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Ecology and Development Series

No. 37, 2006

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1 INTRODUCTION

Uzbekistan comprises an area of around 447,400 square kilometers with potentially fertile soils and sufficient irrigation water resources, where various types and varieties of agricultural crops could be grown. Almost 85 % of Uzbekistan's territory is covered by desert and semi-desert, including the largest desert in Central Asia, the Kyzylkum. Due to the agro-climatic conditions, agricultural production fully relies on irrigation. In the early 1950s, a substantial development and improvement of Uzbekistan's agricultural sector was initiated. This went in line with an expansion of the arable land and an increase in productivity. Until the end of the last century, the total irrigated land increased from 1.2 million ha to 4.2 million ha (Abdullaev, 2003). Agriculture in Uzbekistan is one of the most important sectors of the economy providing 22.5 % of the GNP in 1996 (BPSP, 2000). Moreover it constitutes the main income for the rural population.

One of the most important crops in Uzbekistan is cotton, also referred to as "white gold". In the mid-1990s, Uzbekistan was the world's fifth cotton producer and second largest cotton exporter, exporting annually almost 80 % of the cotton harvest (Spectrum Commodities, 2004). Today, Uzbekistan is the fourth largest producer of cotton in the world, with 20 % of the total world production (Petr et al., 2003).

Growing cotton in the semi-arid climate conditions and on saline soils requires intensive irrigation. The cultivation of cotton consumes about 50 % of the total irrigation needs in the region (Tsutsui and Hatcho, 1995). Through intensive irrigation, the achieved crop yields are relatively high. According to the Regional Department of Statistics (OblStat), the average yield of raw-cotton in 1991-2001 in Uzbekistan was 2.4 t ha^{-1}, but in the intervention zone Khorezm it constituted 2.7 t ha^{-1} (OblStat, 2004). Although mature cotton plants are salt tolerant, they are very sensitive to soil salinity during germination and at the juvenile stage. Therefore, in order to wash salts from the surface horizons, high water amounts are applied during the winter-spring leaching period. On average, 4300 m^3 ha^{-1} of water is applied for leaching on 85 % of the irrigated land in Khorezm (Djanibekov, 2005).

The ambitious plans during Soviet times for agricultural development in Uzbekistan led to the environmental degradation of the Aral Sea region and the desiccation of the Aral Sea itself. This has had drastic impacts on agricultural production and the livelihood of the rural population, as about 56 % of the total irrigated area of the country is concentrated in the basin of the Amu-Darya River, the largest of the Aral Sea's tributaries (Abdullaev, 2003). High water amounts were and still are applied for cotton and rice production, while water management at the field level is poor and efficient drainage lacking. This is all leading to a rising groundwater table, drastically changing the local and regional hydrology and causing problems of secondary soil salinization. Abdullaev (2003) mentioned that the entire irrigated area in the Khorezm region has secondary salinization problems.

The Amu-Darya River is also the main water source in the Khorezm region, which is located at the southern edge of the Aral Sea Basin in northwest Uzbekistan. The region encompasses a complicated network of irrigation systems and drainage water collection canals, which have been constructed since the early 1950s. There is a need to maintain the irrigation and drainage systems in good shape by yearly removal of sedimentation and weeds from the bed and sides of the canals. Irrigation water quality is degrading due to partial disposal of the polluted drainage waters into the river system. This also imposes a risk for the human health of the local population, which also has to cope with a range of serious problems, such as water scarcity and salinization in response to unsustainable agricultural management. It has been reported that the region regularly experiences shortages of water resources (e.g., a severe shortage during 2000-2001). Soil salinity is often reported to have increased in the past decades. For instance, according to Shirokova (2003, *unpublished*), at least 94 % of the irrigated areas are saline. However, for a profitable crop production in semi-arid regions avoiding plant water stress and soil salinity are two important aspects (Homaee et al., 2002). Effective water management practices are supposed to cover these aspects by maintaining favorable soil moisture and omitting salinity stress by reducing the salt content in the root zone during leaching (Vrugt et al., 2001).

