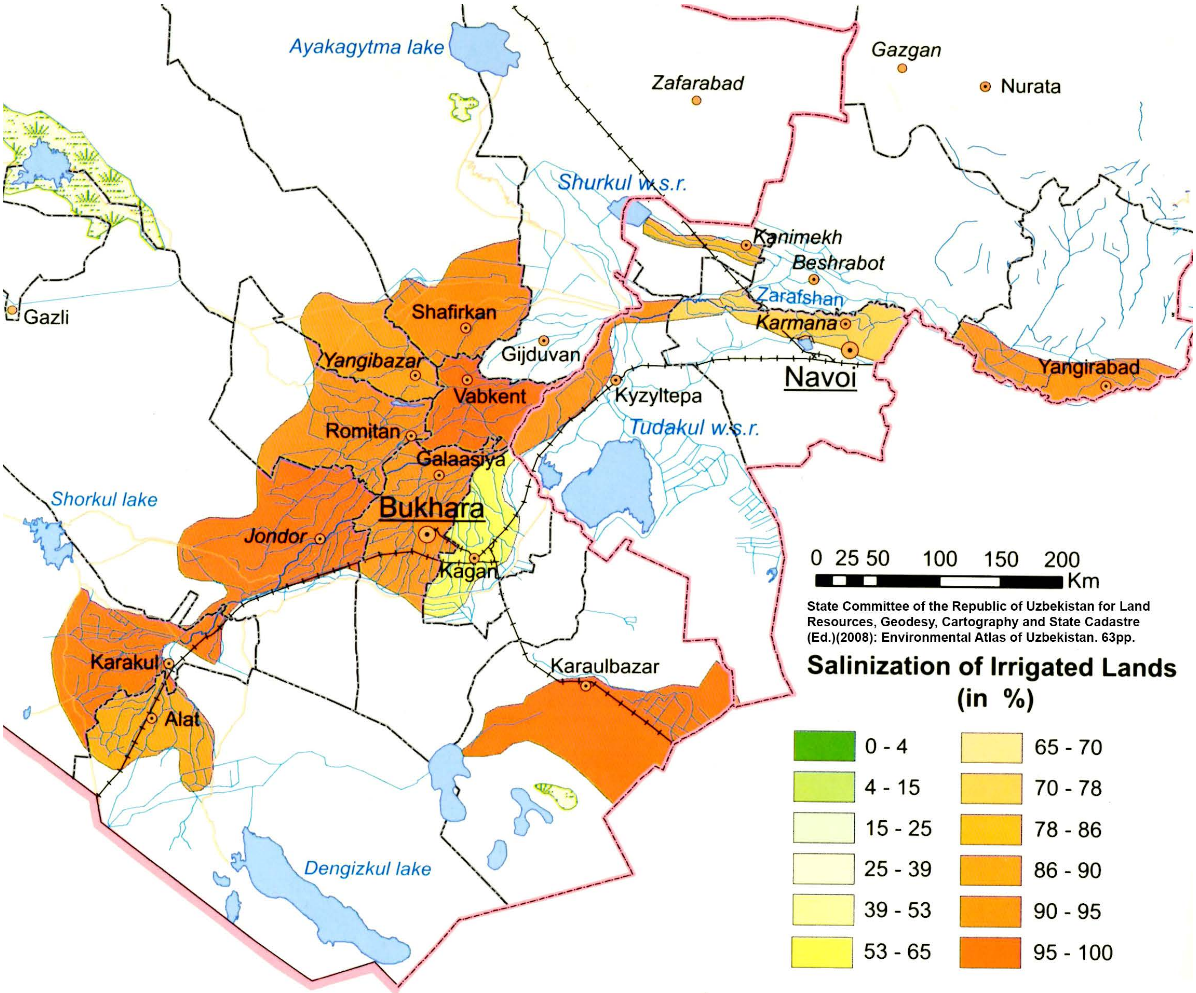


Figure 7. Soil salinization in the Bukhara oasis [49].

or the precipitation (R^2_{temp} = 0.028; R^2_{precip} = 0.059; **Figure 8**), though the strong decrease of the soil salinization in 2002 and 2003 coincides with above average rainfall (359 mm and 353 mm) in the same period. A better connection has been identified between the soil salinization and the groundwater salinity (R^2_{gwsal} = 0.38; **Figure 8**) in that the soil salinization for several years (2001-2004) followed the development of the groundwater salinity with a one-year delay (see **Figure 5** & **Figure 6**). But the best correlation can be seen between the soil salinization and the groundwater table (R^2_{gwtab} = 0.65). An especially good match is the rising groundwater level and the increase of the soil salinization since 2009 (see **Figure 4** & **Figure 6**). The irrigation intensity (in m^3/ha) on the other hand did not show a clear connection to the soil salinization (R^2_{irrig} = 0.41). The data indicate that the soil salinization slightly decreases with an increase of the irrigation water consumption, but this probably only symbolizes the short-term effect of the leaching and does not reflect the long-term soil deterioration caused by extensive irrigation in arid regions.

