IWMI Research Report

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Front cover photograph shows Mr. Turdali Nassredinov, Consultant to IWMI, and Mr. Abdusalom Kayumov, Head of the Water Management Administration of the Besharyk District, Besharyk, Fergana Province, Uzbekistan, discussing the potential for increasing aquifer recharge (May, 2009) (*Photo credit*: Dr. Akmal Karimov, IWMI).

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Contents

Summary

As a result of the growing demand for food and energy, the competition for water between upstream and downstream users in the Syrdarya River Basin has increased. The change in the upstream reservoir operation from a conjunctive irrigation/hydropower mode to exclusively hydropower generation resulted in reducing the river flow downstream in the summer and increasing it in the winter. This phenomenon caused a downstream water shortage of 2,000-3,000 Mm^3/year in the summer and an excessive, often unutilized, flow of the same magnitude in the winter. This study suggests that the current practice of sequential in-channel reservoirs is not coping well with the needs of both upstream and downstream water users. Furthermore, it examines the alternative approach of managed aquifer recharge (MAR) in the upstream of Fergana Valley with a view to adapt to new water management reality. Favorable hydrogeology conditions prevailing in the Fergana Valley are envisaged to create benefits from MAR both at local and regional levels. The study follows a stepwise procedure of implementing MAR in the Fergana Valley, starting from the regional assessment of the MAR potential to testing MAR at the pilot scale through field and modeling studies. The regional assessment shows that over 500,000 ha, or 55% of the currently irrigated land in the Fergana Valley, can be shifted from canal irrigation to conjunctive surface water-groundwater irrigation. This will reduce the return flow to the river by 30% (or by 1,000 Mm^3/year), and form free storages of 500 Mm^3 in the command areas of main canals. Pilot-scale studies for Isfara and Sokh aquifers in the Fergana Valley support the results of regional assessment. Overall, groundwater development for irrigation and MAR in the Fergana Valley is expected to reduce the winter flow of the Syrdarya River at the valley outlet by 1,500 Mm^3/year, and consequently increase its summer flow by the same magnitude. This report proposes a major shift in the focus of development projects in the Fergana Valley, from rehabilitation of dense drainage systems to groundwater development for irrigation and MAR.

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Introduction

The Syrdarya River Basin in Central Asia with its main tributary – Naryn – has a catchment area of 219,000 km^2 and generates about one-third of the total flow that used to feed the Aral Sea. Irrigated agriculture has been practiced in the basin from ancient times. But it was the massive scale of flow regulation in the second half of the twentieth century, and subsequent geopolitical changes in the 1990s with the formation of the newly independent states that dramatically changed the hydrology of the river and complicated the overall water management of the basin downstream.

Under current conditions, the middle and the downstream parts of the Syrdarya Basin face severe seasonal water shortages for agriculture and the environment. These shortages are caused, primarily, by three factors:

- *Non-uniform distribution of limited water*. The middle and the downstream of the basin generate only 10.9 km^3 of flow (29% of the long-term mean annual flow (MAF) of the entire basin), while the needs of the downstream agriculture and environment are at least twice as high (Abdullaev et al. 2007). As a result, with an increasing demand for water, the middle and the downstream water users become more dependent on the upstream inflow.
- *Growing competition for water*. The growing competition for water between hydropower generation operations located upstream, and agriculture and environment demands downstream also causes water shortages. The shift of the upstream reservoir on the Naryn River from irrigation to hydropower generation mode in the beginning of 1993, and associated increase in winter discharges and reduced summer flow, caused an estimated shortage of 3 km^3 of water annually from the required amount for the middle and the downstream water requirement for agriculture (Mustafaev et al. 2006). The coincidence of the occurrence of peaks in the winter hydropower releases and return flow from the irrigated land in the Fergana Valley results in excessive flows that complicate the operation of the downstream reservoirs. There is not enough free storage in the middle and the downstream reservoirs to accumulate the releases from the upstream reservoir in winter for use in the summer.
- *Global climate change and its impact on water resources*. Over the last 70 years, the air temperature has increased by 0.029 ^{o}C per year followed by high fluctuations in precipitation. According to the Hydrometeorology Service of Uzbekistan, the reduction of the Syrdarya River flow by 2050 may be around 6-10%, with increased frequency of extreme, high and low flows, which will require more storage capacity (Agaltsceva and Pak 2007).

The cascade of reservoirs located along the Syrdarya River, as recent history shows, is not able to meet the requirements of both upstream and downstream users. Excessive river flow in

winter and lack of free storage, which causes freshwater discharge into the saline depression in the midstream of the river, and the resultant shortage of water for irrigation in the summer, are the main implications of the current water management practices in the basin.

This emphasizes the need for alternative/ additional storage capacities. One potential option is associated with subsurface storage. The upstream of Fergana Valley in the Syrdarya River Basin has favorable hydrogeology conditions to store extra winter flows for summer use. Two main and multiple small tributaries form and feed the Syrdarya River in the Fergana Valley. Subsurface storage, which at this stage is almost full, is estimated to be 200 km^3 (Mavlonov et al. 2006). Renewable fraction of this water needs to be beneficially used, and this will also free some storage to accommodate winter flows – using managed aquifer recharge (MAR) (Dillon 2005, 2011).

First attempts to implement MAR were exploited in Uzbekistan for municipal water supply (Mirzaev 1972; Akramov 1991). Artificial groundwater recharge structures, such as open ditches, were constructed in 1970 to store the flow of the Chirchik River underground - to supply Tashkent City with drinking water. Similar recharge structures were used for village water supply in Karakalpakistan and Khorezm in the downstream of the Amudarya River. In the sandy areas of Karakalpakistan, groundwater recharge structures were constructed in several locations aimed to increase leakage from canals during July-August (high water season), when water salinity is low. The leakage from the main canals forms temporary freshwater lenses above the saline brackish water. This water is then extracted to supply the rural population with drinking water. Modeling studies carried out by the Institute of the Hydrogeology and Engineering Geology estimated an optimal regime of groundwater extraction, which would facilitate the prevention of freshwater and saline water mixing, and thereby maintain the water quality in the lenses at the supply level that is acceptable for drinking purposes until the next high water season (Inna Gracheva, Groundwater Modeler, Institute of Hydrogeology and Engineering Geology, December 18, 2009 pers. comm.).

The MAR for agricultural needs in Uzbekistan was investigated in 1970-1990 by Mirzaev, 1972; Akramov, 1991; and Sherfetdinov, 2000. During this period, a number of aquifers were identified as having a high potential for aquifer recharge. They were Kitab-Shahrisabz in Kashkadarya River Basin, Iskovat-Pishkaran, Osh-Aravan, and Isfara and Sokh in the Fergana Valley (Akramov 1991). Free capacities of the Osh-Aravan Aquifer were estimated at 500 Mm^3, and at 200 Mm^3 in the Sokh Aquifer (Akramov 1991). Field studies conducted at the Kitab-Shahrisabz Aquifer demonstrated that groundwater extraction increases free storages to 950 Mm^3. Additionally, modeling of the Iskovat-Pishkaran Aquifer indicated that groundwater extraction with discharge of 5.5 m^3/s will increase free capacities to 500, 800 and 1,043 Mm^3 after 10, 20 and 30 years, respectively. The main limiting factor for MAR was found to be free flow of rivers rather than free storages of aquifers. In the past, artificial groundwater recharge for agricultural purposes in Central Asia was limited to theoretical studies and modeling.

The main difference in agricultural water use in the Syrdarya River Basin as compared to other countries of Asia is that agriculture, which is entirely dependent on the canal system with furrow irrigation, produces a major part of groundwater recharge. There are few irrigation projects that are based on the conjunctive use of groundwater and canal water in the foothill areas of the Fergana Valley (Tihonova 1972; Mirzaev 1972). Irrigation systems within Kazalinsk, Asht and Dalversin project areas demonstrated benefits of conjunctive use in preventing soil salinization and waterlogging. Groundwater abstraction achieved its maximum level in the mid-1990s, but then declined due to reduced investment in infrastructure in the countries undergoing transition.

The growing shortage of surface water in the Syrdarya River Basin requires the consideration of alternative sources including groundwater. Advance planned MAR activities may prevent the potential negative consequences that arise

from a shift from canal use to conjunctive use. Groundwater use for agriculture is low in the Central Asian region as compared to canal irrigation and MAR implementation, both of which have been adopted only to a limited extent at this stage. However, MAR implementation on a wide scale may significantly alleviate the looming water scarcity and improve water management, both, at local and regional levels. This report reviews the experiences of MAR in the arid regions of India, China, Australia and USA and proposes a way of implementing MAR in the Fergana Valley. This report aims to bring the attention of policymakers and practitioners to the benefits of adopting MAR practices in the region and proposes its implementation procedure for the Fergana Valley.

Managed Aquifer Recharge: Concept and Examples

MAR is intended to regulate groundwater recharge to increase water resources, improve water quality in subsurface horizons and regulate return flow from irrigated lands. The adoption of MAR practices may yield the following benefits:

- Temporarily storing ('banking') water in subsurface horizons for later use.
- Sustaining groundwater levels and preventing groundwater depletion or raising the water level, minimizing salinity and waterlogging.
- Reducing non-processed water depletions for evaporation, flow to sink and pollution.
- Flood control.
- Improving surface water and groundwater quality.
- Environmental gains (for example, stored water intended for landscape irrigation or baseflow to rivers).

Various methods of MAR and preparatory activities can be applied in agriculture, including the following:

- Regulating groundwater natural recharge.
- Creating artificial groundwater recharge to increase or replenish groundwater storages.
- Adoption of water-saving technologies to reduce areal or linear groundwater recharge caused by saline fluxes from the vadoze zone.
- Using groundwater extraction to increase leakage from riverbeds, floodplains, canals and drains.
- Using groundwater extraction to create free subsurface horizons.
- Effecting changes in the cropping pattern and soil tillage.

In the last few decades, there has been a phenomenal increase in groundwater extraction worldwide. Unsustainable groundwater development was followed by drawdown of groundwater levels over large areas and degradation of the water quality (Shah et al. 2000). Higher rates of depletion are observed in many countries, including India, China, USA and Mexico, where increasing population pressure and expected economic gains resulted in the depletion of the resource (Rosegrant et al. 2002). In some areas, this made groundwater extraction uneconomical and prompted farmers and authorities to look for mitigation options.

India

India has an agriculture-based economy and the shortfall of 174 km^3 in surface water storage has made groundwater resources development imperative to the country. This is because surface water storage is needed to meet the different

needs of water use sectors, especially agriculture. The uncontrolled development of groundwater through the construction of 19 million open wells/ shallow tube wells and subsequently deep tube wells, increased the irrigated area from 6.5 million hectares (Mha) in 1950 to 58.5 Mha in 2009 (Sakthivadivel 2007; Sharma 2009). While the area irrigated by surface water increased by 28%, the area irrigated by groundwater increased by 105% over the same period. The increased development of groundwater resources therefore, met the major requirements of irrigation and drinking water for a rural population of 700 million and the needs of more than 50% of the urban and industrial sectors. However, the unregulated development of groundwater in arid and semi-arid areas resulted in a continuous decline of water levels over an area of about 340,000 km^2. From 1992 to 2005, the number of 'unsafe blocks' (areal units) increased from 325 to 1,615, including 839 overexploited blocks (Kumar and Rajput 2005). The groundwater depletion is highest in western India; the number of overexploited blocks continues to grow at the present rate of 5.5% per annum, and it is expected that by 2018, approximately 36% of India will face serious water shortages due to depletion of groundwater (Kumar and Rajput 2005).

While declining groundwater levels cause huge environmental, social and economic costs, there is potential for increasing groundwater recharge. The total annual precipitation is 4,000 km^3, of which about 1,240 km^3 forms surface runoff. It has been estimated that 872 km^3 is still available for recharge and it is feasible to have a subsurface storage of 214 km^3 (Tuinhof et al. 2003). Being aware of this potential, India has developed a strong focus on groundwater recharge and is widely promoting watershed development across India. Micro-watershed management, including the construction of check dams and percolation ponds, currently costs over USD 500 million per year (Central Ground Water Board 2005). A comprehensive quantification has recently been published in the *Master Plan for Artificial Recharge to Ground Water in India* (Central Ground Water Board 2005). It is estimated that an area of 448,760 km^2 — about 14% of total land area of India — is suitable for MAR and that a volume of 36,453 Mm^3 is available for recharge annually. These figures have been estimated in some detail at the State level and equated to an average recharge of 80 mm over the entire recharge area. This will be achieved with 3.7 million rooftop structures in urban areas and 0.225 million rooftop structures in rural areas, 37,000 percolation tanks (each of 0.2 Mm^3), 110,000 check dams (each of 0.03 Mm^3), 48,000 recharge shafts/dug wells (each of 0.03 Mm^3), 26,000 gully plug/gabion structures (each of 0.005 Mm^3) and further development of 2,700 springs in hilly areas, among others (Central Ground Water Board 2005; Romani 2005).

China

Groundwater resources in China are unevenly distributed and utilized across the regions. The annual natural recharge of fresh groundwater resources in China is 884 km^3, and groundwater resources account for about one-third of the nation's total water resources (Ministry of Land Resources of China 2005). About 70% of the groundwater resources are located in southern China, and only about 30% are found in northern China. Here, the intensity of groundwater use, however, occurs in a much different pattern. Rural and urban users in northern China are using more than 70% of the known groundwater resources in the region. In contrast, less than 30% of the known groundwater resources in southern China are being used (Jinxia et al. 2007). In the early 2000s, groundwater use exceeded 100 km^3 or 20% of the total water utilization of China (Ministry of Water Resources of China and Nanjing Water Institute 2004). However, this share is uneven, with only 14% in southern China and 49% in northern China, where groundwater was, and is, critical for the emergence and expansion of agriculture, in particular, and the regional economy, in general. The intensive use of groundwater has also created many environmental problems, related to an overdraft in northern China, in particular (Ministry of Water Resources of China and Nanjing Water Institute 2004). The problem is widespread in that

a 48% decline was observed in the water tables of villages in six provinces (Wang et al. 2005). With a falling water table, pumping costs have risen by CNY 0.005 per cubic meter and, in many cases, agricultural wells have been abandoned and replaced by new deeper tube wells (Ministry of Water Resources of China and Nanjing Water Institute 2004).

Two approaches were taken up to arrest the problem: a) agricultural water-saving measures; and b) MAR. The demand management effected through agricultural water-saving measures is primarily for the purpose of obtaining 50 mm/yr of 'real water savings' and thereby have a reduction in groundwater abstraction for irrigation. The measures found to be capable of reducing the rate of decline in the water table are as follows: irrigation water distribution through low-pressure pipes (instead of open earth canals); drip and micro-sprinkler technology; improve irrigation scheduling; agronomic measures such as deep ploughing, straw and plastic mulching; and the use of improved strains/seeds and drought-resistant agents (Jinxia et al. 2007).

MAR implementation in China uses two methods: a) low-cost technologies, and b) underground reservoirs. Low-cost technologies include small gulley dams, diversion canals, rubber-dams, village pits and ponds, flooding of maize fields (following wet season storms), and diversion of river flow to flood-retention reserve land. In the North China Plain, Xu et al. (2009) have identified seven specific regions that could be targeted for MAR using low-cost technologies, all of which are alluvial fans in the piedmont of the Taihang Mountains, where regional recharge occurs. The source of water diverted for recharge could be a combination of treated urban wastewater and, potentially, excess surface water (e.g., from southern China, delivered via the South to North Water Transfer Scheme) during wet years. Artificial recharge experiments were implemented in some parts of the North China Plain. The first site is located in the downstream of the Chaobai River channel; nine weirs (width: 300-400 m, height: 3-5 m) were constructed from 1984 to 1998 to capture releases from the upstream of the Miyu Reservoir and recharge the overexploited shallow groundwater. The second site is located in the downstream of the Yongding River channel, which included artificial recharge in 2001, from both shallow groundwater and deep groundwater (Jia and You 2010).

Recently, more advanced technologies were used for aquifer recharge. In 2009, well injection was applied to fill the groundwater reservoir in the Futuo River Basin (i.e., upstream of Ziya River). From August 20 to September 7, 2009, 18 Mm^3 of water from the upstream of the Huangbizhuang Reservoir was infiltrated underground (Jia and You 2010). Multipurpose underground reservoirs were constructed in different locations in China, including: Wanghe underground reservoir in Laizhou, with a regulating storage capacity of 56.9 Mm^3; Dagu River underground reservoir in the Jiaodong Peninsula with a capacity of 238 Mm^3; and others (Ishida et al. 2011). The reservoirs are built by constructing underground dams by grouting or with clay walls.

Australia

Unmanaged aquifer recharge, or 'intentional water-related activity known to increase aquifer recharge, which usually has been undertaken to dispose of water rather than to recover it' (EPA 2009), has a long history in many cities and towns of Australia. Disposal of water in the form of roof runoff infiltration (since 1829) or storm water drainage wells have been used since the 1880s. However, the role of drainage wells in sustaining groundwater supplies was appreciated only much later, and steps have been successively introduced since the 1970s to protect groundwater quality. In the 1960s and 1970s, the significant MAR schemes in Australia were surface infiltration schemes primarily related to agriculture (Charlesworth et al. 2002). Since 1990, water injection and recovery from the same well, called 'aquifer storage and recovery' (ASR), is the most common type of MAR employed in Australia (Parsons et al. 2012). A few examples of MAR use in agriculture are given below.