Many studies have been conducted by national and international organizations and researchers to restore the Aral Sea and to rehabilitate the degraded environments (Micklin and Williams, 1994). However, the Khorezm region, which is also a part of Aral Sea Basin, has not received special attention in those studies. Thus ZEF, in collaboration with national and international partners (among others UNESCO, DLR, University of Urgench and Tashkent Institute for Irrigation and Mechanization in Uzbekistan), initiated a bilateral German-Uzbek research program on the “Ecological and Economical Restructuring of Land and Water Use in the Khorezm Region of Uzbekistan – a Pilot Project for Development Research” that aims at providing options for a regional development based on sustainable and efficient land and water use (Vlek et al., 2003).

Field studies are included to increase the understanding on how farmers deal with and manage irrigation water, water deficits and soil salinity during and outside the vegetation periods. However, field studies alone are insufficient to gain insight into how the different parts of the soil-plant-atmosphere system interact (Evett and Lascano, 1993). Here the model application is one of the options of research.

A generally shallow groundwater table is on the one hand the consequence of excessive application of irrigation water. On the other hand, it is a result of imperfect drainage, which in Khorezm is caused by several factors. Since, due to institutional shortcomings, irrigation water is sometimes not available when needed, farmers in Khorezm tend on such occasions to manually block drains and irrigation canals and maintain high soil moisture prior to and after the planting of cotton. Furthermore, the general drainage system is also dysfunctioning and consequently about 34 % of the area of Khorezm has a saline and shallow (<1.0 m) groundwater table (MAWR, 2004).

Shallow groundwater not only advances secondary salinization, but also contributes significantly to crop water demand (Kiseliova and Jumaniyazov, 1975). Yet little is documented on the quantification of the groundwater contribution to meeting the crop water demands, mainly because a precise quantification of capillary rise into the rooting zone of the crop *in situ* implies cost- and labor-intensive experimental setups (e.g., construction of lysimeters). Modeling in this regard provides an effective alternative, as it can help to understand temporal as well as spatial aspects of soil water and solute fluxes. It also is a cheap alternative, since it does not require expensive and laborious lysimeters installations.

Short-term experiments (less than 10 years) are considered appropriate for testing and parameterizing simulation models, which further can be applied for water balance studies based on long-term climate data (Keating et al., 2002). Pereira et al. (2003) argued that experiments in combination with simulation models offer the possibility to gain detailed insights into the system behavior, both in space and in time. Such a combination would also bypass the constraint that field experiments are often site-specific and time consuming to conduct. Despite the fact that by now numerous models exist, the need to test and upgrade them is still high (Xu and Singh, 1996).

One of the existing models, the HYDRUS-1D, was selected and applied in the current study and adapted to local conditions. The HYDRUS-1D software package is a finite-element numerical model for simulating the one-dimensional movement of water, heat and multiple solutes in variably saturated media (Simunek et al., 1998a).

Many studies in Uzbekistan have been carried out to establish water and salt balances for different crops and groundwater regimes under conditions of furrow irrigation with a shallow groundwater (Abdullaev, 1995; Faizullaev, 1980; Isabaev, 1986; Jabbarov et al., 1977; Rysbekov, 1986; Yusupov et al., 1979). However, the reports of modeling results are poorly introduced in the literature. In some cases, the different general implications of these models cannot be assessed because of differing system parameters and input variables, and hence various research institutes worked with their own independently elaborated or modified models. Usually the capillary rise from groundwater can not be modeled, and this has been merely estimated by additional lysimeters studies. For these reasons, existing models have not become widely used, also due to the existence of unfriendly user interfaces. Therefore, the well known HYDRUS-1D model was applied for the first time in Uzbekistan.

Besides application of the model, the agricultural management carried out by the farmers on the cotton fields was monitored to evaluate the consequences with regard to the established water and salt balances and subsoil water fluxes. Thus, this study was undertaken to:

- establish a water and salt balance of the irrigated fields under cotton;
- estimate capillary rise from the groundwater table during the non-vegetation and vegetation seasons;
- assess the agricultural management of cotton growing.

The current regional conditions of soil, irrigation and drainage networks, problems of water management in Khorezm and the arising needs as well as the state-of-the-art of soil water and salt modeling are reviewed and discussed in Chapter 2. After a general introduction to the study region given in Chapter 3, Chapter 4 is dedicated to the description of the field-data collection methodology and description of the model used in the study. In Chapter 5, the analyses of water and salt balances are performed and discussed. Simulation of water and solute transport for different locations in the fields will be presented, and the effect of the soil properties variability on the water and salt balance will be examined. Special attention is given to a quantification of the subsoil water fluxes and leaching requirements. The findings of the comparison of two vegetation seasons are also reported in this section. Chapter 6 discusses the results of the study, comparing the findings with previously conducted studies in the region, while Chapter 7 closes with conclusions.

