Modeling the Managed Aquifer Recharge for Groundwater Salinity Management in the Sokh River Basin

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Abstract

The vulnerability of surface water sources in the Syrdarya River Basin, due to their transboundary nature and climatic change, raises the importance of the shift from canal irrigation to conjunctive use of surface water and groundwater. However, groundwater development for irrigation may increase salinity of water due to leaching of dissolved solids from the salt-affected vadoze zone and blending of freshwater and saline water. In this paper managed aquifer recharge and discharge are analyzed as a strategy to maintain the groundwater quality of the Sokh aquifer of the Fergana Valley located upstream of the Syrdarya River Basin. Field studies suggested that groundwater recharge from the river floodplain may contribute to maintaining good-quality water in the groundwater system. The modeling study examines groundwater salinity change over a 5-year period under different managed groundwater recharge and discharge scenarios. The modeling results show that adopting water saving technologies and increased groundwater recharge through the river floodplain allows maintaining low groundwater salinity. The studies found that developing groundwater for irrigation increases salinity in the aquifer due to downward saline water fluxes. The results indicate that managed aquifer recharge and discharge contribute to maintaining salinity levels in the vadoze zone and groundwater.

Keywords: Managed aquifer recharge, groundwater use for irrigation, numerical modeling and scenario analysis, Fergana Valley, Central Asia

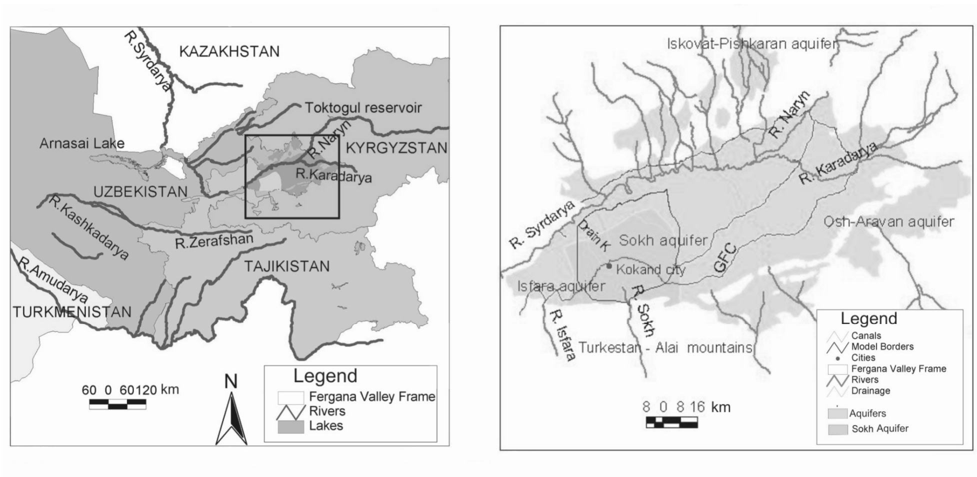
Introduction

Vulnerability of surface water sources in the Syrdarya River Basin due to their transboundary nature and climatic change raises the importance of shifting from canal irrigation to conjunctive management of surface water and groundwater. This strategy is important for the Fergana Valley located upstream of the river basin. Although the valley has plenty of underdeveloped groundwater resources, surface water diversions for irrigation exceed one-third of the river flow. Whereas high water shortage occurs in the midstream and in the lower reaches of the basin, the surplus of groundwater resources of the Fergana Valley causes waterlogging and salinity issues. These issues emphasize the need to shift from surface irrigation to conjunctive use of groundwater and surface water.

However, conjunctive use associated with extensive groundwater abstraction may cause degradation of groundwater quality due to leaching of salts from the vadoze zone and blending of groundwater of different layers. This may increase the salinity of both groundwater of shallow aquifers, which are the sources of irrigation water, and deeper aquifers, which are the sources of drinking water supply. Under such conditions it is important to develop a strategy to ensure water quality in the shallow aquifers suitable for irrigation and in the deep aquifers for drinking water supply. The goal of this study was to develop a strategy of managed aquifer recharge and discharge aimed at maintaining water quality under intensive groundwater abstraction for irrigation uses. The objectives of the study were to assess 1) the effect of the groundwater recharge on water quality (salinity), and 2) the efficiency of different managed aquifer recharge strategies aimed at maintaining groundwater quality. In this paper, two strategies were analyzed:

1) water conservation and managed aquifer recharge and 2) managed aquifer recharge and discharge by constructing shallow wells for irrigation.

