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Coupling hydrological and irrigation schedule models for the management of surface and groundwater resources in Khorezm, Uzbekistan

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For my family whose prayers helped me to achieve this milestone

After the demise of prophet Musa's (AS) mother, when He visited Koh-e-Tur (the mountain) and stumbled and was about to fall, he heard a sound from heaven, saying, "Musa come carefully, the lips that would supplicate for you are silent today.

ABSTRACT

The irrigated agriculture in the Khorezm region of Uzbekistan is characterized by huge water withdrawals from the Amu Darya River. The vast infrastructure built for extensive irrigation, together with inappropriate drainage infrastructure, leads to a build-up of very shallow groundwater (GW) levels, followed by waterlogging and salt accumulation in the soil profile. Previous studies revealed deficits in the management and maintenance institutions, inappropriate and inflexible irrigation strategies, poor linkages between field level demands, and in the operation of the network. No flexible water management tool is currently in use that, by pre-conceiving mitigation strategies, would aim at reducing the current yield reductions. This study aimed to develop and introduce such a tool at the irrigation scheme level, illustrated at the example of the Water Users Association (WUA) Shomakhulum in Khorezm (about 2,000 ha of farmland). The tool can support managerial decisions on optimization of water use, particularly under the deficitary water supply predicted under climate change. Remote Sensing (RS) techniques (SEBAL) were used in combination with real-time hydrological measurements (e.g., ponding experiments to estimate losses in canals) to assess the operational performance of the WUA. Delivery performance ratio (DPR), relative evapotranspiration (RET), depleted fraction (DF), drainage ratio (DR), overall consumed ratio (OCR), field application ratio (FAR) and conveyance ratio (CR) were used as performance indicators. Using the current and target values for FAR and CR, three improved irrigation efficiency scenarios were developed (S-A: baseline or business-as-usual (BAU), S-B: improving CR; S-C: raising FAR; S-D: improving FAR and CR together). Recharge to the aquifer was determined for these scenarios by the water balance approach. Spatial dynamics of GW levels and soil characteristics (factors that affect recharge) were represented by dividing the WUA into 'hydrological response units'. The FEFLOW-3D model was used to simulate GW dynamics under the scenarios. Recharge rates—through which the scenarios impact on GW— were a major input to this model. Simulated GW levels served in turn as an input to the HYDRUS-1D model used to estimate the capillary rise contribution of the GW to water demands of the key crops cotton, winter wheat and vegetables. The daily capillary rise was in turn fed into the CROPWAT model to simulate optimal irrigation scheduling (IS) and different water management scenarios. This novel hierarchical coupling of RS/GIS with the FEFLOW, HYDRUS and CROPWAT models was applied to the WUA area for an optimal management of surface and GW.

Operational performance of the irrigation system under BAU is very poor. Although RET (0.82) is near to target value (0.75), a DPR >1 indicates inefficient use of the supplied water. The FAR shows that under BAU 57 % of the delivered water is lost during application. The values of DF (0.4), OCR (0.51) and DR (0.55) do not match target values postulated in the literature, suggesting severe flaws in water distribution. Results of the water balance model show that the average recharge to the WUA under BAU (4 mm d^{-1}) can be reduced to 3.4, 1.8 and 1.4 mm d^{-1} in S-B, S-C and S-D, respectively. FEFLOW simulations show that improvements in irrigation efficiency alone can lower the GW levels by 12 cm (S-B), 38 cm (S-C) and 44 cm (S-D) compared to the BAU. Furthermore, HYDRUS-1D modeling shows that GW contributes up to 19% to the WUA's total water requirement under BAU. This would be reduced to 17, 11 and 9 % for S-B, S-C and S-D, respectively, leading to lower salt accumulation but higher net irrigation requirements. Simulated IS under BAU shows a 7 % (official IS) and 41.6 % (farmers' practice) reduction in cotton yield from the optimum IS. To mitigate adverse effects of water scarcity, the optimal IS was developed assuming 25 and 50 % reduced surface water supplies. Minimum yield losses with 25 % reduced water supply will be in the range of 10-20 %, and with water reduction of 50 % will be up to 22-30 %. Three water saving scenarios (WSS-1: introducing crops of low water demand, WSS-2: leaving marginal land out, and WSS-3: improving the irrigation efficiency) were introduced. Water savings of 9, 20 and 41 % can be achieved for WSS-1, WSS-2 and WSS-3, respectively. The results of the study provide important guidelines for the water management institutes in the region.