By describing and quantifying the actual water and solute fluxes as well as seasonal salt dynamics in the soil, the results of the modeling contribute to identifying the problems of water management. Moreover, the model can be used in combination with models on irrigation scheduling and management as well as crop-growth analysis within the framework of an integrated modeling and decision support system.

2 LITERATURE REVIEW

The Aral Sea Basin is a region with water scarcity problems due to an arid climate and poor water management (Micklin, 1991). To solve the water scarcity in the region, crop irrigation management has to be improved, including the management of salinity in the region (Horst et al., 2004). In this regard, it is necessary to understand how water can be used efficiently for agricultural needs. The agricultural production in the region, as well as in entire Central Asia, largely depends on irrigation using water from the two main rivers, Amu-Darya and Syr-Darya. Due to the large-scale irrigation systems constructed since the 1950s, less water from both rivers flows into the Aral Sea, causing it to shrink in size. Between 1960 and 1994, the surface area of the Aral Sea shrunk by more than 50 %, and the "salinity risen by more than three-fold to near that of the ocean" (Micklin and Williams, 1994). At the same time, water losses in agriculture are notoriously high. For more than 30 years, the infrastructure of the irrigation and drainage has operated without rehabilitation and modernization (Abdullaev, 2003). Hence, by 1994, about 63 % of the diverted river water for irrigation was lost before it reached the fields (FAO, 1997). The crop water needs for the two major crops, cotton and winter wheat, produced in Uzbekistan are not well known to the present farming population, which has led in most cases to over-irrigation, high groundwater tables and an increase in soil and groundwater salinity (Evett et al., 2002). Crucial questions such as "How much water is enough to grow crops?" and "What is the level of seasonal salt accumulation in the crop rooting zone?" or "How efficiently do crops use the applied water?" are difficult to answer. However, a successful water management scheme for irrigated crops requires knowledge on the relationship of different key factors in the soil-water-plant-atmosphere system.

2.1 Soil properties of the Khorezm region

The Khorezm region is an irrigated oasis with a history of more than 2000 years (Ablyazov, 1973). Long-term settlement practices caused changes in soil structure and influenced soil salinity. Medium and heavy loam soil textures prevail in the region, while clayey, light loam and sandy loam soils are less widespread and often located either in the lower parts of lake sedimentation or in former riverbeds and adjacent sites.

Faizullaev (1980) determined four groups of soils in the region according to permeability and hydraulic conductivity:

1. Soils of light texture, usually homogeneous with high permeability during the first hour of 70 mm hour^{-1}, and a coefficient of filtration of 0.52 m d^{-1}. These are so-called newly irrigated meadow sandy loams.
2. Soils of medium and heavy loamy texture, homogeneous and heterogeneous, lightening to the bottom with a good permeability of 50-70 mm during the first hour and a coefficient of filtration of 0.45 m d^{-1}. These are both old and newly irrigated meadow soils, usually slightly saline.
3. Soils of different soil textures with clayey layers having a satisfactory permeability of 30-50 mm hour^{-1} and a coefficient of filtration of 0.36 m d^{-1}. These are both old and newly irrigated meadow and bog-meadow soils of medium and high salinity, as well as solonchaks.
4. Soils of different soil textures becoming heavier downward with a low permeability of less than 30 mm per first hour and a coefficient of filtration of 0.2 m d^{-1}. These are solonchaks and soils with compacted top layers.

Abdullaev (1995) summarized the basic water and physical soil properties depending on soil texture: The water permeability of sandy soils is 230-360 cm d^{-1} and in sandy loam soils between 12 and 230 cm d^{-1}. Data on saturated hydraulic conductivity for soils in the Khorezm region were not found in the literature. There is a general lack of data in available soil hydraulic databases for application in model simulations on soils in the Khorezm region.

2.2 Water management and problems of soil salinization in the Khorezm region

Worldwide, soil salinity is a latent threat within irrigated agriculture. Improper irrigation can lead to a rising groundwater table in particular when the drainage system is not working properly. Hence, this directly changes the local and regional groundwater movements. Salt accumulation in the crop root zone is a logical consequence of raising saline groundwater tables under conditions of potentially high evapotranspiration as prevailing in an arid environment such as in Khorezm.