The effect of the proposed strategies on groundwater salinity is analyzed taking the Sokh aquifer, one of the typical aquifers of the Fergana Valley, as an example (Figure 1).



a) b)

Figure 1. The upstream of the Syrdarya River Basin (a) and location of the Sokh aquifer in the Fergana Valley (b)

Recently, Gracheva et al. (2009) tested managed aquifer winter recharge (MAWR) at the Sokh aquifer through the hydrodynamic modeling and found that the groundwater abstraction at 620 million cubic meters per year (Mm^3/yr.) creates free capacities at 300 Mm^3/yr. available for banking the winter flow of the Sokh and Naryn rivers. However, these promising results were obtained without considering possible water-quality changes in the groundwater system. That is why these field and modeling studies were initiated aimed at understanding possible changes in water quality, which is important prior to wide dissemination of the recommendations on groundwater banking (Karimov et al., 2010). Studies on field water budgeting were carried out in 2009 to estimate groundwater recharge from the river floodplain. Based on the findings of the field study, long-term groundwater recharge from the floodplain was estimated using the river flow data followed by examining the correlation between the groundwater recharge and water salinity under the current conditions. Finally, modeling of groundwater quality was applied to assess the efficiency of managed aquifer recharge strategies to maintain the quality of the groundwater.

This paper starts with the description of the study area, applied field studies and modeling approach, and continues with the collection of initial data for compiling the groundwater salinity model of the Sokh aquifer. This is followed by the results of the model calibration. Groundwater recharge from the river floodplain is estimated for current conditions. Then, changes in water quality are predicted under maximum groundwater abstraction levels. Finally, three strategies of managed aquifer recharge were analyzed to maintain groundwater quality.

Methodology and characterization of the study area

Characterization of the study area

The Sokh River Basin extending over 180,000 ha has two geomorphological zones with steep coarse shingle deposits upstream and flatter loamy clay deposits lower down. There are two main sources of water in the study area: Sokh River and the Big Fergana Canal (BFC) delivering water of the Naryn River to the water-short areas of the Fergana Valley. The Sokh River flows north from the Turkestan-Alai Mountains into the alluvial valley along the Syrdarya River. In the upper part of the study area the river has a floodplain 600 m wide and 10,000 m long formed by shingle and gravel deposits. The head works of Sarykurgan on the river can be found just as the river enters the study area. The river, which has a long-term average flow at 12 m^3/s, is fed by snowmelt from glaciers, with a maximum flow in summer and a minimum flow in winter. The BFC delivers water of the Naryn River during the dry summer months, when the flow of the Sokh River does not cover irrigation demand of the basin. The Sokh aquifer, selected for the modeling studies spreads in deposits of the fan of the Sokh River. The water-bearing strata in the study area consist of upper quaternary (Q_{III}), intermediate quaternary (Q_{II}) and lower quaternary (Q_{I}) deposits. These deposits contain gravel and shingle with an interlayer of loamy sand and loamy deposits. The gravel and shingle deposits predominate in the southern part of the study area with increasing proportions of loamy sand and loamy soils in the northern parts. The depth to groundwater varies from 72 to 116 meters (m) at the head of the system, and can be as little as 0.5-2.5 m below ground level in the discharge zone.

Six zones were specified within the Sokh aquifer for water and salt budgeting. In the natural recharge zone, which is in the head part of the river basin, the transmissivity of the water-bearing strata exceeds 2,000 m^2/d (Figure 2).