Intensive groundwater extraction during 1970-1990 caused drawdown and increase in salinity in

many parts of southern Australia. These regions are Angas Bremer and Barossa Valley, southern Australia, and the Lower Burdekin, Queensland (GHD Pty Ltd. and AGT Pty Ltd. 2011). The Angas Bremer Region is an important premier wine district in South Australia, with about 80% of current irrigation dedicated to vineyards. Extraction of groundwater in the years before 1980 (up to about 20 Mm^3/year) caused regional drawdown and an increase in salinity due to lateral movement of more saline water from the basin margins and downward leakage of saline water from the overlying aquifer. From the 1980s, irrigators began experimenting with diverting flows from the Angas and Bremer rivers into irrigation bores. The peak of MAR activities occurred in the wet spring of 1992 when 2.4 Mm^3 of water was injected into about 30 wells. Water pressures in the region were measured and found to have risen close to levels that had not been seen since the 1950s (GHD Pty Ltd. and AGT Pty Ltd. 2011).

Another example is the wine region in the Barossa Valley, where water resources are managed according to the 'Water Allocation Plan'. Some wine growers had insufficient groundwater allocated to them to irrigate the additional area, and were not able to get their licensed allocation of groundwater increased. Hence, they turned to MAR. At that stage, surface water resources were not prescribed and could be accessed without a license. Water of low salinity and turbidity was pumped from the river to a tank prior to being fed to the vineyard irrigation bore. Hydrogeology conditions in many other parts of southern and eastern Australia are found to be suitable for managed aquifer recharge.

USA

Adoption of MAR has a long history in the USA. A very wet period suffered in Arizona in the 1980s indicated the need to store surface water surpluses by means of artificially recharging drafted aquifers. The laws adopted in 1980 and 1986 established the legal framework for all MAR aspects, including ownership of the recharged water and were the base for important artificial recharge projects in Arizona, i.e., Salt River, Central Arizona Project and others. Since then, direct surface and direct subsurface recharge methods have been successfully used to store water in many aquifers of the Arizona State. Water spreading methods using in-channel and off-channel basins are used to store large volumes of surplus surface water. In 1986, the Salt River Project (SRP), which is Phoenix's largest water purveyor in partnership with six municipalities of the metropolitan area constructed and operated the State's largest underground storage facility. The Granite Reef Underground Storage Project (GRUSP) is a surface water spreading operation located in the east of Phoenix, consisting of seven basins and occupying an area of 150 ha. It is built in a secondary dry channel of the Salt River, isolated from normal river flows, approximately 5 km downstream from SRP's Granite Reef Diversion Dam. This facility has a capacity to store 250 Mm^3/year in the aquifer. It recharges imported water from the Salt, Verde and Colorado rivers and a very small volume of reclaimed water. Since 1994, this project has stored in the aquifer in excess of 1,200 Mm^3 of water. In 2007, the SRP was completed and began operating the New River-Agua Fria Underground Storage Project (NAUSP). This facility also uses surface basins for recharge and has an annual storage capacity of 100 Mm^3.

The Central Arizona Project (CAP), the steward of Arizona's Colorado River water entitlement of 2,700 Mm^3/year, and operator of the 550 km long CAP Aqueduct, has water spreading recharge facilities with an aquifer storage capacity of 460 Mm^3/year (Lluria 2009). These facilities consist of three projects near Phoenix, three near Tucson and one between the Colorado River water diversion point of the CAP Aqueduct and Phoenix City. The latter facility, called the Tonopah Recharge Project (TRP), has a capacity of 185 Mm^3/year and is utilized predominantly for the recharge of water credits for the states of Nevada and California in accordance with a Tri-State agreement. According to this agreement, Arizona stores water allocations of the Colorado River for Nevada and California in the wet years

in exchange for its (Arizona's) water allocations from the Colorado River in the drought years. In dry periods, Arizona recovers its water allocation from the Colorado River from the underground storage at the TRP. The city of Tucson has two large water spreading recharge projects with a total capacity of 185 Mm^3/year (Lluria 2009). It also has a 36 Mm^3/year water spreading recharge operation called the 'Sweetwater Recharge Project', which stores only reclaimed water underground. The Viddler Water Company, a private corporation, operates a 123 Mm^3/year water spreading facility near Phoenix to bank water for sale in the future. The recharge units are basins developed in abandoned agriculture fields with a slow infiltration rate. There are many smaller water spreading recharge facilities in Arizona.

There are other examples from Mexico, Spain, Nepal and other countries when groundwater depletion was attempted to be resolved by MAR (Dillon 2005). The main lessons from the MAR experience in the above countries are: i) advance planning of MAR can prevent negative impacts of groundwater development; ii) there are a variety of MAR methods which can be selected depending on hydrogeological and socioeconomic conditions of a target area; iii) simple methods of MAR have to be a priority, although advanced methods should also be considered; and iv) MAR inclusion into river basin water management can bring benefits both at the local and basin scale.

MAR in the Fergana Valley

Study Area

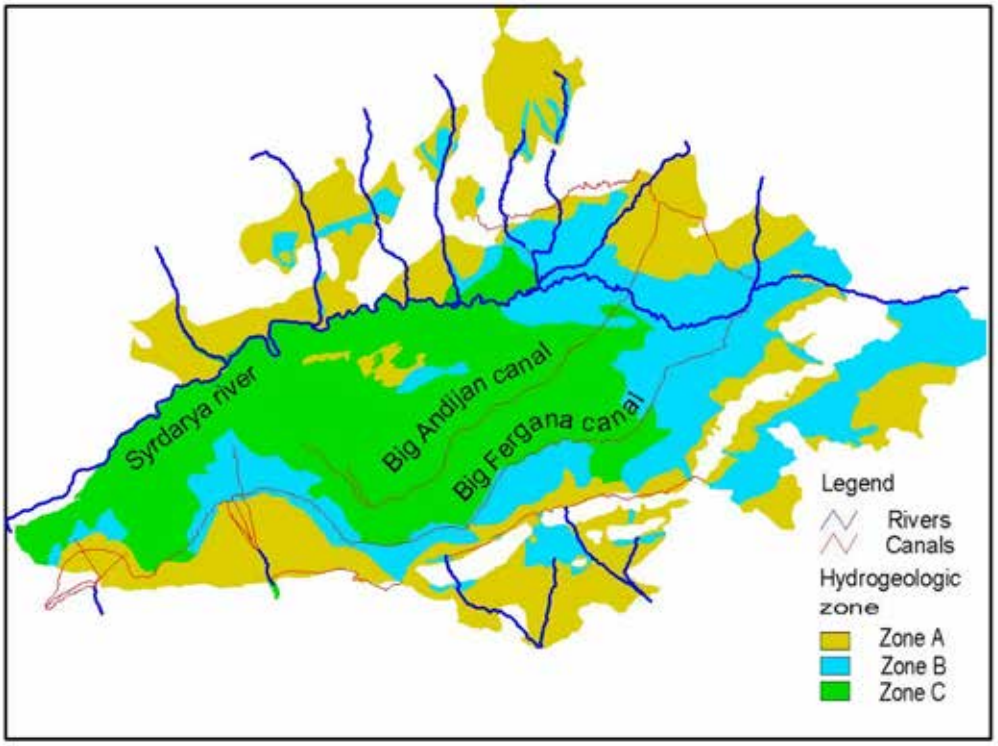
The Fergana Valley depression is the area spread between the mountains of Kuramin and Chatkal on the north, Atoinak and Fergana on the east, and Alai and Turkestan on the south (Lange 1964). The Fergana Valley covers a central part of the depression bounded by the outcrops of the Mesozoic and Paleozoic formations. This study is limited to the part of the Fergana Valley within Uzbekistan with an area of 17,000 km^2. The irrigated area totals to 897,000 ha. The climate is semi-arid with low quantity of precipitation and high summer temperatures. The annual precipitation rate varies from 100 to 200 mm in the central part of the valley and increases to 300 mm in the piedmont areas. The mean average temperature is at 14 ^oC. The altitude increases from west to east from 330 meters above sea level (masl) to 600 masl. The valley is filled with alluvial deposits of rivers washed out in the mountain zone. By source of supply, the rivers of the Fergana Valley are divided into four types: (1) glacier-snow; (2) snow-glacier; (3) snow; and (4) snow-rain. The Naryn River, the Sokh River and the Isfara River are of glacier-snow type. The Karadarya River and its tributaries are of snow-glacier type. Over 55% of the irrigated soils are prone to salinity, including 71,922 ha that is highly saline.

Mirzaev (1974) specified three hydrogeological zones in the Fergana Valley: (1) groundwater natural recharge and transit (Zone A); (2) spring (Zone B); and (3) groundwater dispersion (Zone C) (see Figure 1).

Zone A represents the upper part of the fans of the small rivers in the Valley. The rivers and canals supply groundwater which is deep in Zone A. Water-bearing deposits of Zone A are represented by coarse shingle and gravel deposits, forming favorable conditions for water storage. These highly permeable deposits are gradually replaced by the loam and sandy loam deposits on the periphery of the fan, which belongs to Zone C. Between these two zones there is a narrow Zone B, where groundwater

forms springs and discharges into the drain system (Figure 1). Transmissivity of the water-bearing stratum increases from Zone C to Zone A, and varies from 50 to 16,000 m^2/day. On the other hand, groundwater level and soil salinity increases from Zone A to Zone C. Groundwater abstraction, which was at a maximum level of 4.4 km^3 in the beginning of the 1990s, had decreased to 2.7-2.8 km^3 by 2005 (Mavlonov et al. 2006).

FIGURE 1. Hydrogeological zones in the Fergana Valley.



Source: Mirzaev 1974.

The Proposed MAR Strategy for the Fergana Valley

The 'excessive' flow available in the Fergana Valley for MAR includes the following:

- *Winter flow of small rivers*. The average flow of small rivers entering the Fergana Valley from October 1 to April 1 is about 1,000 Mm^3/year (Ivanov Yuri, Head of Department, the Uzhydromet, Tashkent, Uzbekistan, and Consultant to IWMI, pers. comm. 2009). At present, this flow, which is partially used for agriculture, supplies groundwater and forms the return flow to the Syrdarya River. Shifting from canal irrigation to groundwater irrigation in small rivers and upstream sub-catchments and adoption of water-saving technologies will intendedly preserve the in-stream flow and thereby increase the groundwater winter recharge.
- *Hydropower releases from the upstream reservoir on the Naryn River.* The shift in the beginning of the 1990s of the upstream reservoir operations from irrigation to a hydropower generation regime increased the

winter flow and reduced the summer flow of the upstream reservoir. There are no free capacities in the downstream reservoirs for storage of extra winter flow from the Fergana Valley. Furthermore, the ice-cover of the river flow in the downstream does not allow water to be delivered to the river delta and to the Aral Sea. This extra winter flow varies from 2,000 Mm^3 in low water to 3,000 Mm^3 in high water years (Mustafaev et al. 2006).

- *Precipitation in the natural recharge zone of groundwater*. The groundwater natural recharge zone has an area of approximately 400,000 ha (Zone A on Figure 1), including irrigated and non-irrigated lands, where precipitation rate in winter is 126 mm, on average. Total precipitation available for groundwater recharge in Zone A is at 500 Mm^3/year. Since current groundwater recharge from precipitation in winter is estimated at 100 Mm^3/year, the adoption of appropriate technologies of soil tillage, crop selection and water harvesting may significantly increase groundwater recharge.
- *Subsurface flow from the upstream*. Subsurface flow from the upstream irrigated land occurs along the valleys of small rivers and is estimated to be 950 Mm^3/year (Mavlonov et al. 2006). Since the groundwater level is shallow in half of the study area (Dukhovny et al. 2005), most part of the summer subsurface flow discharges into the drainage system and enters the Syrdarya River in winter.

The water resources available for MAR make 13-17% of the total inflow to the Fergana Valley, amounting to 24,600-28,300 Mm^3/year in low and high flow years, respectively. MAR will allow increasing groundwater abstraction from 2,700 to 5,000-5,500 Mm^3/year, mainly for irrigation purposes (Mavlonov et al. 2006). Implementation of this strategy at the regional scale may require different technologies. Simple structures, such as infiltration basins and percolation from the riverbeds and floodplains, can be used in some of the aquifers, while deep underground dams are the only option for subsurface water banking in other aquifers. The alternative option is to adopt water-saving technologies that will gradually create additional free subsurface storages in the aquifers with favorable conditions for water banking. Saved water can be used for improving water quality.

This approach differs from the activities under implementation in the Fergana Valley by different development projects aimed to gain local benefits (Wandert 2009). The projects aim to lower the groundwater level by increasing drainage capacity. This way they increase the return flow to the river in the winter season when there is shortage of free storages in the river downstream. The approach, proposed in this report, suggests saving excessive winter flows in subsurface horizons and recovering this water in summer. This approach can reduce evaporation, flow to sinks and pollution – all for an overall regional benefit. The proposed MAR implementation strategy consists of several steps:

- *Step 1*: i) Assessment of potential for MAR in the Fergana Valley aimed to determine the subsurface free water storage available, or enhanced storage created by intensive groundwater abstraction; ii) determining appropriate technologies for MAR; and iii) estimating irrigated areas that have the potential to shift from canal irrigation to conjunctive use and considering the adoption of potential water-saving technologies.
- *Step 2:* MAR activities in one of the pilot aquifers should spread along the main canals. Since the groundwater level is high in the canal command areas, it is appropriate to start MAR implementation by intensifying the groundwater abstraction for irrigation purposes and lowering the groundwater level. Then focus on storing winter flow of the Naryn River and small rivers in the subsurface horizons. At the same time, create incentives for farmers to adopt water-saving irrigation technologies in the river upstream to reduce saline fluxes from topsoil to groundwater. The shift from canal irrigation to conjunctive use in the Fergana Valley will increase the summer flow of the Naryn River for downstream use. Under new conditions, power stations can be

installed in main canals to produce power for the operation of wells.

MAR activities should be initiated in the Isfara River Basin located in the tail end of the Big Fergana Canal (BFC) as it is easy to estimate the impact of MAR and make the necessary refinements in the Isfara Basin. Then move to the next subbasin along the BFC, which is the Sokh River Basin.

- *Step 3*: Shift from the canal irrigation to conjunctive use in the Sokh River Basin and adopt water-saving irrigation (including improved furrow and advanced drip) technologies in the river upstream and the midstream. In the upstream, low barriers, proposed across the riverbed will increase the groundwater recharge. This groundwater recharge will contribute to maintaining water quality and storage. In the BFC zone, after lowering the water level, recharge structures such as infiltration basins, boreholes and shafts can be constructed along the canal for storing the winter flow of the Naryn River in the subsurface horizons. Then the capacity of the power stations on the main canals can be increased to produce energy for the operation of wells. Then move to the next subbasin along the BFC.
- *Step 4:* When the objective is achieved for all separate aquifers along the main canals, consider MAR at the regional scale within the whole Fergana Valley.

The following sections describe the first three steps, progress achieved and results obtained to date. Step 4 is not yet considered here, as it has to include more advanced stages of technology development and has to capitalize on the success of steps 1-3.

Assessing MAR Potential in the Fergana Valley

Methods and Data

The MAR potential in the Fergana Valley is evaluated considering factors, such as potential for water storage, depth to water table, groundwater salinity, availability of excess water and other factors. Areas selected with favorable conditions for water storage include parts of small river basins where free subsurface capacities are available, and areas where free capacities can be created by intensive groundwater abstraction or reducing the groundwater recharge by the adoption of water-saving technologies. The last approach contributes to decreasing groundwater salinity by reducing saline fluxes from the vadoze zone and increases the river free flow in summer, which is available for groundwater recharge. The areas suitable for groundwater storage were defined in the groundwater (GW) natural recharge zone (Zone A) and in the main canal commands with transmissivity of the water-bearing stratum above 300 m^2/day and groundwater level below a 3 m depth. Sources available for MAR are (1) free winter flow of small rivers; (2) the flow of small rivers, which can be released by the adoption of water-saving technologies or increasing groundwater irrigation; (3) precipitation in Zone A; (4) subsurface inflow from the upstream; and (5) the winter flow of the Naryn River. Winter flow of small rivers can be used for increasing natural recharge in Zone A, which spread above the main canal commands. Natural recharge can be enhanced by increasing the leakage from the riverbed and the floodplain, canal and stream channels. The winter flow of the Naryn River can be stored underground by: a) increasing the leakage from the canals; b) installing infiltration basins; and c) boreholes or shafts. Open drains, after lowering the water table, may be used

under favorable geology conditions as recharge structures as well.