Kaurichev et al. (1989) noted that the soil water regime is an aggregate of events of water infiltration into the soil, its movement, retention in the soil layers and loss from the soil profile. Quantitatively it is expressed through a water balance, which characterizes the water influx into the soil profile and discharge out of it. A soil water balance allows judging the reserves of the soil water available to crops. Ratliff et al. (1983) pointed out that an accurate calculation of the soil water balance is important because of the need to manage water as efficiently as possible. The amount of irrigation water required for crops can be calculated considering the water balance of the crop root zone, taking into account crop water requirements.

Over the past centuries, people have gained knowledge and experience on how to use saline soils and water to produce crops. One of the commonly applied remedies is applying high water amounts to remove harmful salts by downward percolation beyond the crop rooting zone (Hillel, 2004) during special leaching periods or irrigation. Unless the salts are leached out, they poison the root zone. Hence, the necessary amount of water for leaching highly depends on the salt content of soils, drainage system conditions, irrigation and groundwater salinity (Ferrer and Stockle, 1996). The crop salt tolerance, climate, soil and water management should be taken into consideration as well as economic aspects for determining the frequency and total amount of leaching water.

However, not only leaching *per se* plays an important role within irrigated agriculture, but also the timing for leaching. This is usually determined on the basis of climatic factors such as first frosts in autumn or air and soil temperatures above a certain threshold in spring. Kiseliova and Lifshits (1971b) concluded that in Khorezm the first soil freezing occurs in mid November in 50 % of all years based on monitoring from 1953 onwards. Since early frosts complicate the autumn to spring field activities, such as leaching and ploughing, leaching activities in Khorezm are conducted in February-April, when climatic conditions are more favorable.

Cotton is considered as a salt tolerant crop (Allen et al., 1998), although during the germination period it is sensitive to salinity. Thus, in order to achieve acceptable plant establishment rates and ultimately yields, leaching is necessary if the electrical conductivity of the soil solution before planting is greater than 7.7 dS m^{-1} (Rhoades et al., 1992). At the same time after leaching, the soil moisture content is high to secure seed germination. The timing of the first irrigation, especially under saline conditions, is crucial for unrestricted crop growth and rooting system development (Kruse and Ayars, 1996). Already in the early 19th century, farmers used groundwater as sub-surface irrigation by blocking the drains after the leaching. They kept them closed for a few weeks, thus maintaining soil moisture at favorable levels for crop germination.

Naturally, soil salinity is not constant and uniform in time and space. Depending on leaching and/or irrigation rates and the height of the groundwater table and its salinity, the salt distribution may be uniform along the soil profile with slow changes with depth, or may be irregular, with high concentrations on top or at the bottom of the root zone (Hutson et al., 1996). Numerous factors such as soil physical and chemical properties, crop water and solute uptake, and water and solute application rates affect solute transport in the vadose zone (Dudley and Shani, 2003; Rose, 2004). In arid environments with shallow groundwater tables, the capillary rise of water and solutes from the groundwater into the rooting zone has to be taken into account. Thus, water and solute uptake by plant roots greatly affects rootzone concentration and fluxes of salts from or towards the groundwater.

Abdullaev (1995) pointed out that at the lower reaches of the Amu-Darya River, the groundwater under the irrigated soils is mainly evaporates and transpires, while a minor part is discharged to the collectors and deep percolation. Therefore, the groundwater flow contributes to the vertical water exchange, i.e., it is hydrostatically connected to the surface water. Kats (1976) mentioned that in the Khorezm region the vertical movements of groundwater prevail over horizontal movements in large areas. Thus, the groundwater table changes very fast in response to changes in the water level in the irrigation and drainage systems. Under such circumstances, difficulties arise with regard to a precise determination of groundwater depth. Moreover, Yusupov et al. (1979) mentioned that the actual groundwater table is 20-30 cm lower than the water table measured with observation wells. They attributed these deviations to the hydrostatic pressure building up in the observation wells due to a sandy groundwater aquifer overlaid by a less-permeable loamy soil layer. They finally concluded that the height and rate of groundwater table rise depends on soil texture. The existence of a hydro-dynamical connection between groundwater and filtration fluxes from the irrigation canals and collectors in stratified soil structures creates a low positive