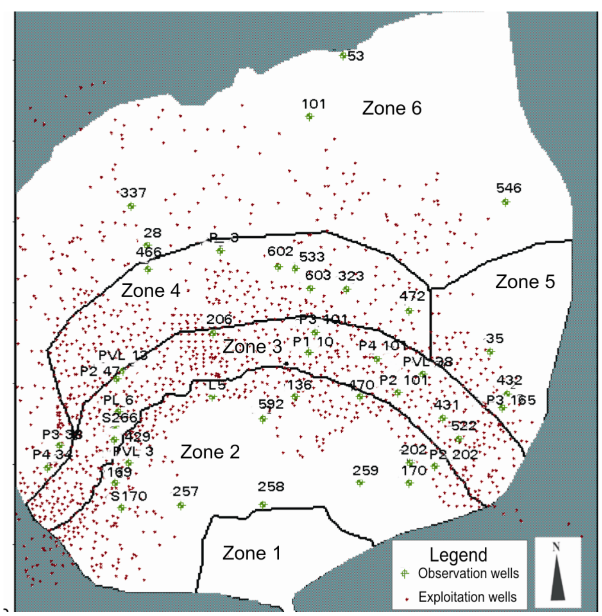


Figure 2. Hydrogeological zoning of the Sokh River Basin

A wide groundwater transit zone replaces the natural recharge zone to the north. The replacement of highly permeable deposits by low-permeable loamy deposits creates the spring zone. This zone has a narrow belt with boundaries 3-5 km to the south from the BFC and 5 km to the north. Managed aquifer recharge is focused on these three zones called the management zone to the north of which spread two zones of groundwater discharge to the drainage zones and a wide groundwater dispersion zone. In the paper, these last three zones are together called the discharge zone.

Field studies on groundwater recharge

The flow of the Sokh River is fully withdrawn into canals at the Sarykurgan head works. The head works operation organization uses the following procedure to ensure safe maintenance of the structure:

- When the river flow is less than 40 m^3/s, no flow is released to the floodplain of the river, and the river flow is diverted fully into the irrigation canals.
- When the flow exceeds 40 m^3/s, but less than 80 m^3/s, the organization, which has built a temporary dam 1 km far from the head works across the riverbed, releases the flow exceeding 40 m^3/s into the river floodplain (upper part).
- When the river flow exceeds 80 m^3/s, the flow exceeding 40 m^3/s is released to the river floodplain. The water surface covers a floodplain area of 600 ha up to the second flow-regulating structure, which is 10 km from the head works (main part of the floodplain).

Water budgeting studies were organized in 2009 to estimate water releases to the river floodplain and groundwater recharge. The flow released to the floodplain and diverted to irrigation canals was measured three times per day. Then the groundwater discharge was calculated as the difference between the inflow and the outflow. The long-term groundwater recharge from the river floodplain was estimated using the data on river flow and the operating procedure of the head works. Finally, the correlation between groundwater salinity and volume of the groundwater recharge from the river floodplain was analyzed.

Modeling salinity of water of the Sokh aquifer

A three dimensional (3-D) finite-difference numerical model of the Sokh aquifer was developed using the US Geological Survey (USGS) software: the MODFLOW groundwater code (Harbaugh et al. 2000). The model top is the land surface topography. The area represented by the model covers 54.75 km x 50.25 km in a grid of 335 rows and 365 columns with a fixed cell size of 150 m x 150 m. The aquifer system is represented by three distinct geologic units—QIII, QII and QI. The three geologic strata are represented as five layers in the model:

- Layer 1: Soil surface to 20 m below ground level, at the head of the valley; the layer contains no water, but in the valley the water table is 0.5-3.0 m below ground level.
- Layer 2: From the bottom of layer 1 to an elevation defined by the base stratigraphic layer QIII, typically between 280 and 350 m amsl.
- Layer 3: The elevation of the base of this layer corresponds to the stratigraphic boundary between geologic units QII_1 and QII_2 and varies from 253 to 218 m amsl.
- Layer 4: The base elevation of this layer is marked by the stratigraphic boundary of geologic units QII_2 and QI_1 and varies from 218 to 125 m amsl.
- Layer 5: The base of this layer is set at 50 m amsl and is impermeable.