Areas suitable for groundwater irrigation or conjunctive use may be specified within each hydrogeological zone based on transmissivity of subsurface horizons, water depths and quality (at first approximation – salinity) in the following order:

1) Subdistrict or hydrogeological zone (See Figure 1).
2) Blocks, or part of a subsurface horizon, selected on the basis of the transmissivity of the water-bearing stratum in the top 0-100 m layer and categorized into several groups:
   - blocks with poor transmissivity of deposits less than 100 m^2/day;
   - blocks with low transmissivity from 100 to 300 m^2/day;
   - blocks with good transmissivity from 300 to 1,000 m^2/day; and
   - blocks with high transmissivity above 1,000 m^2/day.
3) Subblocks selected on the basis of the depth of the groundwater level are as follows:
   - Subblocks with the groundwater level less than 3 m in depth from the ground surface;
   - Subblocks with the groundwater level ranging from 3 to 7 m in depth;
   - Subblocks with the groundwater level ranging from 7 to 12 m in depth; and
   - Subblocks with the groundwater level deeper than 12 m in depth from the ground surface.
4) Micro-blocks separated on the basis of the salinity of groundwater:
   - Micro-blocks with salinity less than 2,000 mg/l;
   - Micro-blocks with salinity ranging from 2,000 to 4,000 mg/l; and
   - Micro-blocks with salinity above 4,000 mg/l.

Groundwater irrigation is proposed for the area with the transmissivity (T) of deposits above 300 m^2/day, the groundwater level is less than 3 m depths and the salinity less than 2,000 mg/l. Conjunctive use of groundwater and canal water is recommended for the area with T > 300 m^2/day and salinity less than 4,000 mg/l. The rest of the area is kept under canal irrigation. This area has a groundwater level below 12 m and/ or T < 300 m^2/day. Single wells are proposed for the area with 100 < T < 300 m^2/day. Groundwater irrigation area was specified using the data of the Institute of Hydrogeology and Engineering Geology and the Institute UzGIP (Mavlonov et al. 2006; Khasanhanova et al. 2006). Using these data, several GIS themes were created, such as: hydrogeological zones, specific water yield, transmissivity of the deposits, depth of the groundwater level, groundwater salinity, etc. Groundwater budgets were compiled for low (2001) and high (1995) water years for each aquifer of the Fergana Valley to determine the potential of groundwater abstraction within the selected areas.

Results

The data given in Table 1 indicates that free capacities exceeding 3,000 Mm^3 in Zone A are available for storing the winter flow of small rivers, which varies within a range of 1,000-1,200 Mm^3/year and are predominantly allocated for winter crop irrigation. The indicated area is located at higher altitudes above the commands of the main canals, which deliver water from the Naryn River to water-short areas of the Fergana Valley. Free capacities available and those that potentially can be created within the main canal commands are illustrated by Figure 2 and Table 1.

The data given in Table 2 indicate free subsurface capacities in the zone of the main canals, available for water banking, totaling 760 Mm^3. Additional capacities which can be released by lowering the groundwater level are estimated at 186 Mm^3 per meter of groundwater level drawdown. These data show availability of subsurface horizons for storing the winter flow. However, detailed

TABLE 1. Free capacities of the subsurface horizons of the Fergana Valley.

Aquifer	Recharge zone	
	Area[a] (ha)	Free capacity (Mm^3)
Almaz-Varzyk	19,825	231
Kukumbai	2,658	54
Kasansai	4,351	30
Iskovat-Pishkaran	19,439	359
Sokh	34,589	1,452
Altyaryk-Beshalysh	7,366	28
Namangan	5,196	77
Isfara	4,385	90
Mailisu	17,513	22
Karaungur	3,944	5
Naryn	28,393	167
Chust-Pap	7,936	147
Andijan-Shahrihan	7,919	16
Chimien-Aval	3,651	88
Osh-Aravan	21,223	324
Nanai	4,349	71
Total	192,737	3,161

Source: Mavlonov et al. 2006.

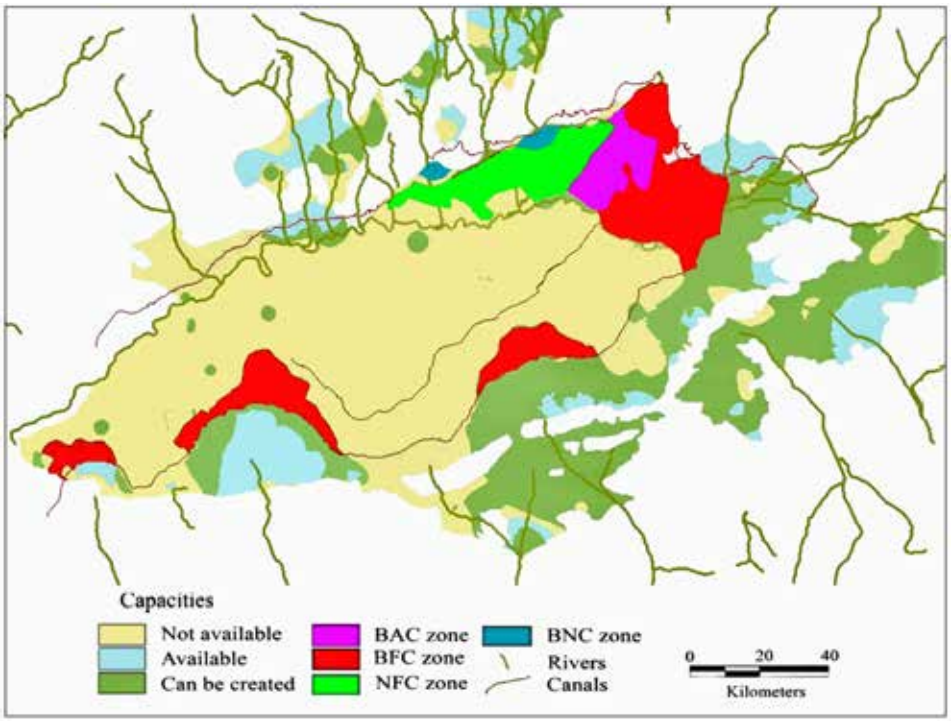
Note: [a]The area within the recharge zone where free capacities are available.

modeling and economic analysis are required to estimate the optimal level of groundwater abstraction and recharge. MAR has to be preceded by increasing the groundwater abstraction to lower the water table. The areas suitable for groundwater irrigation and conjunctive use in the Fergana Valley are illustrated in Figure 3a.

The estimates show that the area suitable for groundwater irrigation totals to 290,000 ha and 243,000 ha for conjunctive use. The rest of the area can be kept irrigated using canal water. The potential volumes of groundwater extraction depend on hydrogeology conditions (Zones A and B) and the replenishable groundwater resources. Total groundwater recharge in Zones A and B (Figure 1) is estimated to be in the range of 5,624-6,005 Mm^3/year in low and high water years, respectively.

Expanding the area under conjunctive use and the adoption of water-saving technologies (Figure 3b) will decrease the groundwater recharge in summer due to reducing losses from canals and irrigated fields. Recharge deficit (~1,000 Mm^3/year) can be compensated using the winter flow of the Naryn River and small rivers. The data given above indicate the potential for MAR at the regional level and the next step is assessing the MAR potential at the pilot aquifer level.

FIGURE 2. The areas with favorable hydrogeology conditions for storing winter flow of the Naryn River.



Source: Karimov et al. 2010.

Notes: BAC – Big Andijan Canal; BFC – Big Fergana Canal; NFC – Northern Fergana Canal; BNC – Big Namangan Canal.

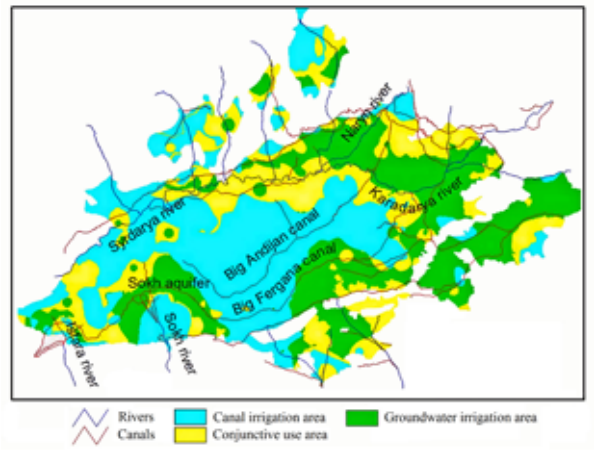
TABLE 2. Available and potential capacities within the Fergana Valley for storing winter flow of the Naryn River.

Aquifers	Source of GW recharge (canal)	Area[a]	Free capacities	Potential capacity (per meter of groundwater level drawdown)
		ha	Mm^3	Mm^3/m
Naryn	BFC	36,859	158	37
Naryn	BAC	24,440	52	24
Naryn	NFC	23,769	85	24
Naryn	NFC	20,228	181	19
Namangan	BNC	5,371	77	5
Mailisu	BFC	20,547	5	20
Andijan-Shahrihan	BFC	4,443	0	4
Altyaryk-Beshalysh	BFC	17,171	0	17
Sokh	BFC	27,561	126	28
Isfara	BFC	8,828	85	8
Total		189,217	769	186

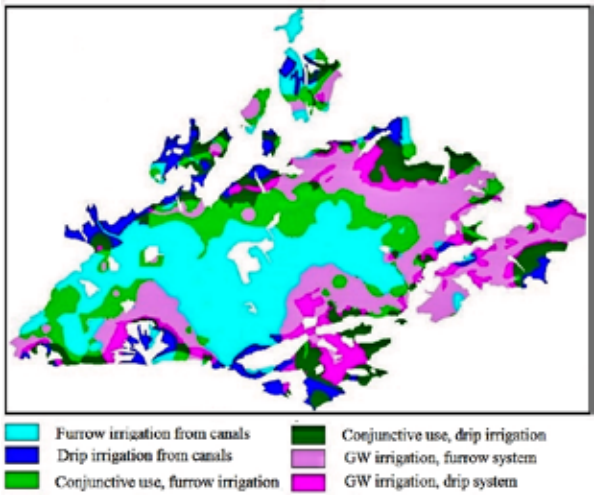
Notes: [a]The area where free capacities can be created by lowering the groundwater level; BAC – Big Andijan Canal; BFC – Big Fergana Canal; NFC – Northern Fergana Canal; BNC – Big Namangan Canal.

FIGURE 3. The area with favorable conditions for: a) groundwater irrigation, and b) adoption of water-saving technologies.

a)



b)



Pilot MAR: The Isfara River Basin

Site Description

The Isfara River originates by the melting of glaciers and snow on the Alay Mountains. Long-term average discharge of the river is at 14.7 m^3/s. The BFC crosses the aquifer in the upper part of the basin, which allows the use of simple structures for recharging the surface water into the subsurface horizons. Leakages from the BFC, the riverbed and streams and widespread canal system are the main sources of the recharge of the Isfara Aquifer. Gravel and shingle deposits (more than 100 m thick), representing the upper part of the river basin, form favorable conditions for groundwater recharge. To the north of the BFC, the gravel and shingle deposits are gradually replaced by loams and sand loams. The groundwater has a subsurface outflow to the northeast of the Syrdarya River and to the northwest of the Kairakum Reservoir. Salinity of the groundwater is less than 1,000 mg/l in the upper part, and 1,000-3,000 mg/l on the

periphery of the basin with some isolated spots where groundwater salinity exceeds 3,000 mg/l. Irrigated soils spread in the upper part of the basin to the south of the BFC (that receive water from the Isfara River, and water lifted from the BFC in part) and soils located on the periphery of the basin are irrigated from the BFC. Groundwater extraction for irrigation purposes is 53 Mm^3/year against a much higher 600 Mm^3/year from the canal system. In the upper part of the basin, farmers grow mostly orchards and intercrops, such as vegetables, legumes, maize and sorghum for silage; whereas in the downstream in the canal command, they grow mostly cotton and winter wheat.

Field Experiments of Artificial Recharge

Methods and Data

A simple method of groundwater recharge was applied in the Isfara River upstream. One of widespread depressions along the BFC, a trench of 40 m x 25 m x 2 m size, was used in this study as an infiltration basin (Figure 4). The soil profile of the selected site was presented by shingle and gravel deposits filled with sand, and was representative for the area along the BFC in the river upstream (Figure 4c). The recharge study was carried out in two stages. In the first stage, from April 1 to 17, 2010, water of the BFC was infiltrated underground from the infiltration basin of 0.1 ha area. Before the trial, the walls and the bottom of the trench were leveled. Two water level meters were installed at the bottom of the trench. The water was entering the basin without initial treatment.

The discharge of the water entering the trench was measured using a fixed channel. Measurements were done every hour in daytime and three times during nighttime. Altogether, 11 monitoring wells, located 100-1,000 m away from the infiltration basin, were installed to monitor the change of the groundwater level. Evaporation from groundwater was measured using the pan evaporator installed next to the infiltration basin. Precipitation data was obtained from the nearest weather station. The concentration of the suspended sediments was analyzed in laboratory conditions using the de-silting method. Soil samples were collected from the bottom of the trench before and after the groundwater recharge trial from depths of 0-25, 25-50, 50-75 and 75-100 cm below the ground. Soil samples were taken to determine particle size distribution, total dissolved solids, gypsum and carbonates by using standard methods applied in the region (Arinushkina 1970).

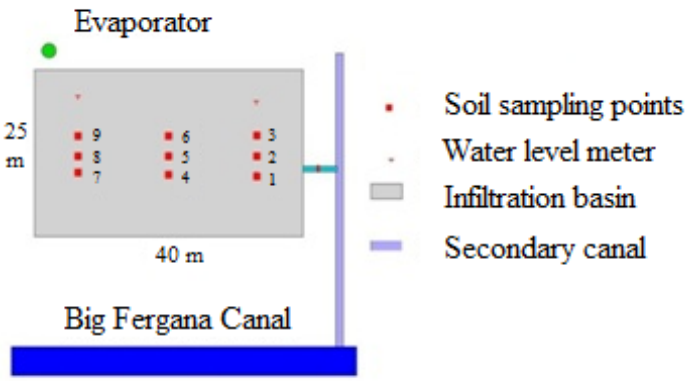
The second stage of MAR was carried out from March 26 to April 26, 2011. Unlike in the first stage, two de-silting basins were built of 3 m diameter and 1 m water depth before the infiltration basin. Three monitoring wells, equipped with divers to get hourly observation data, were also installed 3, 30 and 35 m, from the north of the basin. The divers were installed on April 5 and dismantled on May 31, 2011. Before the second stage experiment, sediments accumulated at the bottom of the basin were collected and transported to the closest fields. Infiltration rates were measured in three replications before and after the experiment using the method of infiltration rings. The infiltration rate was measured in the beginning, middle and in the end of the infiltration basin at 1, 5, 10, 15, 30, 45 and 60 minutes after starting the experiment, and then after each 30 minutes. The measurements continued until stable infiltration rates were achieved, which were from 6.5 to 8.5 hours. After testing the MAR at the pilot field scale, groundwater modeling was applied to estimate the water banking potential of the entire Isfara River Basin.

Results and Discussions

Stage 1. Starting from April 1, 2010, water of the BFC was supplied to the infiltration basin. Due to the high percolation rate, the bottom of the basin was covered by water only from day 3 after starting the experiment. The water level in the basin stabilized on day 5 at 58 cm and was continuous for the next 10 days. After interrupting the water supply, the water disappeared in the basin after 3 days. Figure 5 shows that the

FIGURE 4. Artificial recharge of the Isfara Aquifer using water of the BFC (April, 2010): a) scheme of the study area; b) infiltration basin; and c) soil profile.

(a)



(b)

(c)

infiltration rate had maximum values in the first 3 days, when it exceeded 4.5 m/d, and then was stable at 2-3.5 m/d starting from day 4 up to the end of the experiment (Figure 5). Small regular variations of the water level can be explained by the high speed of the water entering the basin, especially in the first 3 days during the initial stage of infiltration, forming waves and due to high turbidity of the supplied water. Daily observations of the water levels showed that the groundwater level rose by 35-45 cm at a distance of 250 m from the infiltration basin (Figure 6).

In total, 40,000 m^3 of water was supplied into the basin, of which 2,000 m^3 evaporated and 38,000 m^3 infiltrated to the groundwater. This was a significant amount of water infiltrated from a small basin. Since the length of the canal within the Isfara River Basin is 15,000 m, about 150 similar infiltration basins can be constructed along the BFC for groundwater recharge. The potential of full-scale MAR using these structures is modeled.

To avoid over-estimation of groundwater recharge potential at the upscaling stage from

FIGURE 5. Infiltration rate (m/d) during the recharge experiment in the Isfara River upstream.