The data presented here indicates that several factors are influencing the soil salinity and that the weight of those factors might shift from year to year. Depending on the overall factor constellation, the rainfall (2002-2003), the groundwater salinity (2001-2004) or the groundwater table (2009-2013) determine the further development of the soil salinization. Based on this complex system, excessive leaching is not an effective tool for the stabilization of the irrigated areas, especially as the irrigation water consumption does not correlate as well with the soil salinity as the other parameters (with exception of the average air temperature). In order to prevent a further spread of the soil salinization in the Bukhara region the water logging and the groundwater table have to be managed in more efficient ways. Potential measures for this could be:

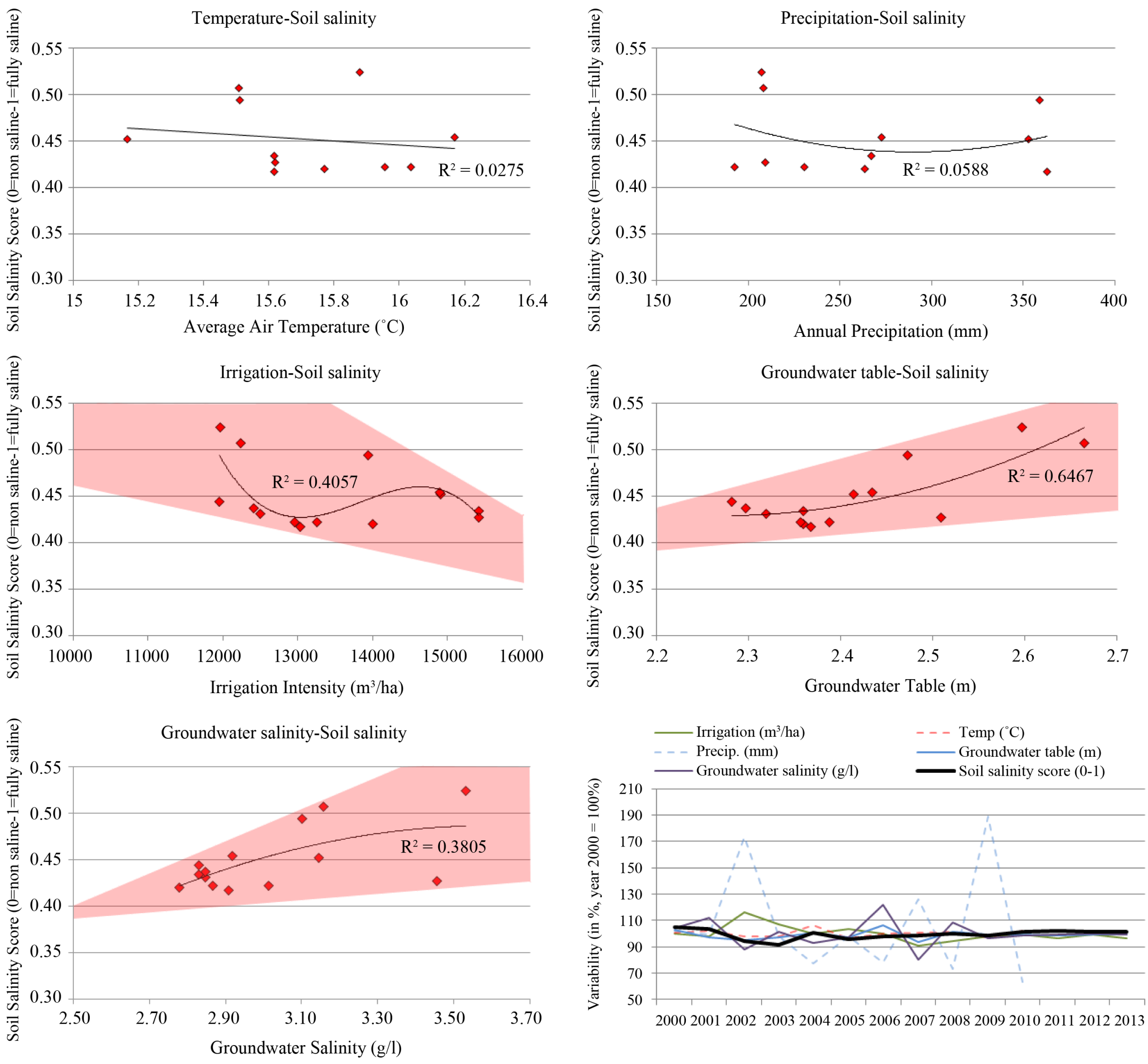


Figure 8. Correlations between the soil salinization and its influencing parameters.