The boundary condition along the eastern and western edges of the model is no-flow. The northern boundary is taken as a constant head. Groundwater in layer 1 is unconfined while in layer 2 it is unconfined in the recharge but confined in the discharge zone, and in layers 3, 4 and 5 it is confined. The initial values of horizontal hydraulic conductivity and storage parameters were taken from the hydrogeologic surveys conducted in the study area by the GIDROINGEO (Mirzaev 1974; Borisov 1990; Gracheva and Miryusupov, 2006).

There are several sources of the groundwater recharge. The Sokh River and the BFC were included in the model to provide local recharge of the groundwater. There is also deep percolation flows from irrigation and rainfall. The BFC was included in the model as a “River.” Natural surface leakage along branches of the Sokh River was included as linear recharge. In other areas, areal recharge from irrigated lands predominates. Groundwater discharge in the

spring zone is represented as the inflow to a 3-m deep surface drain with a constant flow depth of 1 m. During 1992-1996, the groundwater abstraction was 620 Mm^3/yr.; altogether 1,061 wells were in operation, including 661 for irrigation, 195 for drainage and 200 for domestic needs. Other hydrogeological input data used in the model given in Gracheva et. al.(2009).

Initial groundwater salinity data were from the regional database of the GIDROINGEO for 1992-1996 (Gracheva, personnel communication). The salinity of groundwater in the natural recharge zone is in the range of 150-300 mg/l. While moving from the natural recharge zone to the discharge zone, the salinity of groundwater increases in the upper layer to 2,500-5,500 mg/l. Salinity of the groundwater in the second layer varies in a wide range from 200-350 mg/l in the recharge zone to 1,500-2,500 mg/l at the edges of the cone where water moves through the less-permeable deposits and vertical flows dominate over the horizontal flows. In layers 3, 4 and 5, salinity of groundwater is low and varies from 200-300 mg/l in the natural recharge zone to 500 mg/l at the edges of the cone.

Salinity of water of the Sokh River recharging groundwater in the natural recharge zone is below 300 mg/l. More solids enter the groundwater system in the irrigated zone north of the BFC. The salinity of water percolating from the irrigated fields in this zone was calculated based on the concentration of soluble salts in the topsoil and then converted into the ESRI polygon shape file for reading from the MODFLOW. After compiling the model and input data, the model was calibrated using long-term groundwater levels and salinity data for 1992-1996. The results of the calibration are given below.

Calibration of hydraulic parameters of the model

Calibration of the model was undertaken using a combination of a manual method and PEST (Waterloo Hydrogeologic Inc. 1999). PEST software was run to improve values of the storage parameters using monthly observations of water heads for 1992-1996. A comparison between observed and the model-generated monthly water heads during the calibration stage showed a high correlation coefficient (CC) value at 0.969. Salinity change in the groundwater system was similarly estimated. Dispersion parameters were updated to improve convergence between the actual and calculated values of the salinity of groundwater. Final values of the dispersion coefficient of water were found to be 2.46 m for the management zone and 12 m for the discharge zone. A comparison between observed and the model-generated values of groundwater salinity during the calibration stage showed a CC value at 0.723. The obtained values of CC show that the model gives valuable estimates of water heads and salinity.

These calculations were carried out for the current conditions with the groundwater abstraction at the level of 657 Mm^3/yr. Then groundwater salinity predictions were made for conditions when the water abstraction will reach the maximum level (scenario 1: maximum). Scenario maximum (1) reflects the situation with increasing groundwater abstraction from 657 to 750 Mm^3/yr. or at 57% of the groundwater recharges. New wells are considered for the management zone where water quality is good and the hydrogeologic conditions favor groundwater development. Under this scenario irrigation shifts from canal use to conjunctive use. Most of the Naryn River summer flow becomes available for downstream uses.

Since the intensive groundwater abstraction in scenario maximum may affect the quality of groundwater, two different managed aquifer recharge scenarios are tested to maintain salinity levels at the groundwater system:

- Scenario 2: Scenario maximum, water saving in the recharge zone and banking the saved water in the subsurface aquifers and maintaining high water depth at the BFC (water saving and managed aquifer recharge).
- Scenario 3: Water saving, managed aquifer recharge and construction of shallow wells in the discharge zone (managed aquifer recharge and discharge).