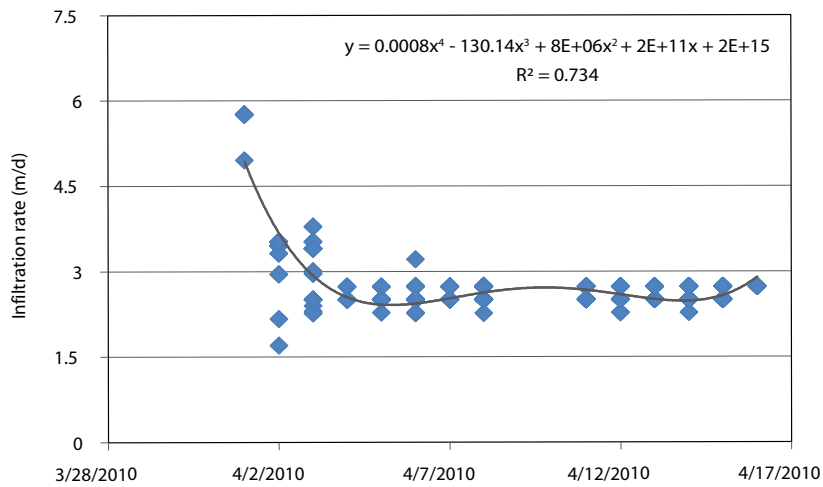
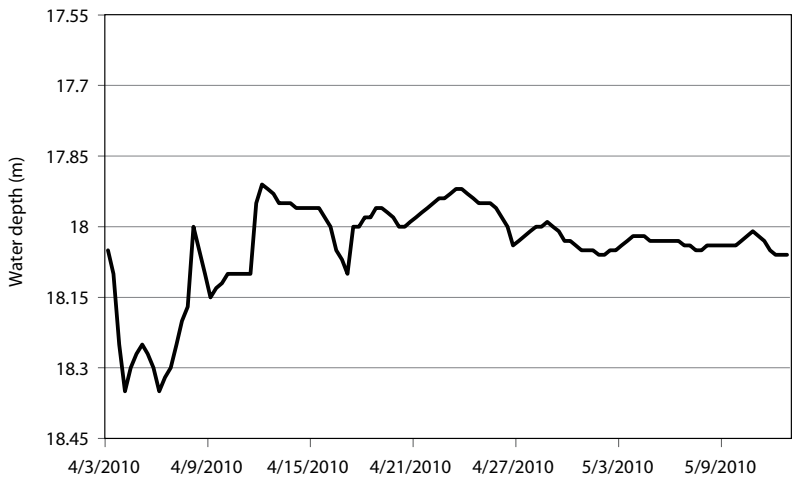


FIGURE 6. Changes in groundwater level due to recharge from the infiltration basin.



Note: Well 1*- located 250 m far from the infiltration basin.

single point (0.1 ha) to the sub-catchment (15 ha), the recharge rates used in the modeling were 1.5 times to twice as less when compared to values found at the pilot site.

The pilot GW recharge study indicated the risk associated with high turbidity of the BFC water (Table 3). Data given in Table 3 shows that the sum of silt particles (diameter from 0.002 to 0.05 mm) and clay particles (diameter less than 0.002 mm) exceeds 95% of the total suspended particles contained in the water of the canal. This data indicates a possible risk of soil porosity being blocked. However, the analysis of the particle size distribution indicated that the major part of the silt and clay particles is deposited at the bottom of the basin and above the topsoil, and much less in the soil profile. The thickness of the deposits was 10 cm in the head part, 7 cm in the middle and 3 cm in the tail end of the basin (Table 4).

Soil texture given in Table 4 for November 2010 indicates the content of the silt and clay particles in the soil profile after the recharge trial carried out before the rainy season. As seen from the Table, the deposits form a separate layer on the topsoil and can be easily removed from the basin after completing the MAR trial. The data given for March 2011 indicates soil texture after the rainy season. A comparison of the content of the silt and clay particles in the soil profile in the infiltration basin before and after the rainy season indicates an increase in the content of the silt and clay particles in the soil layer by 0-25 cm in the winter season (Table 4). If during the groundwater recharge trial, clay particles accumulated mainly above the topsoil, the rainy season changed the distribution of the fine particles in the soil profile. In spite of the high content of the fine particles in the water of the BFC, their movement in the soil

TABLE 3. Mechanical composition of the soil samples from the bottom of the infiltration basin.

Sampling point	Depth (cm)	November 2010			March 2011
		Particles (%)			
		Sand	Silt	Clay	Clay
Suspended particles, BFC		5.6	69.4	25.0	
Control[a]	0-10	57.2	34.9	7.9	5.6
	10-25	77.6	18.2	4.5	2.6
	25-35	84.8	12.3	2.9	0.7
	35-50	85.0	12.3	2.9	0.7
Infiltration basin	Deposits	11.7	76.3	12	15.3
Head part	0-10	85.2	11.9	2.9	3.2
M = 10 cm	10-25	88.4	9.2	2.4	9.6
	25-35	89.7	7.9	2.4	1.5
	35-50	86.8	10.6	2.6	1.5
Middle part	Deposits	11.1	67.5	21.4	33.0
M = 5 cm	0-10	85.0	12.0	3.0	7.9
	10-25	86.8	10.6	2.6	7.6
	25-35	87.2	10.1	2.7	0.6
	35-50	92.2	6.9	0.9	0.6
Tail end	Deposits	15.4	62.3	22.3	36.4
M = 3 cm	0-10	79.2	16.1	4.7	10.4
	10-25	83.9	12.8	2.9	0.5
	25-35	85.6	12.1	2.3	0.8
	35-50	85.6	11.3	2.1	0.8

Notes: [a]Stone particles were removed before analysis of the mechanical composition of the soil; M – thickness of the deposits in the infiltration basin.

TABLE 4. Mechanical composition of the deposits on the bottom of the infiltration basin (2011).

Basin	Particles (%)		
	Sand	Silt	Clay
	1-0.05 mm	0.05-0.002 mm	< 0.002 mm
Head part (M = 18 cm)	4	69	27
Middle part (M = 7 cm)	5	55	40
Tail end (M = 2 cm)	5	54	41

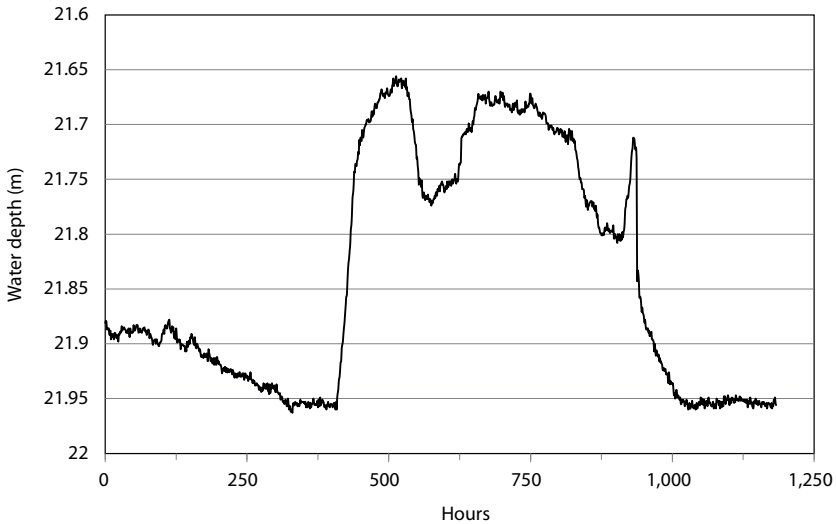
profile had taken place mainly during the rainy season after the completion of the groundwater recharge experiment. This data emphasizes the need for removing the deposits from the infiltration structure before the rainy season.

Stage 2. The second experiment on the artificial recharge was carried out from March 26 to April 26, 2011. The concentration of the suspended particles was 2,030, 1,887, 62 and 30 mg/l in the water of the BFC, in the second de-silting pit, in the middle and in the tail end of the infiltration basin, respectively. Towards the end of the experiment, the content of the suspended particles was 807, 783, 327 and 43 mg/l in the BFC, in the second de-silting pit, in the head part and in the tail end of the basin, respectively. It was noted that in spite of the availability of the de-silting pits before the infiltration basin, the content of the suspended particles was still high in the head part of the basin. An analysis of the mechanical composition of the suspended particles in the water of the BFC showed that 68% of the particles was from silt and 31.3% from clay particles. In the second stage of the experiment in 2011, the thicknesses of the deposits were 18 cm in the head part and only 2 cm in the tail end of the basin (Table 3).

In total, from March 26 to April 26, 2011, the volume of the water infiltrated from the basin to the groundwater was 20,200 m^3, and evaporation from the groundwater level during the experiment was estimated at 139 m^3. The rise of the groundwater level monitored at the monitoring well equipped with the diver is given in Figure 7.

Figure 7 shows that groundwater level is raised by 30-35 cm in the well located next

FIGURE 7. Changes of groundwater level as affected by infiltration from the basin (March – April, 2011).



Note: Well 2*- located 3 m far from the infiltration basin.

to the infiltration basin. The groundwater level rise was at 10 cm at the wells located 30 and 35 m from the basin. Water budgeting studies confirmed that infiltration rate during stage 2 was less than stage 1, despite the duration of the second stage being longer. The volume of groundwater recharge in stage 1 was twice that of stage 2. This was caused by: i) smaller flow discharges entering the basin, and hence less water heads in the basin; and ii) late removal of the deposits from the infiltration basin – after the rainy season. The results of the study suggest the importance of removing the deposits after completing the recharge trial without delay before the rainy season sets in. In spite of these limitations it was found that the recharge structures that have been tested have good potential to be used for water storing along the BFC. This concept was further tested through the groundwater modeling.

Modeling MAR

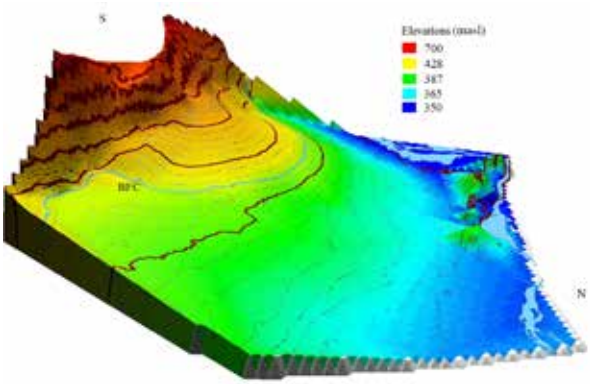
Model Description

A three-dimensional model of the Isfara Aquifer (Figure 8a) was constructed using Visual MODFLOW software (Waterloo Hydrogeologic Inc. 2000). Visual MODFLOW is a widely used Microsoft Windows-based version of the US Geological Survey 3-D Finite Difference Groundwater Flow Model, MODFLOW (Harbaugh and McDonald 1996). The Isfara Aquifer Model covers approximately 380 km^2. Grid spacing in the x and y model dimension is 50 m x 100 m, and in the areas with dense irrigation canals and drainage ditches the model has 50 m x 50 m resolution.

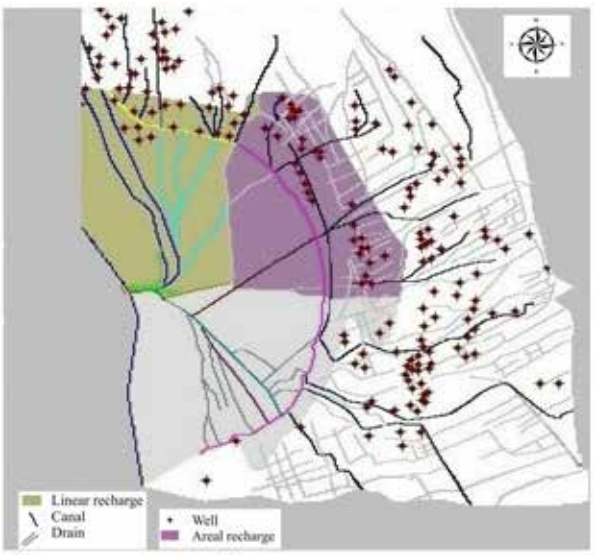
The model boundary conditions were set based on the results of the hydrogeological studies carried out by the HYDROENGEO (Miryusupov, Chief Hydrogeologist, Institute of Hydrogeology and Engineering Geology, pers. comm. 2010). The surface of the groundwater level acted as a recharge boundary. The loamy/ clay layer that is 300 m deep was set as a no-flow boundary to represent the lower boundary condition. In the south, there is the subsurface inflow from the uplands through the valley of the river. The groundwater level in the northeast is sourced by the Syrdarya River and in the northwest it is provided by a constant head. There is a zone of natural groundwater recharge on the south and a discharge zone to the north of the BFC (Figure 8b).

FIGURE 8. Three dimensional model of the Isfara Aquifer: a) three dimensional view, and b) plan.

a)



b)



Source: Karimov et al. 2012.

The model has eight layers; first, third, fifth and seventh layer are represented by gravel and shingle deposits in the recharge zone and by loam and sandy loam deposits in the discharge zone. Groundwater is unconfined in the recharge zone and confined in the discharge zone in layers two to eight. Main canals in the upper part are given in the model as a 'recharge boundary condition' because of their deep groundwater level. Canals that spread in the discharge zone are given as a 'river boundary condition' because they supply the groundwater in summer and drain it in winter. Recharge of a 'boundary condition' also includes percolation losses of precipitation and infiltration losses of irrigation water. The infiltration losses pattern depends on the soil type, crop and groundwater table that is given in the model on a monthly basis. The BFC in the study area is 2 m deep and 5 m wide. The water depth in the canal is 1.5 m and thickness of the deposits at the bottom is 0.3 m. Initial depths of the groundwater level were taken from the database of the Institute of the Hydrogeology and Engineering Geology. The initial groundwater level was 20 m deep in the recharge zone and 1 to 2 m below the ground to the north of the BFC.

Initial values of the parameters were determined from pumping tests, carried out by the HYDROENGEO in the study area from 1980-1985. During that time 13 pumping tests were carried out including 9 in the unconfined zone and 4 in the confined zone. Location of the monitoring wells was dependent on the hydrogeological profile. For a uniform profile, the number of the observation wells taken was 2-3 in the upstream, 3-4 in spring zone and 4-10 on the periphery of the basin with a confined aquifer. The pumping tests were carried out with fixed yields of the wells so as to simplify the analysis of the obtained data. The yields were from 25 to 100 l/s and the groundwater level drawdown by 3-4 m in the exploited well. The yields of the wells were selected to achieve quasi-stationary regime and groundwater level drawdown by 20 cm in the remote well after 5-10 days. Duration of the pumping test was 10-15 days in the unconfined zone and 15-20 days in the confined zone. Groundwater level drawdown data was collected for each 1-10 minutes at the beginning of the pumping and three times per day at the end stages and at the remote well. The hydrogeology parameters were estimated using groundwater level drawdown and restoration data through analytical solutions of the Theis equation. According to these estimates, transmissivity of the water-bearing deposits varies in the range of 40-555 m^2/day and specific yield from 0.13-0.22 m^3/m^3 in the unconfined zone and at 0.0001 m^3/m^3 in the confined zone.

Model Calibration and Verification

Simplified models using Visual MODFLOW were compiled for each of the 13 wells exploited for pumping tests. The size of each model was 1,000 m x 1,000 m. The simplified models were represented by eight layers, repeating the layers of the main model of the Isfara Aquifer. The model grid was non-uniform – 5 m near the well and was increased to 20 m closer to the border of the model. In total, the model had 100 rows and 100 columns. The boundary of the model was taken as the constant head considering that short-term pumping will not affect the water levels at 500 m distance from the well. A low permeable clay layer that is 300 m deep was taken as an impermeable layer to represent the lower boundary of the model. In the beginning, the models were run using values of the parameters, coefficient of filtration and specific yield, determined from an analytical solution of the Theis equation. Later, the model parameters were specified using WINPEST, included into the Visual MODFLOW package (Waterloo Hydrogeologic Inc. 2000). Running WINPEST was aimed to correct values of the parameters by increasing the convergence with actual data obtained during the pumping tests. The comparison of the actual and the model calculated values of the water elevations showed a coefficient of correlation at 0.85-0.95. Based on the values of the parameters obtained from the WINPEST, the values of the coefficient of filtration and specific yields were corrected. Subsequently, the historical groundwater budget data, obtained by the HYDROENGEO Institute from April 1, 1981

to April 1, 1983, were used for model calibration. The actual values of the groundwater budgets and elevations were compared with the model simulation results. The comparison showed a high convergence. The value of the coefficient of correlation was at 0.989. Changes in the groundwater budget (groundwater extraction, recharge and evaporation) since 1980 were considered in the formulation of the modeling scenarios.

Modeling Scenarios

Four alternative water management scenarios were considered:

- Scenario 1 (Sc1). The baseline scenario simulates actual trends in groundwater extraction for irrigation. The groundwater resources are preserved for domestic and industrial requirements as well as to cover irrigation water shortages. The groundwater extractions are at minimum levels of 1.7 m^3/s, while the number of wells is 190 (Figure 9a).
- Scenario 2 (Sc2). Conjunctive use of groundwater and canal water for irrigation. This scenario proposes groundwater development for irrigation in the upper part of the system and irrigation from the BFC in the downstream. The wells extract the annual groundwater recharge in the summer season. The number of wells is 230, of which 40 are projected along the BFC – 0.5-2 km from north and south. This scenario aims gaining local benefits – more water available for irrigation in the Isfara Basin, but with no water saving for the downstream of the Syrdarya River.
- Scenario 3 (Sc3). The groundwater extraction exceeds its annual recharge by 20% and is aimed to lower the groundwater level on the periphery of the basin and arrest the salinity and waterlogging issues.
- Scenario 4 (Sc4). Managed aquifer recharge = Scenario 3 plus storing 100 Mm^3/year of the winter flow of the Naryn River in the subsurface aquifers. The stored water in winter is projected to be withdrawn for irrigation in summer. This scenario proposes long-term regulation of groundwater storages by storing the winter flow of 100 Mm^3/year each 2 years of 3 starting from year 5 of intensive groundwater extractions. Infiltration basins are modeled along the BFC. Location of the wells is given in Figure 9b.