- Increasing the density of the drainage systems so that a larger percentage of the irrigated area can be drained;
- Better maintenance and rehabilitation of the hydraulic structures in order to increase the efficiency of both the irrigation and the drainage system;
- Increasing the water quality of the irrigation water (in the lower Zarafshan River catchment untreated drainage water has to be used for irrigation purposes as there is an annual water deficit of 1.6 km^3) [6];
- A more sustainable use of the water and land resources (irrigation and fertilization based on the demand rather than on a quota).

4.6. Soil Conditions of Reclaimed Irrigated Lands

As the agricultural sector is of great importance for the Uzbek economy, protecting and improving the condition of the irrigated areas is of national interest, as can be seen in the presidential decree 3932 "on measures to radically improve the system of land reclamation" [50]. The actions taken for the rehabilitation of the irrigated areas result in an overall mostly "satisfactory" condition of the reclaimed land (74.3% of all reclaimed areas). A smaller portion (7.7%) even has a "good condition" while the reclaimed land with an "unsatisfactory condition" cover 18.1% of the area (**Figure 9**). Between 2000 and 2008 the average condition of the reclaimed areas improved slightly (from a score of 0.434 to 0.47), but since then the condition was deteriorating again (back to 0.426).

Figure 9. Temporal dynamic of the condition of the reclaimed irrigated areas (in % and condition score between 0 (unsatisfactory) and 1 (good)).

The temporal development of the condition of the reclaimed land shows a good correlation to the irrigation intensity (in m³/ha, $R^2_{irrig} = 0.7$, see **Figure 3**). The recent worsening could furthermore be explained by the raising groundwater table and the accelerated spread of the soil salinization since 2009 (see **Figure 4** and **Figure 6**). Especially the shallow groundwater is critical in certain areas, as the crop yields show significant losses if the groundwater table is at 1.5 m or less [47]. This threshold was in 2013 exceeded by 8.2% of the irrigated area (22,500 ha), while in 2000 only 3.25% of the irrigated area (8900 ha) had been affected by this.

The crop yield losses are aggravated by the soil salinity, as can be seen in **Table 4**. Both wheat and cotton—the two dominant crop types in the Bukhara province are not well suited for the cultivation on saline soils, as they suffer crop losses of 50% or more even on moderately saline soils, which make up 27.6% of all irrigated areas in the region. On soils with an even higher salinity (7.8% of all irrigated areas) the yield losses are higher than 80%. For cotton this translates to yields of 0.9 - 1.25 t/ha on saline soils in comparison to 1.6 - 2.1 t/ha on non-saline soils. Other crop types, like beets, corn, alfalfa or eggplants can tolerate higher salt concentrations. Especially beets can be grown on highly saline soils and still produce yields of more than two thirds of their maximum capacity [51].

5. Conclusions

Due to the arid climate the agriculture in the Bukhara region depends heavily on extensive irrigation. But as the flat topography does not provide sufficient natural drainage, water logging and raising groundwater tables are serious problems for the agricultural productivity. The combination of the high salinity of the irrigation water and the generous application of fertilizers leads to a widespread soil salinization. Excessive leaching is supposed to reduce the top soil salinity, but as the drainage system is only covering a small portion of the irrigated areas and is in need of maintenance, this process only contributes to the ongoing salinization and the reduction of soil fertility and crop yields.

The data shown here for the years 2000 to 2013 indicate that the groundwater table is rising throughout the

Table 4. The influence of the soil salinity on crop yields (modified after: [51]).

Type of crops	Crop yields (%) for different soil salinity classes				
	Non-Saline	Slightly Saline	Moderately Saline	Highly Saline	Very Highly Saline
Cotton	100	94	50	22	6
Wheat	100	80	39	15	0
Corn (fodder)	100	98	72	57	35
Alfalfa	100	96	73	53	39
Potato	100	90	68	0	0
Tomato	100	98	74	54	34
Pea	100	66	27	0	0
Eggplant	100	92	74	48	32
Beet	100	95	88	73	66

region while the groundwater salinity is decreasing. The soil salinity on the other hand is, after an improvement during the first half of the study period, slightly increasing since 2009, which is also reflected in the slight worsening of the condition of the reclaimed land during the same period.

The groundwater-soil-meteorology-irrigation system is highly complex, so that not a single parameter is controlling the salinization process at all times. Different parameters seem to dominate the system at different times, which also means that such a simple solution as excessive leaching will not work in the long term.

In order to manage the groundwater table and the soil salinity more effectively, the data from the existing monitoring network have to be implemented into the agricultural practices, so that the water usage can be tailored to the actual demand and the on-site capacity. Further advisable actions include the rehabilitation and extension of the drainage system, an increase of the irrigation efficiency, the improvement of the irrigation water quality and the consideration of more salt-tolerant crop types.

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