The scenario of water saving and managed groundwater recharge (scenario 2) simulates conditions when water saving irrigation technologies is applied to the upper part of the basin and saved water is turned to the river floodplain and recharged into the aquifer in summer and winter. Adoption of the water saving irrigation technologies, such as cut back furrow irrigation, in the upper part of the basin on 48,000 ha of irrigated area allows reducing water diversions from the riverbed to 3,000 m^3/ha in winter and 9,000 m^3/ha in summer against the current 5,000 and 12,000 m^3/ha, respectively. The saved water is forwarded to the subsurface aquifers through the river floodplain to maintain the quality of the groundwater. The scenario of managed aquifer recharge and discharge (scenario 3) simulates increased groundwater abstraction in the management and the discharge zones by adopting 25-30 m deep shallow wells against the currently used 60-100 m deep wells. The groundwater abstraction amounts to 730 Mm^3/yr. The groundwater recharge is the same as in the previous scenario. This scenario is forwarded to reduce blending of the groundwater of different layers by adoption of shallow wells. Results of the modeling for different scenarios of the groundwater management are given below.

Results and discussions

Groundwater recharge from the floodplain of the Sokh River

In 2009, the river flow exceeding 40 m^3/s was released to the river floodplain during June-September. The water budgeting studies found that 31% of the flow released to the floodplain from June to September recharged the groundwater. Then, the long term river flow releasing to the river floodplain was estimated using the flow data monitored by the Sarykurgan Department of the Sokh-Syrdarya Irrigation System Administration at the Sarykurgan head works and given in Figure 3.

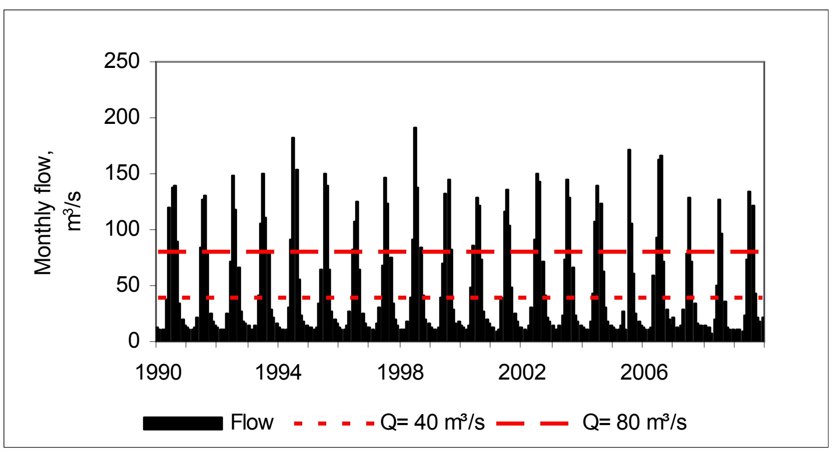


Figure 3. The long-term flow of Sokh River at the Sarykyrgan station (Shokirov, 2010)

The data presented in Figure 3 show that the volume of the river flow at the Sarykurgan head works varies from 650 to 1300 Mm^3/yr. The estimates show that the flow released to the river floodplain is in range of 414 to 584 Mm^3/yr. The estimates of the groundwater recharge from the river floodplain and the salinity of the groundwater are given in Figure 4.