Simulations were done for each scenario for 13 years starting from 2011, and the water extraction regime was fixed under scenario 1, seasonal variations are considered under scenario 2 and long-term variation under scenarios 3 and 4 (Figure 10).

Modeling Results

Results of the modeling is shown in Figure 11 and indicate high groundwater levels under the current baseline scenario (Sc1) and forming the free capacities under scenario 2. A significant lowering of the groundwater level under scenario 3 is the consequence of the intensive groundwater extractions exceeding the groundwater recharge. The regime of filling and draw off of the subsurface reservoir is shown in Figure 12.

Under scenario 1 (Sc1) of minimum extraction levels of groundwater for irrigation, the subsurface reservoirs are filled during summer and drawn off in winter for subsurface outflow and discharge to the drain system. Intensive groundwater extraction for irrigation (Sc3) results in drawing off water levels in summer and minor filling happening in the winter. This increases the risk of groundwater depletion and degradation in quality due to saline fluxes from the Vadoze Zone and surrounding inter-fan depressions. Managed aquifer recharge in scenario 4 sustains the groundwater storages and maintains the water quality, since 100 Mm^3 of freshwater will be stored underground. Groundwater storages are depleted in summer by intensive groundwater extraction but replenished in winter by managed aquifer recharge. This combination aims at sustaining groundwater storages and quality in the long run (see Figures 11 and 12).

The water-saving effect of the alternative strategies expressed in the reduction of the nonproductive depletions is given in Table 5. Data presented in Table 5 demonstrates the dependence between the return fraction, a ratio between water extraction to recharge, and free

FIGURE 9. Location of the wells in the Isfara River Basin under the: a) scenario 2, and b) scenarios 3 and 4.

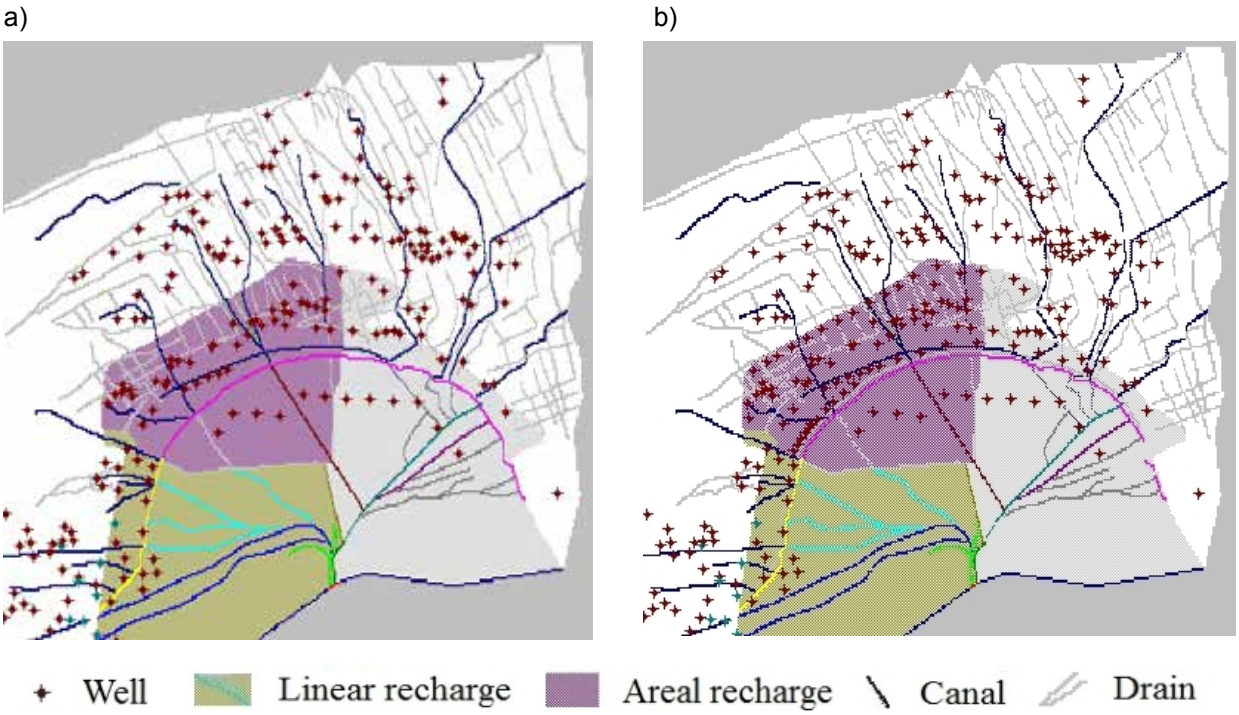


FIGURE 10. Groundwater extraction regime under different scenarios of groundwater management.

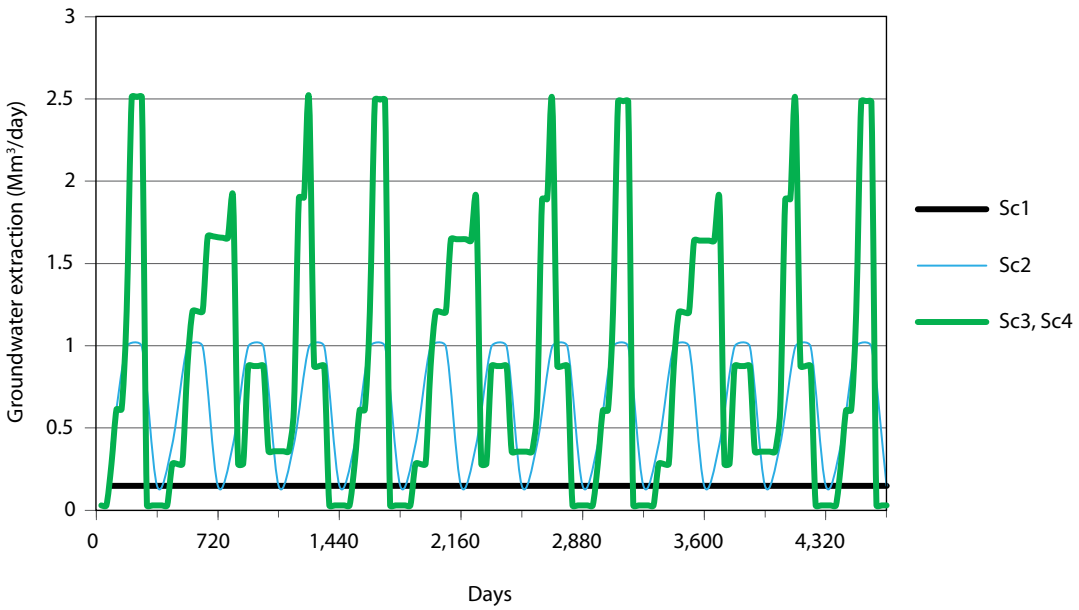


FIGURE 11. Water elevations in the upstream of the Isfara River as affected by the different water management scenarios.

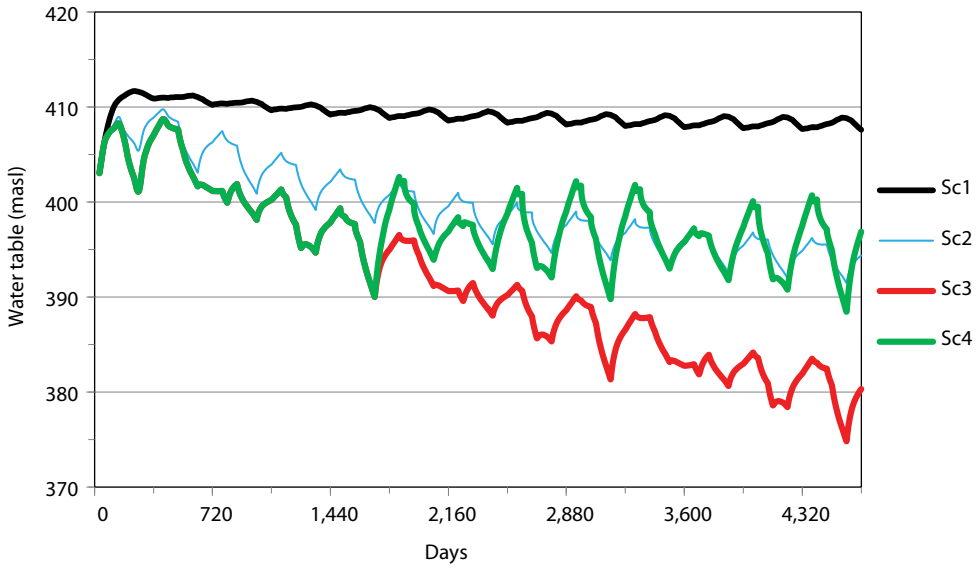


FIGURE 12. Regime of filling and withdrawing from the subsurface reservoir as affected by the alternative scenarios of the groundwater management.

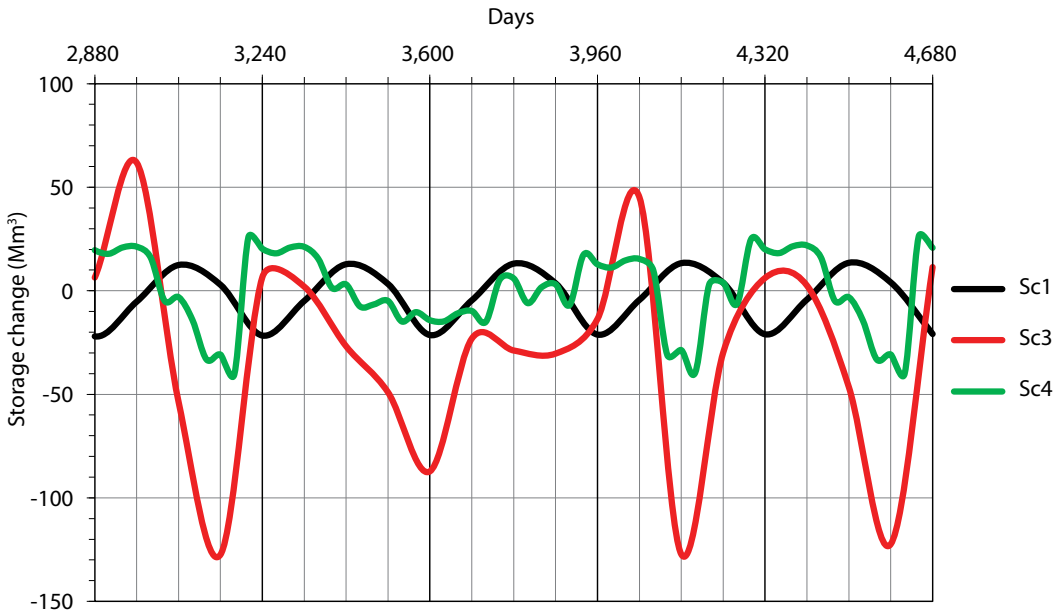


TABLE 5. Changes of the groundwater storages in the Isfara Aquifer as affected by different scenarios of the groundwater management.

Items	Sc1	Sc2	Sc3	Sc4
		Mm^3/year		
Areal recharge	182	182	191	291
Leakage from the BFC	33	39	50	38
Groundwater extraction	53	228	295	309
Return flow	130	37	37	58
Evapotranspiration from groundwater	60	41	20	35
Nonproductive depletions[a]	76	30	33	51
Including evaporation	18	12	6	11
Return winter flow	58	17	27	41
Return fraction	0.25	1.03	1.22	0.94
Storage change (as compared to scenario 1)		-58	-83	-45
Free capacities	90	148	173	135
Recovery efficiency				0.79

Notes: [a]Nonproductive depletions considered are the part of the evapotranspiration from groundwater table for physical evaporation and flow to sinks. The flow to sink in this case is the return flow to the river in winter, when the downstream reservoirs are full and there are no free storages.

capacities. Increasing the return fraction from 0.22 to 1.22 increases free capacities from 90 to 173 Mm^3 (see Tables 1 and 5).

The resources stored in the subsurface horizons under scenario 4 were used in the following way: 14% was used for irrigation in summer; 15% contributed for transpiration from shallow groundwater level; 21% contributed to the return flow to the river in the summer season; and 38% was still available in the subsurface horizon. Nonproductive depletions constituted 5% for evaporation and 14% for return flow to the river in winter. Furthermore, decreasing the groundwater storages under scenario 4 indicates the potential for additional recharge. Recovery efficiency of the aquifer recharge was estimated at 0.79.

Modeling results indicated differences in the realization of the alternative strategies of the groundwater management. The first strategy of preserving the underdeveloped groundwater will result in expanding the area with high groundwater levels in the Isfara River downstream. Thus, it will also cause a further increase in the salt affected and waterlogged areas. In addition, this strategy will produce high non-process water depletions including evaporation, flow to sinks and pollution. The second strategy of seasonal regulation of the groundwater storage will result in the reduction of non-process depletions for evaporation, flow to sinks and pollution. However, regional benefits of this strategy will be insufficient. Unregulated groundwater extraction (Sc3) may result in the degradation of water quality and drawdown of the groundwater level, especially in the upper part of the basin where the groundwater is of high quality. Finally, MAR strategy will facilitate the prevention of groundwater depletions by storing up to 100 Mm^3/year of the winter flow from the Naryn River. This strategy aims to effect regional benefits by reducing the winter return flow by 17 Mm^3/year and storing 100 Mm^3/year of the winter flow of the Naryn River in the subsurface horizons of the Isfara Aquifer.

Wide-scale adoption of the alternative strategies requires different approaches. Farmers

growing cotton and wheat under the State patronage, such as subsidized resources, including water, have little impetus to save irrigation water. In contrast, farmers growing market crops, such as orchards, grapevines and vegetables, in the upper part of the system are more inclined to get access to the groundwater. However, construction of wells may require a significant amount of their income. The use of low quality pumps, available in the local market, would be a high risk exercise and result in considerable losses for farmers who intend shifting to groundwater irrigation for growing perennial crops, especially during their establishment stage. Therefore, under the first strategy, there is a high risk of incurring losses for small farms, which are located in the water deficit zone and are attempting to get access to the groundwater.

The second strategy can be adopted by allocating preferential credit to the farmers for installing wells and to cover the operational expenses during the first year of the establishment of the orchards and grapevines, when farmers do not have free resources to invest into groundwater development. The benefit of this strategy is lowering the risk of losses for small farmers shifting to groundwater irrigation and increasing the area used for high-value crops. Intensive groundwater extractions in the upper zone may, with time, cause negative processes such as: degradation of the water quality in the upstream and the surrounding area due to saline fluxes from the vadoze zone; and groundwater level drawdown which will make water extractions uneconomical. Since groundwater and surface water use is regulated under the same water law in Central Asia, there is a strong procedure to be followed to get special permission to access groundwater. The special permission restricts the amount of water that can be pumped and, as such, creates the basis for preventing groundwater depletions.

The third strategy focuses on long-term regulation of the groundwater storage by accumulating the excessive flow of the rivers in the subsurface horizons in winter and its recovery in summer for irrigation. The modeling results indicate the regional benefits of this strategy. The shift from canal irrigation to conjunctive use will release the summer flow of the Naryn River for downstream use. Low groundwater levels in summer due to groundwater extraction will reduce the area prone to salinity and waterlogging and also the area suitable for high-value crops. Increasing winter recharge using the freshwater of the rivers will contribute to sustaining the water quality and reducing the return winter flow from the study area.

Increasing groundwater irrigation may increase consumption of electricity in the Fergana Valley. However, there is a widespread area under lift irrigation, which consumes even more energy. Shifting to conjunctive use will reduce the area under lift irrigation, and decrease consumption of electricity in those areas. In addition, small power stations proposed to be installed in the canal system can generate power for the operation of wells in the summer and for rural population needs in the winter.

Pilot MAR: The Sokh River Basin

Site Description

The Sokh River Basin extends over 183,738 ha from the northern foothills of the Turkestan-Alay mountain system till the Syrdarya River. The southern part of the basin is represented by the belt of the elevations elongated in the latitudinal direction with altitudes of 800-950 masl. The Sokh River crosses the elevations from south to north by narrow deep valley. Then to the north

from the hills there is the fan formed by the river covering the main part of the study area. In the northern part of the study area, the periphery of the fan merges with the alluvial valley of the Syrdarya River with altitudes at 354-362 masl (Geintsc 1967).

The Sokh River is fed by meltwater from glaciers, with a maximum flow in the summer and a minimum in February, when the baseflow is almost 100% sourced from groundwater. The head reach of the river across the alluvial fan is a natural recharge zone, contributing 44.5% of mean annual flow to groundwater. The Sokh River supplies water for irrigation in the upper part of the basin, where soil cover is represented by gravel and sand, and is also the main source of the groundwater recharge. The river flow is distributed into irrigation canals at the headwork called Sarykurgan, built on the river right after the elevations.