Die Kopplung hydrologischer Bewässerungssteuerungsmodelle mit Bewässerungssteuerungsmodellen für die Bewirtschaftung von Oberflächen- und Grundwasserressourcen in Khorezm, Usbekistan

KURZFASSUNG

Ausgedehnte Bewässerungsanlagen und hohe Wasserentnahmen aus dem Fluss Amu Darya kennzeichnen die Bewässerungswirtschaft in Khorezm/Usbekistan. Die dadurch in Verbindung mit unzureichender Entwässerung verursachten sehr hohen Grundwasserstände führen zu Vernässung und begünstigen die Bodenversalzung. Bisherige Studien belegen Defizite der für Betrieb und Unterhaltung der Systeme zuständigen Institutionen, unangemessene und starre Bewässerungsstrategien und eine unzureichende Abstimmung zwischen Feldwasserbedarf und Systembetrieb. Es fehlt ein flexibles Bewässerungssteuerungsmodell, das die Erarbeitung vorausschauender Strategien zur Verringerung von Ertragseinbußen ermöglicht. Die vorliegende Arbeit zielt auf die Entwicklung und Anwendung eines solchen Modells für die Wassernutzereinheit (WUA) Schomachulum in Choresm/Usbekistan (2000 ha bewässerte Fläche). Das Modell soll Optimierungsentscheidungen des Wassermanagements unterstützen, insbesondere für den Fall von Dargebotsengpässen, durch globale Klimaänderungen. Fernerkundungstechniken (SEBAL-Algorithmus: potenzielle und aktuelle Evapotranspiration) wurden mit hydrologischen Messungen kombiniert (ponding-Verfahren: Wasserverluste in Kanälen), um die Effizienz des Bewässerungsbetriebs einzuschätzen. Als Indikatoren dienten delivery performance ratio (DPR), relative evapotranspiration (RET), depleted fraction (DF), drainage ratio (DR), overall consumed ratio (OCR), field application ratio (FAR) and conveyance ratio (CR). Derzeitige Beträge und Zielwerte für FAR und CR wurden benutzt, um 3 Szenarien mit verbesserten Wirkungsgraden zu entwickeln (S-A: Ausgangssituation; S-B: verbesserter CR; S-C: erhöhter FAR; S-D: Kombination verbesserter CR und erhöhter FAR). Die Auswirkungen der Szenarien auf die Grundwasserneubildung wurden mit einem Wasserbilanzansatz abgeschätzt. Um räumliche Variabilitäten des Grundwasserstands und der Bodenverhältnisse (Faktoren auf die Grundwasserneubildung) zu berücksichtigen, wurde die WUA in homogene Untereinheiten aufgeteilt (hydrological response units). Das Grundwassermodell FEFLOW ermöglichte die Simulation der Grundwasserdynamik für die Szenarien. Die Neubildungsraten stellen dabei den Einfluss der Szenarien auf das Grundwassersystem dar. Die simulierten Grundwasserstände dienten als Eingangsgrößen in das HYDRUS-1D-Modell, das eine Quantifizierung des kapillaren Aufstiegs als Beitrag zur Deckung des Pflanzenwasserbedarfs für wesentliche Kulturen in der WUA (Baumwolle, Winterweizen, Gemüse) in Tagesschritten erlaubte. Diese gingen in das CROPWAT-Modell ein, womit optimale Bewässerungspläne für die Szenarien erarbeitet werden konnten. Die Effizienz des Bewässerungsbetriebs ist derzeit ungünstig. Obwohl RET mit 0,82 in der Nähe des Zielwertes liegt (0,75), belegt ein DPR-Wert >1 eine ineffiziente Wassernutzung. Das derzeitige Niveau des FAR zeigt, dass 57% des auf die Felder geleiteten Wassers verloren geht. Die Werte für DF (0,4), OCR (0,51) und DR (0,55) weichen von den Zielwerten (aus Literaturauswertung) ab und verdeutlichen Probleme der Wasserverteilung. Im Ausgangsszenario erreicht die durchschnittliche tägliche Grundwasserneubildung 4 mm d^{-1}; für die Szenarien S-B, S-C und S-D ergeben sich 3,4 bzw. 1,8 bzw. 1,4 mm d^{-1}. Die FEFLOW-Simulationen zeigen, dass die mit den Szenarien korrespondierenden Wirkungsgradverbesserungen zu Grundwasserständen führen, die um 12 cm (S-B), 38 cm (S-C) und 44 cm (S-D) unter denen der Ausgangssituation (S-A) liegen. HYDRUS ermöglicht die Einschätzung, dass derzeit 19% des Pflanzenwasserbedarfs durch den kapillaren Aufstieg gedeckt werden. Für die Szenarien ergeben sich Reduzierungen auf 17% (S-B), 11% (S-C) und

9% (S-D), was die Salzakkumulation verringert aber den Nettobewässerungsbedarf erhöht. Im Vergleich mit optimierten Wasserverteilungsplänen (Simulation) führt die offizielle (Norm-basierte) Wasserverteilung zu 7% und die von Landwirten praktizierte Anwendung zu 41,6% Ertragsverlust bei Baumwolle. Das Steuerungsmodell wurde auch genutzt, um die Auswirkungen einer Unterversorgung auf den Ertrag zu minimieren. Bei einem um 25% (50%) verminderten Wasserdargebot läßt sich die Ertragseinbuße auf 10-18% (20-30%) begrenzen. Die Simulation von Wassereinsparoptionen (WSS-1: wasserextensivere Kulturen; WSS-2: Aufgabe marginaler Standorte; WSS-3: Wirkungsgradverbesserung) belegt Einsparpotentiale von 9% (WSS-1), 20% (WSS-2) und 41% (WSS-3). Die Ergebnisse der Arbeit liefern wesentliche Grundlagen für wasserwirtschaftliche Institutionen in der Region.