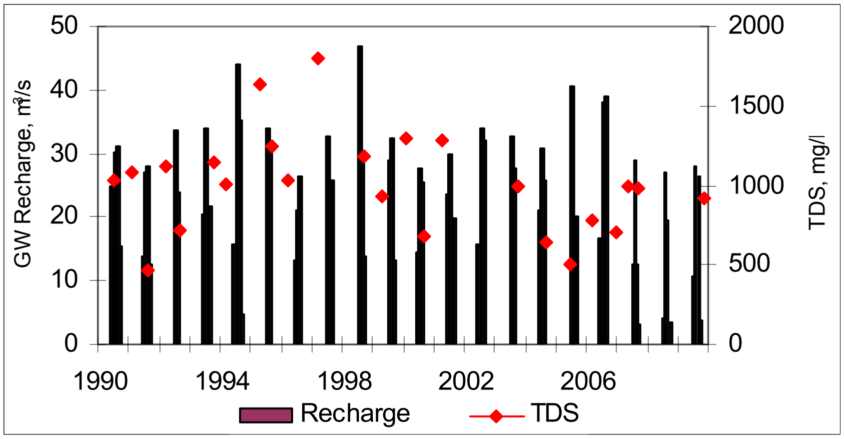


Figure 4. The groundwater recharge from the floodplain of the Sokh River and salinity of the groundwater expressed by total dissolved solids (TDS).

The data given in Figure 4 show that groundwater recharge from the floodplain amounts to 108-200 Mm^3/yr, against a total recharge at 680-750 Mm^3/yr. in the groundwater management zone. These data show that the groundwater recharge from the floodplain is significant and contributes to maintaining high-quality water in the Sokh aquifer. Figure 4 illustrates that the salinity of the groundwater expressed by total dissolved solids (TDS) is lowering in summer. For example, long term TDS of the groundwater for observation well 429 (Figure 2) averages to 1179 mg/l in March – May and to 876 in August – November, which indicates impact of the groundwater summer recharge from the river floodplain. However, data available on groundwater quality did not allow estimating the impact of the groundwater recharge from the floodplain on soil and groundwater salinity. That is why modeling studies were carried out that are presented in the next section.

Current conditions

Calculations for 1992-1996 using actual recharge and water abstraction volumes allowed obtaining a detailed analysis of water budgets for each calculated zone. The total groundwater recharge amounts to 1,114 Mm^3/yr. of which 60% is in the management zone. Leakage from the BFC is estimated at 122 Mm^3/yr. The groundwater recharge from the floodplain varies in the range of 108-200 Mm^3/yr. The groundwater abstraction was 657 Mm^3/yr of which 63% is in the management zone. In this zone, the groundwater abstraction amounts to 50% of the total recharge. The rest of the inflow forms the subsurface outflow to the discharge zone causing waterlogging. The low level of groundwater abstraction in the discharge zone contributes to a mixture of water of different layers in some locations only. In spite of the high drainage outflow from the area at 365 Mm^3/yr, high evaporation from the shallow water table causes accumulation of soluble salts in the topsoil in the discharge zone.

The data obtained show salinity buildup on the 69,557-ha area of the topsoil in the discharge zone. Salinity of the groundwater exceeds 2,000 mg/l on 75% and 5% of the area of the discharge and management zones, respectively, in the first layer. Salinity of the groundwater is in the range of 1,000-2,000 mg/l on 65% and 2% of the area of the discharge and the management zones, respectively, in the second layer. Salinity of the groundwater of the third layer is less than 300 mg/l, which is an indication of high-quality water for drinking water supply on 32% of the management zone area.

Scenario maximum

There are no significant changes in the groundwater recharge under this scenario; however, leakage from the BFC will come to 155-158 Mm^3/yr. The groundwater recharge from the floodplain at the same level is the same as under the current conditions. Increasing groundwater abstraction from 657 Mm^3/yr to 708 Mm^3/yr will decrease the groundwater discharge to the drainage to 350 Mm^3/yr. Evaporation from the water table will be 240 Mm^3/yr. Nevertheless, increasing groundwater abstraction will affect groundwater salinity. Salinity of the groundwater of the first layer will exceed 2,000 mg/l on 73% and 6% of the area of the discharge and the management zones, respectively. These data indicate a gradual increase of the salinity in the groundwater management zone, where groundwater abstraction was increased by 12%. Salinity of the groundwater of the second layer will be in the range of 1,000-2,000 mg/l on 66% and 2% of the area of the discharge and the management zones, respectively. These data also indicate a gradual increase of the salinity in the discharge zone of the second layer due to reduction of the subsurface inflow from the management zone. Salinity of the groundwater of the third layer will be less than 300 mg/l on 22% of the management zone area. Salinity of the groundwater in the third layer will exceed 1,000 mg/l on 18% of the discharge zone which is similar to the other scenarios. Lowering the water table will reduce salinity buildup in the topsoil. Salinity buildup will take place on 29% of the area in the discharge zone.