The Sokh Aquifer, underlying the Sokh River Basin (Figure 13a), consists primarily of unconsolidated shingle and gravel outwash deposits. In the lower reaches of the river, a spring zone appears in the form of a 3-5 km wide spring line that runs parallel to and slightly upslope of the BFC (Figure 13a, b). Groundwater naturally discharges directly into the drainage system over a 5 km wide belt that lies downstream (just to the north) of the BFC alignment. The flow paths to the discharge zone are almost vertical in the narrow spring zone due to an impermeable anticline that almost intersects the surface (Figure 13b), and gives rise to surface ponding, which then evaporates or flows into the drains.

The water-bearing strata consist of upper Quaternary (QIII), intermediate Quaternary (QII) and lower Quaternary (QI) deposits. These deposits contain gravel and shingle with an inter-layer 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 intermediate Quaternary (QII) layer is subdivided into (QII-1) and (QII-2) layers, with low hydraulic and high hydraulic conductivity, respectively.

The depth to access groundwater varies from 72 to 116 m in the head of the system, and can be as little as 0.5 to 2.5 m below ground level in the discharge zone. More than 800 wells have been in operation since the 1970s, but have generally only been used to supply peak irrigation water demand in the summer in the 1980s to 1990s. The aquifer in the lower part of the basin is locally confined or semi-confined due to the discontinuous layers of clay and loam (Figure 13b) (Miryusupov and Gracheva 2006).

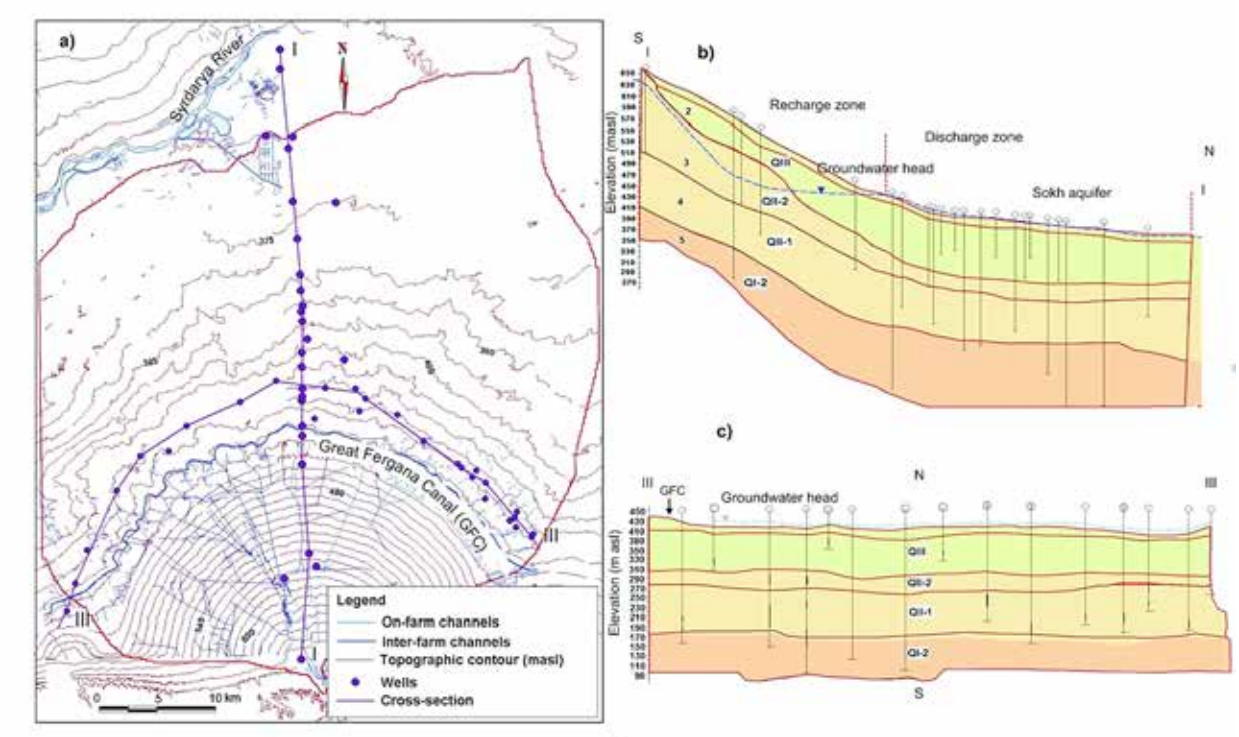
Field Studies of Natural Recharge

Methods and Data

The field study in the Sokh River Basin focused on estimating the leakage from riverbed and the ways in which it could increase. The gravel field of 600 ha area in the upper part of the fan creates a favorable structure for replenishment of the groundwater (Figure 14).

The field study consisted of two parts: (1) water budgeting studies carried out from June to October 2010 (Figure 14); and (2) long-term data analysis of the river flow and water quality. Water budgeting studies included the measurements of: the river flow discharge at the Sarykurgan Headwork; the water intake to the left bank and the right bank canals; the river flow at the downstream of the headwork; and water diversions into the secondary canals. The measurements were carried out three times per day. The groundwater elevations were monitored once in 3 days by monitoring wells located along the riverbed. Water samples were collected once per month for chemical analysis, which was carried out in the laboratory conditions using standard methods applied in the region (Arinushkina 1970). Annually, in May, the water management organization builds a dam across the river to increase the water heads and divert the river flow to the right bank canal. The dam is 600 m long and 3 m high. The water depth in the riverbed was measured three times per day from June to September. Subsequently, a relation was found between the river flow at the headwork

FIGURE 13. The fan of the Sokh River. a) plan, b) longitudinal profile of the fan, and c) cross-directional profile of the fan.

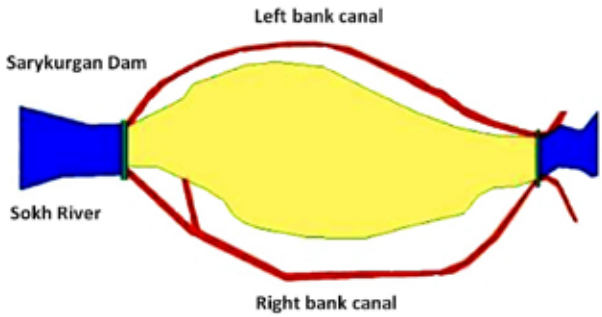


Source: Gracheva et al. 2009.

FIGURE 14. The gravel field: a) in the upper part of the Sokh River Basin (May, 2010), and b) the scheme of the main irrigation canals.

a)

b)



and the leakage from the gravel field on the river. Then this relation was applied to estimate leakage from the river in the long run using the river flow discharge data at the Sarykurgan Headwork from 1995 to 2010, collected from the archival data of the Syrdarya-Sokh Basin Irrigation System Administration.

Results and Discussion

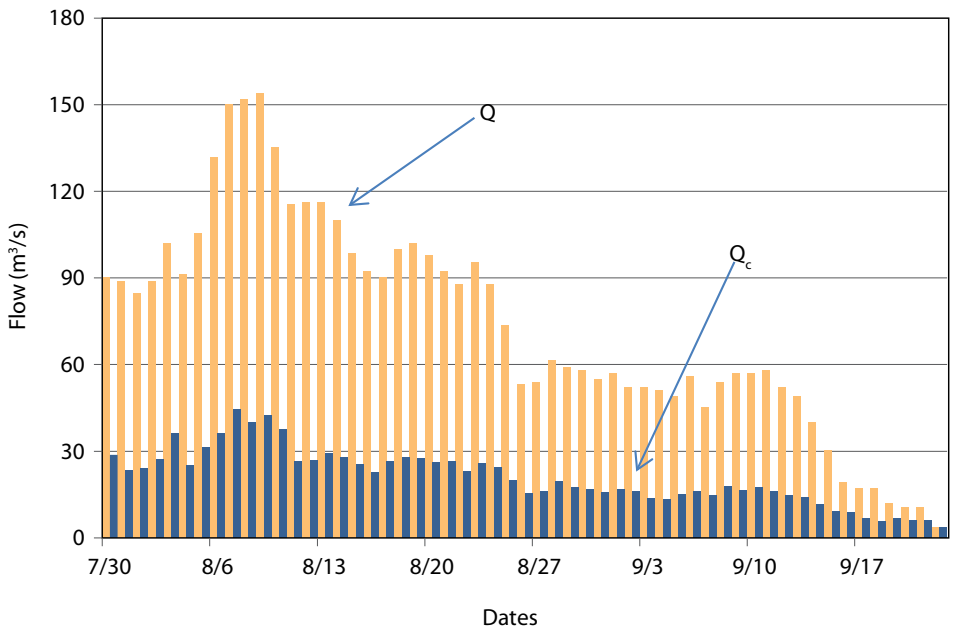
A significant part of the river flow released to the downstream of the Sarykurgan Headwork supplies the groundwater (Figure 15).

The field studies in 2010 found that the leakage from the riverbed in the downstream

averages 30-35% of river flow releases to the downstream (Figure 16).

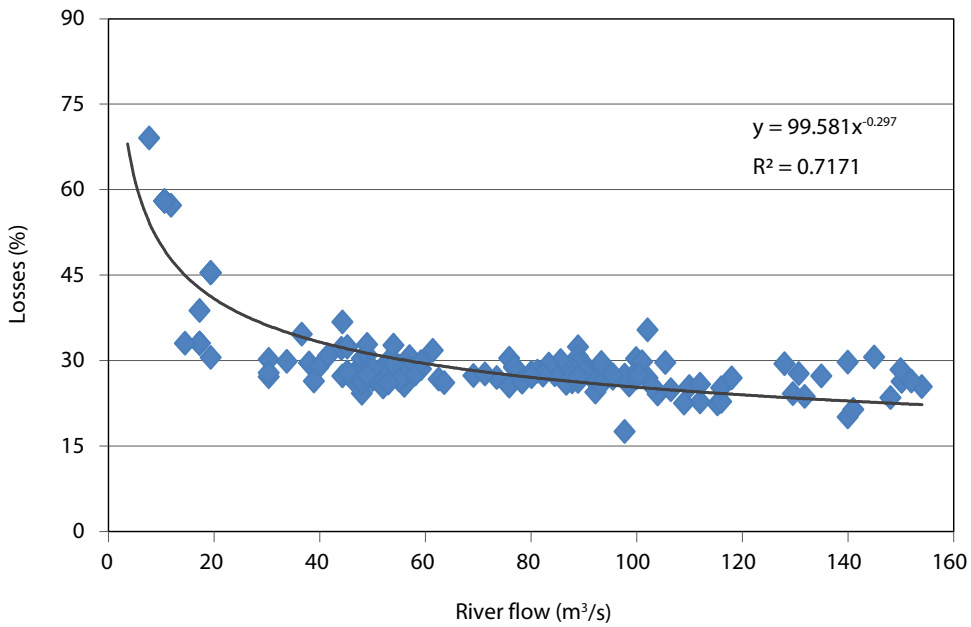
The leakage from the gravel field allows for the maintenance of low concentrations of dissolved solids in the groundwater (Table 6). Figure 16 shows that relative losses are increasing at small discharges and stabilizing at 25-35% for discharges exceeding

FIGURE 15. Flow of the Sokh River in the downstream of the Sarykurgan Headwork (Q) and leakage from the downstream gravel field (Q_c).



Source: Karimov et al. 2012.

FIGURE 16. Relation between the leakage from the river gravel field and the flow discharge in the downstream of the Sarykurgan Headwork.



Source: Karimov et al. 2012.

TABLE 6. Changes in the salinity of the groundwater in the upstream of the Sokh River.

Parameters	Unit	Head part			Inter-fan depression
		20.07.10	8.09.10	21.10.10	20.08.10
TDS[a]	mg/l	417±68	226±55	281±33	790±215
HCO^3	mg-equ/l	2.6±0.5	1.9±0.3	1.8±0.9	4±1.9
SO^4	mg-equ/l	3.9±0.9	1.6±0.5	2.4±1.3	8.4±3.5
Cl	mg-equ/l	0.6±0.2	0.5±0.1	0.5±0.1	0.6±0.5
Ca	mg-equ/l	1.4±0.2	0.9±0.1	0.7±0.3	3.5±1.2
Mg	mg-equ/l	1.9±0.3	1.5±0.3	1.7±0.5	4±1.2
Na	mg-equ/l	3.7±0.9	1.7±1.1	2.3±0.9	5.5±.8
pH		8	8±0.2	7.8±0.1	8±0.1
TH[b]	mg-equ/l	3.3±0.5	2.4±0.3	2.4±0.8	7.6±1.3
CH[c]	mg-equ/l	2.6±0.5	1.9±0.3	1.6±0.4	4±1.9
NCH[d]	mg-equ/l	0.8±0.3	0.9±0.1	1.3±1.1	4.8±1.4

Notes: [a] Total dissolved solids; [b] Total hardness; [c] Carbonate hardness; [d] Non-carbonate hardness.

50 m^3/s. The data presented in Table 6 show a decrease in the concentration of the dissolved salts in the groundwater during the high leakage from the riverbed from July to September, and, thereafter, it begins to increase again. These data represent trends in the salinity change in the central part of the river upstream.

The concentration of the dissolved ions is much higher in the groundwater of the inter-fan depressions. There are two main factors affecting the quality of the groundwater of the aquifer: i) the leakage from the riverbed contributes to the sustenance of the water quality; and ii) the subsurface inflow from the inter-fan depressions and the upstream and saline fluxes from the topsoil, increase the concentrations of the dissolved solids.

During the field studies carried out in 2010, it was found that when the river flow exceeded the transporting capacity of the main canals, it is released to the headwork downstream. Using the relation obtained for 2010, the leakage from the riverbed was calculated for 1995-2010 and is given in Figure 17. Changes in the groundwater salinity in the study area from 1995 to 2010 indicate tight relations between the river flow and the groundwater. Data given in Figure 17 show that the losses from the riverbed in the summer varies from 98 Mm^3 in low water years to 137 Mm^3 in high water years. The salinity of the groundwater, as and when affected by the leakage from the riverbed, begins to decrease in the spring and continues to the fall (Figure 18). The gradual increase in the share of the saline water in the groundwater budget indicates the need for measures to sustain the quality of the water.

There are at least two ways to sustain the water quality: i) to adopt water-saving technologies to reduce losses from the irrigated fields and to increase the natural recharge from the riverbed and other recharge structures; and ii) to restrict irrigation in the upstream of the river. This concept of adopting water-saving technologies for conserving water for enhancing natural recharge of groundwater was further tested through MAR modeling.

FIGURE 17. The Sokh River flow (Q) at the Sarykurgan headwork and the river flow released to the downstream (Q_{rel}).

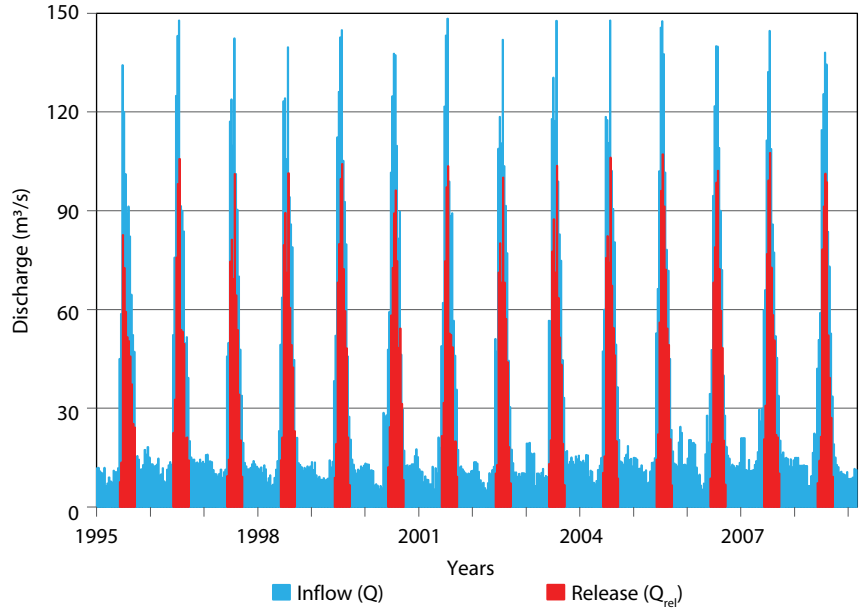
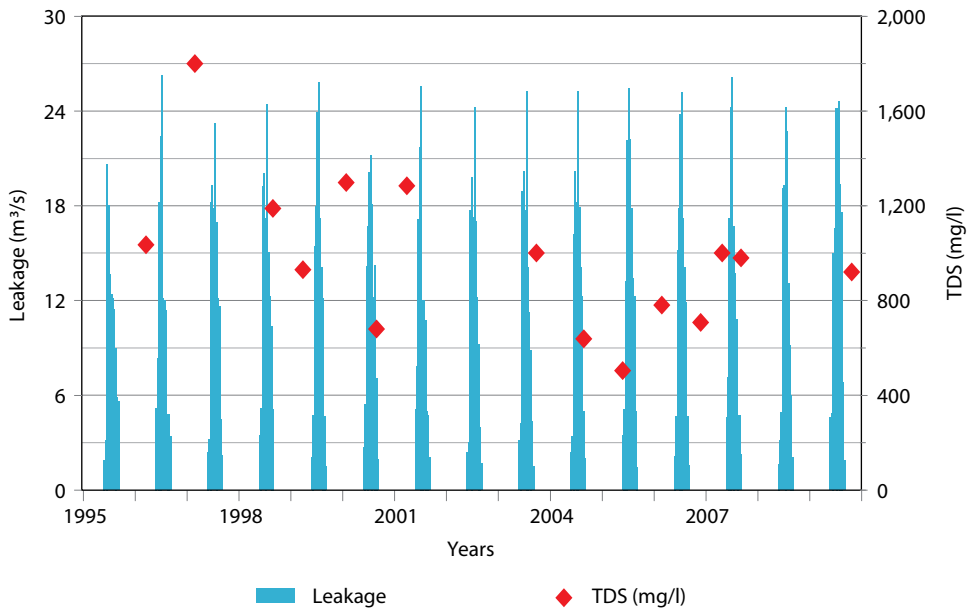


FIGURE 18. Leakage from the Sokh riverbed and the salinity of the groundwater (mg/l).



MAR Modeling

Model Description

The Sokh Aquifer Model was developed using Visual MODFLOW (v. 4.2), with extensive use of GIS (ArcView 9.1) to: (1) prepare the input data and link it directly to the model, and (2) to present model output. The work was developed in four stages: (a) schematization of geology and hydrogeologic conditions; (b) structuring the model and data collection for calibration; (c) calibration of the model to historical data; and (d) scenario development and modeling. Paper maps were scanned and converted to ArcView polygons (Rindahl 2004) and a digital elevation model of

the land surface was created from 1:50,000 scale maps using the Gauss-Kruger (1942) coordinate system. The stream network was transformed into raster format for direct incorporation into MODFLOW. Data was mostly sourced from the HYDROENGEO database and used to create the following thematic layers: location and details of monitoring and pumping wells; groundwater contours; elevations of the top and bottom of each geological layer (in spreadsheets); and hydraulic conductivity of each geological layer. Wells deeper than 100 m are typically used for domestic and industrial water supply, as are those with screens placed at lower depths (>70 m), where water quality is better and cost of pumping is less significant than for irrigation or drainage. As a first step, the boundary conditions, layers and their interconnections were specified. The area represented by the model covers 54.75 × 50.25 km in a grid of 335 rows and 365 columns with a fixed cell size of 150 × 150 m. The aquifer system is represented by three distinct geologic units — QIII, QII and QI (Figure 13). On the basis of the earlier hydrogeology surveys (Mirzaev 1974), each unit was assigned a horizontal and a vertical hydraulic conductivity and thickness.

The three geologic strata are represented as five layers in the model, as illustrated in Figure 19a and described below:

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 groundwater level is 0.5-3.0 m below the ground level.

Layer 2. From the bottom of layer 1 to the base of stratigraphic layer QIII in Figure 13b, typically between 280 and 350 m above mean sea level.

Layer 3. The elevation of the base of this layer corresponds to the stratigraphic boundary between geologic units QII1 and QII2 and varies from 253 to 218 masl.

Layer 4. The base elevation of this layer is marked by the stratigraphic boundary of geologic units QII2 and QI1 and varies from 218 to 125 masl.

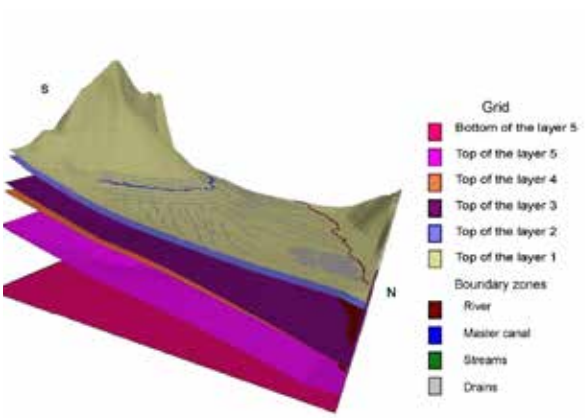
Layer 5. The base of this layer is set at 50 m above mean sea level and is impermeable. The impermeable bed is very deep in the study area and there was no reason to consider such a massive stratum. The bottom of layer 5 is taken as constant to simplify the model and reflects the geological conditions of the study area. It was also assumed that a boundary condition at 300 m below surface will not significantly affect subsurface water abstraction from depths of 40-100 m from the soil surface.

Groundwater in layers three, four and five are confined with a specific storage of 0.0001 1/m. The model is bounded on the north by general head conditions, governing drainage outflow, and the western and eastern boundaries are zero-flow boundaries lying at the edges of the aquifer. The upstream condition is a fixed flow boundary, representing the underground inflow. The Sokh River and the BFC flow in northern and western directions, respectively, and were included in the model to provide local recharge and drainage of the groundwater. The aquifer was divided into six zones as shown in Figure 19b. The discharge zone is divided into the spring discharge (zone 3), upwelling (zones 4 and 5) and dispersion (zone 6). Zone 3 is a belt that runs from 3 km to the south of the BFC to 5 km to its north.

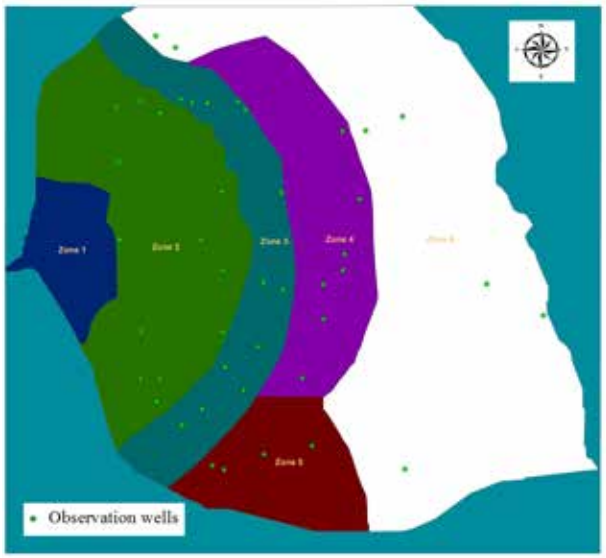
The BFC was included in the model as a river boundary condition. Average groundwater discharge downstream of the canal alignment is 1.99 m^3/s compared to 6.77 m^3/s along the spring-lines upslope of the BFC. The natural surface leakage along branches of Sokh River was included as a linear recharge. The natural recharge rates vary from 3,600 to 43,200 mm/year at the stream channels in the upstream, but then in the transit zone the intensity of the recharge at the stream channels falls to 1,080-18,000 mm/year. In other areas, recharge from irrigated lands predominates. The natural groundwater recharge from precipitation is estimated at 36 mm/year. The groundwater discharge in the upwelling zone is represented as the inflow to a 3 m deep surface drain with a constant flow depth of 1 m. A total of 773 wells were in operation during the study

FIGURE 19. a) The structure of the Sokh Aquifer Model, and b) balance zones.

a)



b)



Source: Gracheva et al. 2009.

Notes: Zone 1: Groundwater recharge zone; Zone 2: Groundwater transit zone; Zone 3: Groundwater spring discharge zone; Zones 4-5: Groundwater upwelling with direct discharge to drainage; Zone 6: Groundwater dispersion zone.

period, of which 667 were for irrigation, 57 for drainage and 49 for domestic needs.

Model Calibration

In 1977-1978, the HYDROENGEO Institute carried out detailed water budgeting studies (Miryusupov and Gracheva 2006). The results of these studies were used to calibrate the model. The observed groundwater level elevations from 44 observation wells were used to create a groundwater contour layer in ArcView 9.1 and were then interpolated to provide values for MODFLOW. The water budget data included all inflow components, such as subsurface inflow, recharge from the BFC, riverbed and streams, and accessions from irrigation and rainfall. This was balanced by discharge data on either side of the BFC, upwelling, subsurface tail flows to the Syrdarya River, groundwater flows to surface drains and direct evaporation. It was observed that subsurface inflow was almost twice the subsurface outflow.

Model calibration was conducted by a stepwise adjustment of the hydraulic conductivity of each layer. The detailed groundwater budget data collected by the HYDROENGEO from January 1977 to December 1978 was used for model calibration. The modeled heads for each month from January 1977 to December 1978 were compared to actual recorded values and other comparators, which included groundwater discharge to the drainage system, and subsurface inflow and outflow to each zone. The aquifer tests had determined hydraulic conductivity for the discharge zone to be in the range of 4 to 12 m/d for the first layer, with 4 m/d used as the initial value. The values of hydraulic conductivity in each layer were increased step-by-step and values that resulted in the best fit between observed and modeled water levels were retained. Vertical hydraulic conductivities were treated in a similar manner, using the observed and modeled flows between the consecutive layers as the objective function. Initially, the ratio of horizontal to vertical conductivity was assumed to be 10:1

in the recharge zone and 100:1 in the discharge zone. The reliability of the model parameters was assessed through the comparison of: observed and modeled groundwater level elevations; drainage flows; and evaporation losses from groundwater and canal seepage values.

Actual and modeled groundwater levels were compared at successive time intervals of 30, 210 and 720 days after the beginning of simulation. Sample plots of observed and modeled groundwater level elevation over time are given for water levels in three different zones in Figure 20a, b and c, which show an acceptable level of overall correspondence, but indicates that further calibration improvements would be obtained through automatic calibration. However, the authors preferred to retain the manual calibration based on adjusted hydraulic conductivities, since this has a physical meaning and is related to their knowledge of the aquifer and its behavior.

The comparison of calculated and actual discharge of groundwater into the drainage network is shown in Figure 21, indicating a good fit between observed and modeled data, within 10% overall. However, the overall drainage volume predicted by the model was approximately 22% less than what was observed, as shown in Table 7, and this is believed to be due to additional unaccounted surface flows entering the drainage network. The amplitude of the recharge is typically 35-50 m^3/s but the fluctuation of the drainage flow is much less, indicating the high regulation capacity of the Sokh Aquifer.

The peak recharge registered in July varied from 81 to 89 m^3/s, but the peak in drainage rate begins 3 months later in October and runs for 3 months at around 20 m^3/s. Finally, the total volume directly evaporated from groundwater amounted to 93.0 Mm^3/year compared to the present value, estimated to be 100.0 Mm^3/year, approximately 7% lower. Calculated values of leakage from BFC were 82 Mm^3/year compared to 97.7 Mm^3/year, or a difference of 16%. Given the uncertainty in the original estimates, both these values were considered to be acceptable for proceeding to simulation. Measured drainage flow includes groundwater discharge to drainage and discharge of irrigation tailwater to drainage. Calculated drainage flow (groundwater discharge to drainage) does not account tailwater losses, which are significant in Zones 5 and 6, presented by lowlands. This may be a reason for the higher difference between the measured and calculated values of the drainage of groundwater.

The corrected values of horizontal and vertical conductivity are given in Table 8.

Inter-layers of low permeability were not initially included in the model and their effect is accounted for through the determination of adjusted values of vertical conductivity. There was no change in the boundary conditions since 1978. Changes in the groundwater budget (groundwater extractions, recharge and evaporation) since 1978 were considered n the formulation of the modeling scenarios.

Modeling Scenarios

Five scenarios were developed to support alternative strategies of groundwater recharge and development in the Sokh River Basin:

Scenario 1 (Sc1) – the groundwater extraction at a minimum level of 3.8 m^3/s. The surface flow is the main source of irrigation water under this scenario.

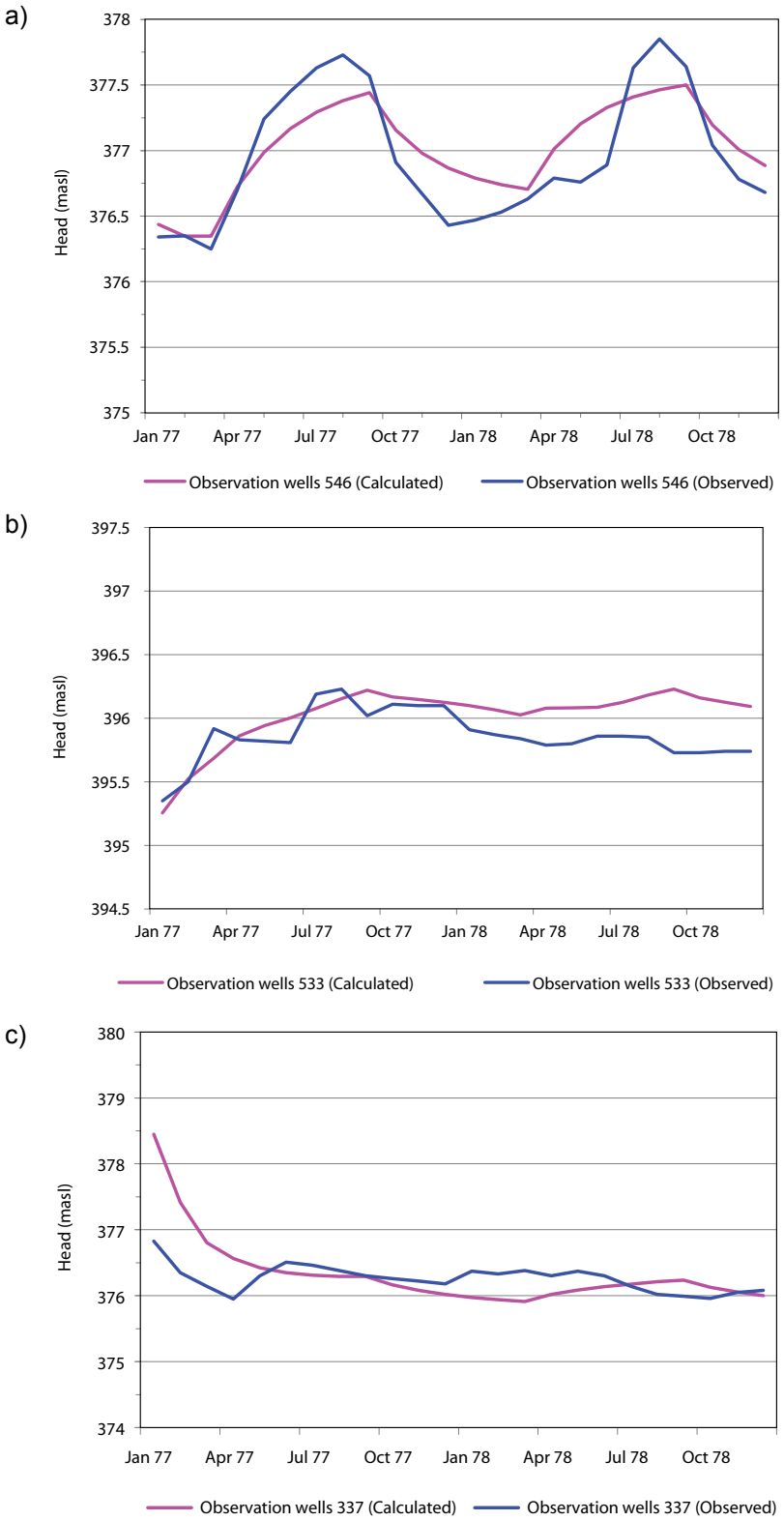
Scenario 2 (Sc2) – on-farm furrow irrigation is improved by introducing water-saving technologies, such as mulches, and alternate and short furrows. It is expected that these measures will reduce the groundwater recharge from the upstream irrigated land by 20%.

Scenario 3 (Sc3) – the introduction of advanced irrigation technologies in the river upstream. It is expected that this measure will produce a 40% reduction of the groundwater recharge in the river upstream.

Scenario 4 (Sc4) – the groundwater abstraction at a maximum level of 22.4 m^3/s. The effect of introducing advanced irrigation technologies in the river upstream on groundwater recharge is accounted for.

Scenario 5 (Sc5) – the groundwater extraction level is the same as in scenario 4 plus increasing groundwater recharge in winter from the Sokh

FIGURE 20. Comparison of observed and modeled groundwater levels in three different zones: a) Zone 4, b) Zone 5, and c) Zone 6.



Source: Gracheva et al. 2009.

TABLE 7. Comparison of predicted and actual values of drainage flow for the Sokh River Basin.