The data presented prove that attempts to prevent salinity buildup in the topsoil by increasing groundwater abstractions at 708 Mm^3/yr against 657 Mm^3/yr may cause an increase in the area with saline groundwater, with salinity above 2,000 mg/l in the first and second layers. Consequently, using the saline groundwater for irrigation may affect yields of the agricultural crops and correspondingly the incomes of the farms. That is why the managed aquifer recharge was modeled to avoid negative consequences of the intensive groundwater abstraction.

Scenario: Water conservation and managed aquifer recharge

It was assumed that adoption of the water saving technologies will reduce water intake from the riverbed in the upstream on an area of 48,000 ha to 3,000 and 9,000 m^3/ha in winter and summer, respectively, against 5,000 and 12,000 m^3/ha, respectively, of the current average. Adopting the water saving technologies will create conditions for increasing the groundwater recharge from the river floodplain. The groundwater will receive additional 269 Mm^3/yr of water from the floodplain. As a result of the rise in the water table, leakage from the BFC will decline to 127 Mm^3/yr, whereas the discharge into the drainage will be at level of 227 Mm^3/yr and evapotranspiration at 260 Mm^3/yr. The data obtained show that adoption of the water saving technologies will contribute to maintaining salinity of the groundwater that a) in the first layer, will exceed 2,000 mg/l on 73% and 4% of the discharge and the management zones, respectively, b) in the second layer will be in the range of 1,000-2,000 mg/l on 64% and 1% of the area of the discharge and the management zones, respectively, and c) in the third layer will be less than 300 mg/l on 48% of the management zone area. A positive salt balance is noted in the vadoze zone on an area of 54,247, or 22.7% of the total area against 29.1% under the current scenario.

The predictions suggest that water saving and increased groundwater recharge from the river floodplain allow maintaining low salinity of the groundwater. However, increased groundwater outflow to the discharge zone will cause a shallow water table and salinity buildup in the vadoze zone. These data show the need for additional measures to eliminate the salinity buildup in the topsoil. Shallow wells were tested in the groundwater discharge zone to eliminate blending of groundwater of different layers.

Scenario: Water saving, managed aquifer recharge and discharge

Increase in groundwater abstraction is achieved thanks to the construction of the shallow wells in the discharge zone, where it reaches 410 Mm^3/yr. As a consequence, groundwater discharge to the drainage decreases to 177 Mm^3/yr. and evapotranspiration to 191 Mm^3/yr. Because of the groundwater recharge from the river floodplain the groundwater resources could be available for

irrigation in the discharge zone. The applied water saving strategy will increase groundwater storages in the management zone by 335 Mm^3/yr. which could be available for use in addition to 731 Mm^3/yr. of the abstracted water. These data show that groundwater can cover over 50% of the irrigation demand in the Sokh River Basin. Salinity of the groundwater a) in the first layer will exceed 2,000 mg/l on 75% and 3% of the area of the discharge and the management zones, respectively, b) in the second layer will be in the range of 1,000-2,000 mg/l on 65% and 2% of the discharge and the management zones, respectively, and c) in the third layer will be less than 300 mg/l on 46% of the management zone area.

Conclusions

The studies indicated the close linkage between groundwater recharge and discharge strategies and water and soil salinity. Adopting water saving irrigation technologies and using saved water for increased groundwater recharge through the floodplain of the river contribute to maintaining good quality of the groundwater. However, this practice may cause a shallow water table and salinity buildup in the groundwater discharge zone in the topsoil. Groundwater development for irrigation may allow avoiding salinity buildup in the topsoil. This approach may not be enough to eliminate the groundwater salinity increase in the discharge zone due to blending of groundwater of the different layers. The shift from deep to shallow wells in the groundwater discharge zone was found to be an effective method to decrease the blending of shallow saline water and deep freshwater.

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