Zone	Annual drainage of groundwater		
	Calculated (Mm³)	Measured (Mm³)	Difference (%)
Zone 3	179.27	213.37	16
Zone 4	66.7	62.63	-6
Zone 5	43.96	72.22	39
Zone 6	50.52	64.55	22
Total	340.45	412.77	18

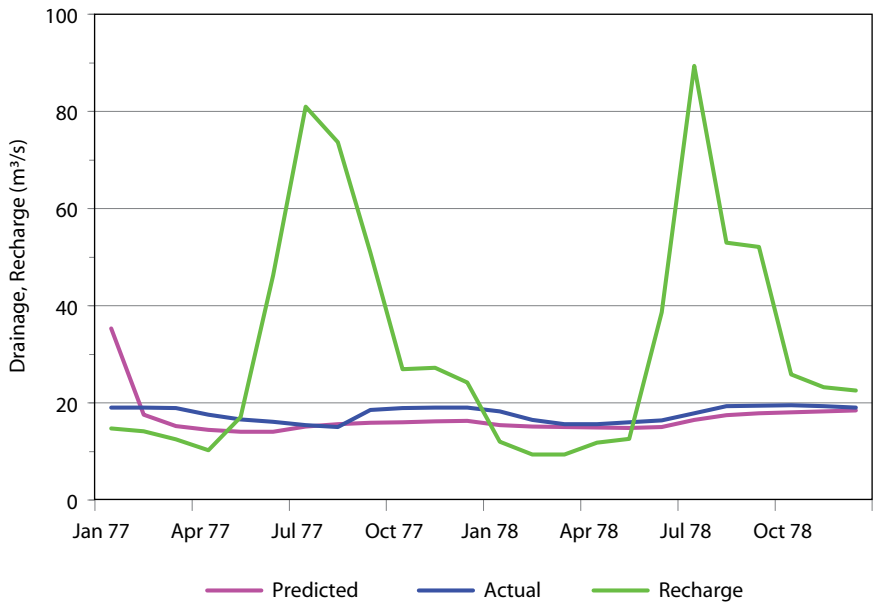
Source: Gracheva et al. 2009.

TABLE 8. Corrected values of hydraulic conductivity.

Layer	Recharge zone (Zones 1 and 2)				Discharge zone (Zones 3, 4, 5 and 6)			
	Horizontal		Vertical		Horizontal		Vertical	
	Initial m/d	Final m/d	Initial m/d	Final m/d	Initial m/d	Final m/d	Initial m/d	Final m/d
1					4-15	10	0.08-12.5	0.05-1.6
2	115-120	90-100	0.08-11.5	0.05-1.6	4-15	10	0.08-12.5	0.05-1.6
3	40-65	35-50	0.047-6.5	0.43-0.7	7-10	8	0.04-6.5	0.43-0.7
4	40-65	35-50	0.047-6.5	0.43-0.7	7-10	8	0.04-6.5	0.43-0.7
5	15-25	12-20	0.047-6.5	0.43-0.7	2-3	6	0.04-6.5	0.43-0.7

Source: Gracheva et al. 2009.

FIGURE 21. Example of comparison of predicted and actual values of drainage flow at drain 'K' and recharge of groundwater.



Source: Gracheva et al. 2009.

River floodplain by 200 Mm^3/year and by transporting water of the Naryn River through the BFC (Figure 13a).

Results and Discussion

The results of the water level modeling are shown in Figure 22. Figure 22 indicates that following the first strategy without (scenario 1) and with (scenarios 2 and 3) on-farm improvements would cause high groundwater levels in both the upstream and downstream parts of the basin, and high return flow to the Syrdarya River in the winter.

Development of groundwater for irrigation purposes under the second strategy (scenario 4) will reduce nonproductive evaporation by 58% and winter return flow by 46% (Table 9). However, this strategy may, with time, deplete groundwater storage, which would affect the quantity and the quality of the groundwater. The regime of filling and draw off of the subsurface aquifer is given in Figure 23.

Under scenario 1, groundwater storage is filled in the summer and draw off occurs in the winter for return flow to the river. Under scenario 4 there is a minor drawdown in the summer and filling is done in the winter. Under the scenario of MAR (Sc5), the storages are filled in the winter and drawdown occurs in the summer. Groundwater extractions at the minimum levels simulated in scenarios 1-3 cause the

FIGURE 22. Changes of the groundwater elevations in the: a) upper, and b) lower parts of the Sokh River Basin as affected different scenarios of the groundwater management.

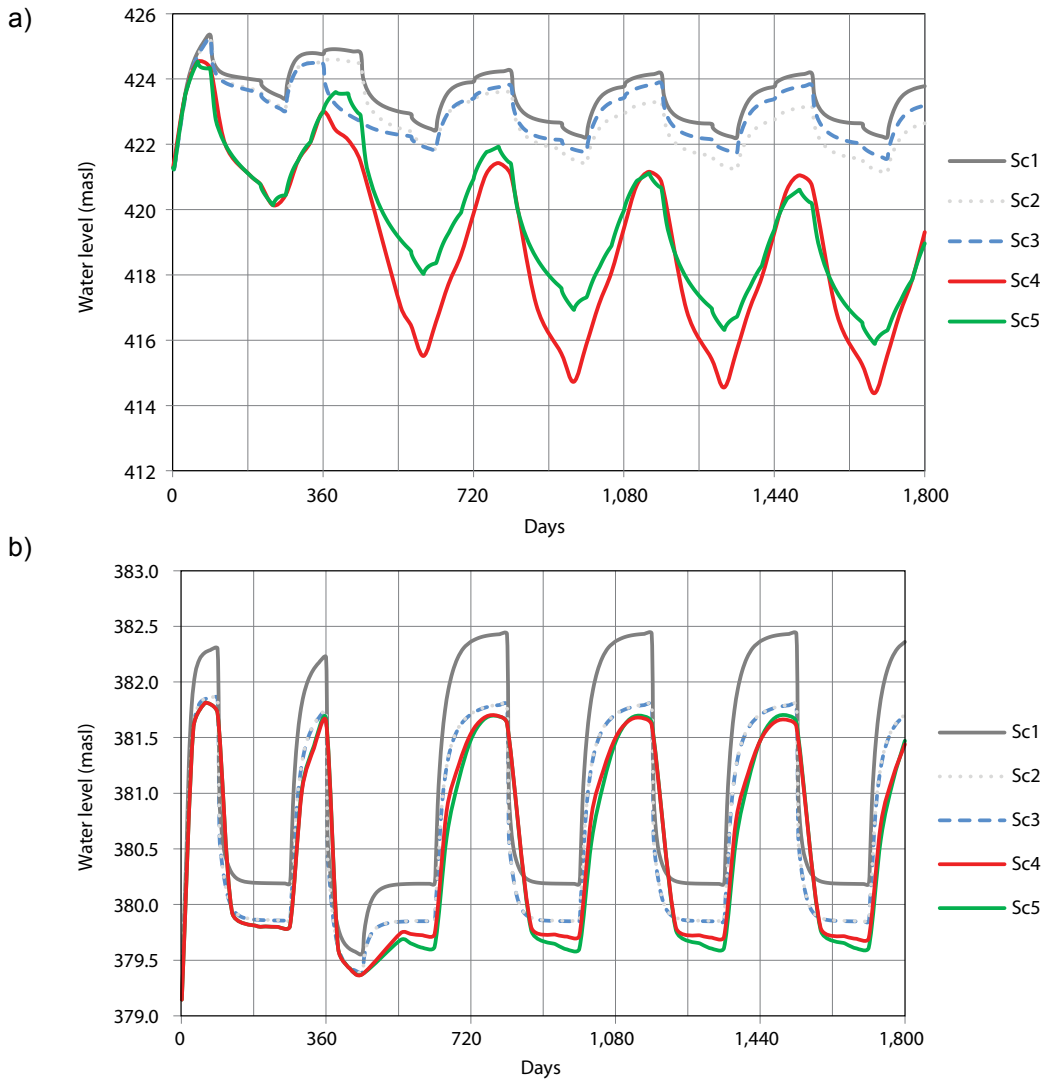


FIGURE 23. Calculated regime of filling and draw off of the groundwater storages in the Sokh Aquifer.

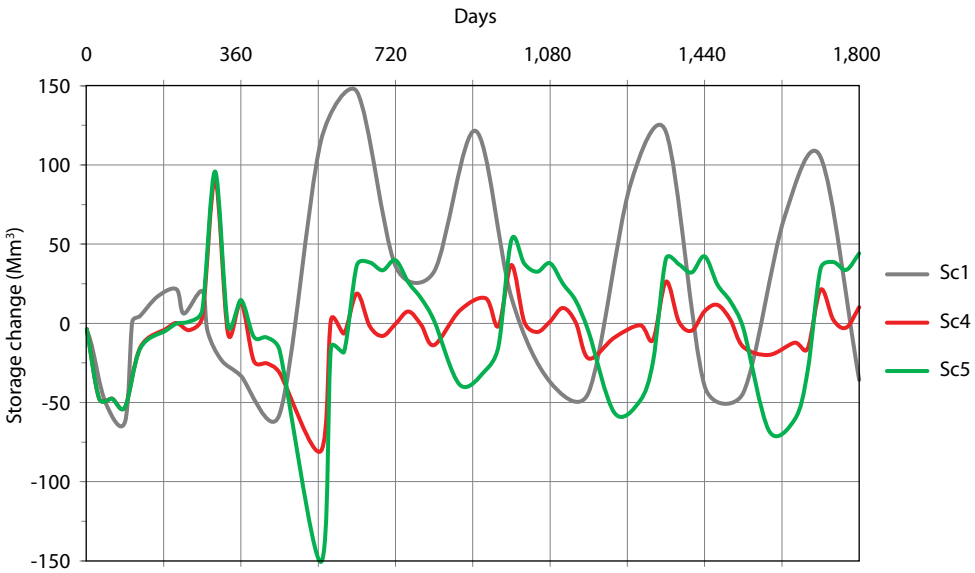


TABLE 9. Changes of the groundwater storages under alternative groundwater management strategies in the Sokh River Basin (Mm^3).

	Sc1	Sc2	Sc3	Sc4	Sc5
Annual					
Recharge	1,113	953	939	991	1,192
Leakage	68	80	81	125	124
Extraction	117	117	117	698	698
Return flow	609	540	533	302	322
Evaporation	470	405	399	198	205
Storage change	92	71	69	-18	118
Winter					
Recharge	288	246	244	253	359
Leakage	23	31	32	51	50
Extraction	0	0	0	107	107
Return flow	393	356	354	214	231
Evaporation	48	41	41	36	37
Storage change	-91	-78	-78	-39	-45
Summer					
Recharge	825	707	694	738	832
Leakage	46	26	49	74	73
Extraction	591	117	117	591	591
Return flow	92	185	179	89	92
Evaporation	422	365	359	162	168
Storage change	121	100	99	-21	45

highest return flow to the river, which is estimated at 52% of the groundwater recharge, and evapotranspiration from the groundwater level, most of which is non-process and at 39-40% of the total recharge. Groundwater storages increase by 92 Mm^3/year under this strategy, and thereby increase the area with shallow groundwater level on the periphery of the fan, followed by salinity and waterlogging issues.

The shift from canal irrigation to conjunctive use, modeled under scenario 4, will reduce the return flow to the river from 52% to 27% of total groundwater recharge and evapotranspiration from 52% to 18%. Gradual lowering of the groundwater level, with time, may cause groundwater depletion and affect its quantity and quality. The last may be caused by saline fluxes from the vadoze zone and from the inter-fan depressions and from the upstream of the Sokh River.

Under scenario 5 of MAR, the return flow to the river is estimated to be 24% to 25% of the total groundwater recharge and the evapotranspiration from 13% to 16%. Storing 200 Mm^3/year of the winter flow of the Sokh River in the subsurface horizons increased the groundwater extraction levels to 27 m^3/s. The lowering of the groundwater levels in the BFC zone increased leakage from the canal from 81 to 125 Mm^3/year, or by 50%. It is important to note that if under scenarios 1 to 3, groundwater storages are filled in summer and draw off occurs in winter, then under scenario 4, where groundwater development is unregulated, draw off occurs in summer and winter; and under scenario 5 of MAR, the groundwater storages are intendedly filled in winter and draw off in summer. Under the MAR scenario the return flow in winter was successfully reduced from 393 Mm^3 to 231 Mm^3 per season (Table 10).

The modeling results given in Table 10 show low efficiency of the groundwater management under strategy 1, which increases to 0.63 under strategy 4, with managed aquifer recharge and conjunctive use of groundwater and canal water for irrigation. Non-process depletions reduced from 48% under strategy 1 to 25% under strategy 3. Similar potential for MAR is available in other aquifers of the Fergana Valley, which demonstrates the importance of this strategy to improve water management in the Fergana Valley and in the Syrdarya River Basin, on the whole.

TABLE 10. Main induces of the alternative strategies of the groundwater management in the Sokh River Basin (Mm^3/year).

Induces	Sc1	Sc2	Sc3	Sc4	Sc5
Groundwater recharge	1,113	953	939	991	1,192
Including MAR using winter flow of the Sokh River					115
Naryn River					27
Groundwater extractions	117	117	117	698	698
Non-process depletions:	534	477	474	273	292
Evaporation	141	122	120	59	62
Return winter flow	393	356	354	214	231
Storage change		-15	-15	-68	105
Free capacities	1,452	1,467	1,467	1,535	1,347
Resource recovery	0.10	0.11	0.12	0.63	0.53

Conclusions

It is observed that there is a growing demand for food and energy, and also an increased competition for water between upstream and downstream users in the Syrdarya River Basin. Furthermore, the change in the upstream reservoir operation from a conjunctive irrigation/hydropower mode to an exclusively hydropower generation mode reduced the flow of the river downstream in the summer and increased it in the winter. The coincidence of peaks in winter hydropower releases and return flow from the irrigated land in the Fergana Valley forms excessive river flows, which complicates the operation of the downstream reservoirs. As a result, there is a water shortage in the range of 2,000-3,000 Mm^3/year affecting downstream water users in the summer and excessive, often unutilized, flows of the same magnitude in the winter. Projected reduction of the river flow by around 6-10% by 2050 due to climate change, with increased frequency of extreme, high and low flows may further complicate downstream basin water management, which is currently accomplished primarily by a cascade of reservoirs. This study suggests that the current practice of sequential in-channel reservoirs is not coping well with the needs of both upstream and the downstream water users.

The study further suggests that MAR in the upstream of Fergana Valley and elsewhere in the Syrdarya Basin may help adapt to a new water management reality. Over 3,000 Mm^3/year of subsurface free capacity is available in the upstream of the small river basins of the Fergana Valley. These capacities can be used for storing excessive flows of small rivers and thereby effectively reduce the return flow to the Syrdarya. Additional free storage for MAR can be created in the command areas of the main irrigation canals by intensive groundwater extraction. The water resources available in the Fergana Valley for MAR include: winter flow of the Naryn River from 2,000 to 3,000 Mm^3/season; winter flow of small rivers at 1,000 Mm^3/year, which could be free by increasing groundwater extractions for irrigation and by introducing water-saving technologies; and winter precipitation at 500 Mm^3/year. The resources available for MAR make 13% to 17% of the total inflow to the Fergana Valley in low to high flow years, respectively.

The study followed the stepwise procedure of implementing MAR in the Fergana Valley. The first step is the regional assessment of the potential for MAR and for shifting from canal irrigation to conjunctive surface water-groundwater use. The second step is the application of MAR for aquifers, located in the tail end of main canals. The next step is to move to the next aquifers along the main canals. When the process is complete for all of the separate aquifers along the main canals, MAR implementation for the entire Fergana Valley is considered.

The regional assessments in the Fergana Valley show that over 500,000 ha or 55% of the currently irrigated land can be shifted from canal irrigation to conjunctive surface water-groundwater use, which will reduce the return flow to the river by 30%, or by 1,000 Mm^3/year, and form free storages of 500 Mm^3 in the command areas of the main canals. Pilot-scale field and modeling studies of MAR for the Isfara Aquifer, located in the tail end of the BFC, found that groundwater extractions in the summer exceeding the annual recharge by 20% will create capacities for storing 100 Mm^3 of winter flow of Naryn River in the Isfara Aquifer.

Pilot-scale field and modeling studies of MAR for the Sokh Aquifer, located next along the BFC, indicated that the seasonal extraction of 63% of annual groundwater recharge and introducing water-saving technologies in the Sokh River upstream will free the river winter flow of 115 Mm^3 for enhancing natural recharge from the riverbed. The increased groundwater extraction will reduce the return flow to the Syrdarya River in the winter by 162 Mm^3 and an additional 100 Mm^3/year of the summer flow of the Naryn River can be released for the Syrdarya downstream. Overall, groundwater development for irrigation and MAR in the Fergana Valley may reduce

the winter flow of the Syrdarya River at the Fergana Valley outlet by 1,500 Mm^3/year and consequently increase the summer flow of the river to the same magnitude.

The results of the study suggest that simple technologies, such as infiltration basins and enhanced natural recharge from riverbeds, can be used for MAR in the Fergana Valley. Small infiltration basins can be constructed along the main canals, delivering the water of the Naryn River to the water-short areas of the Fergana Valley. Enhanced natural recharge from river floodplains is found to be effective for sustaining groundwater storages and preserving the high quality of groundwater in small river basins. To ensure the science-based implementation of MAR at the scale of the Syrdarya River Basin at large, the following need to be examined:

- Potential for introducing MAR in the Syrdarya River Basin, including the foothills of the northern Tajikistan and lowlands of the southern Kazakhstan.
- Potential for adoption of advanced MAR technologies, such as subsurface artificial dams and aquifer storage and recovery technologies.
- Management of groundwater quality by MAR.
- Adoption of water-saving technologies, such as drip irrigation, and MAR.

The results of the study propose (especially for projects already under implementation in the region) shifting the focus from reconstruction of dense drainage systems in the Fergana Valley to groundwater development for irrigation and MAR. The '*Meliorative fund',* established for amelioration of salt-affected and low productive land and functioning under the Government of Uzbekistan, can also be used as a financial instrument for MAR activities.

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