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Acronyms

ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
BAU	Business-as-Usual
BUIS	Basin Department of Irrigation Systems
BVO	Basin Management Organizations (*Basseynoe Vodnoe Ob'edinenie*)
CR	Conveyance Ratio
DF	Depleted Fraction
DPR	Delivery Performance Ratio
DR	Drainage Ratio
D-SCL	Deep-Silt Clay Loam
ETa	Actual Evapotranspiration
ETp	Potential Evapotranspiration
ETc	Crop specific evapotranspiration
FAR	Field Application Ratio
GIS	Geographic Information System
GW	Groundwater Well
HRU	Hydrological Response Units
IS	Irrigation Schedule
MODIS	Moderate Resolution Imaging Spectroradiometer
M-SL	Medium-Silt Loam
OCR	Overall Consumed Ratio
OGME	Hydromelioration Expedition
OW	Observation Well
Pe	Effective Precipitation
RET	Relative Evapotranspiration
RS	Remote Sensing
SEBAL	Surface Energy Balance Algorithm
S-SL	Shallow-Silt Loam
UIS	Irrigation System Authority (= TEZIM)
UNESCO	United Nations Educational, Scientific and Cultural Organization
Va	Actual Flow of Water
Vc	Volume of Surface Water Flowing into the Command Area
Vdr	Volume of Water Drained From the Area
Vi	Intended Flow of Water
WUA	Water Users Association
ZEF	Zentrum für Entwicklungsforschung (Center for Development Research)

1 GENERAL INTRODUCTION

1.1 Water for irrigated agriculture

By the year 2025, worldwide food production must grow by at least 40 % to meet the needs of a world population that will have increased by 33 % by then, and to satisfy the trends for improved nutrition (Bos et al., 2005). About 83 % of the expected 40 % increase in population (to 8.5 billion) is predicted to live in developing countries. In transition countries such as those in Central Asia and the Caucasus (CAC), climate change, specific characteristics and legacies of the past have caused vulnerability to food insecurity (Christmann et al., 2009; Wehrheim and Wiesmann, 2003). Yet the capacity of available resources and technologies to meet the growing demands for food, fuel and fiber, especially in developing countries, remains uncertain.

The world's food production largely depends upon the availability of water resources, but these resources are finite. Ayars et al. (2006) warned that future scenarios predict a worldwide fresh irrigation water scarcity due to a) the competition among the different users (urban, industrial and environmental), and b) the increasing food, fuel and fiber demands resulting from the increase in population. Predictions also indicate an even higher water shortage in arid and semi-arid regions, where water is already a scarce commodity. The role of water as a social, economic, and life-sustaining commodity should be reflected in demand management procedures for coping with supply and be implemented through resource assessment and water conservation and reuse (UNCED, 2002).

1.2 Challenges of irrigated agriculture in Uzbekistan

Irrigated agriculture is one of the critical pillars of Uzbekistan's economy. This sector contributes about 33 % of the country's gross domestic product (GDP) and employs 60 % of its labor force (Djalalov, 2001). Due to the arid to semi-arid climate, agriculture consumes 92 % of Uzbekistan's total water use of 56 billion cubic meters (BCM) (Dukhovniy and Sokolov, 2002). Huge amounts of water are withdrawn from the Amu Darya and Syr Darya rivers (80 % of the total water use), the main sources of irrigation water supply. Nevertheless, since approximately the 1990's, the region frequently experiences insufficient water supply, particularly so in the downstream and middle-stream reaches of the two rivers (Olimjanov and Mamarasulov, 2006), which is attributed to low irrigation efficiency (Conrad, 2006). As 80% of Uzbekistan's water supply comes from neighboring countries, primarily via the Rivers Amu Darya and Syr Darya (Mirzaev, 1996), agriculture and agricultural policy in Uzbekistan also have significant international dimensions. Along with this, competition for water between the local water users has increased substantially (Abdullaev et al., 2008a).

1.3 Problem statement

In the 1960's, the Soviet planners decided to intensify irrigated agricultural production and in consequence, the irrigated land area increased from 4 million ha to 8 million ha in the Aral Sea Basin, including the desert lands of the Khorezm oasis, which is the subject of this study. To fulfill the water requirement for crops, most specifically cotton, complex irrigation network system was spread all over the region. The extensive diversion of water, compared to the potential requirements, from the Amu Darya and Syr Darya River to the established irrigation system has resulted in a shrinking of the Aral Sea (Ressl and Micklin, 2004). This has been labeled as the Aral Sea Syndrome (WBGU, 1998). After the collapse of the Soviet Union, the overexploitation of water resources has continued on the regional level (Conrad et al., 2007). This wasteful use of surface water is unsustainable even in the near future (Gupta et al., 2009).

Previous water balance studies (Conrad et al., 2007; Forkutsa et al., 2009) conducted in the region revealed an inefficiency of the irrigation system due to deficits in management and in network maintenance, inappropriate and inflexible irrigation strategies at field level, and a poor linking between field level requirements and the operation of the network (Figure 1.1).

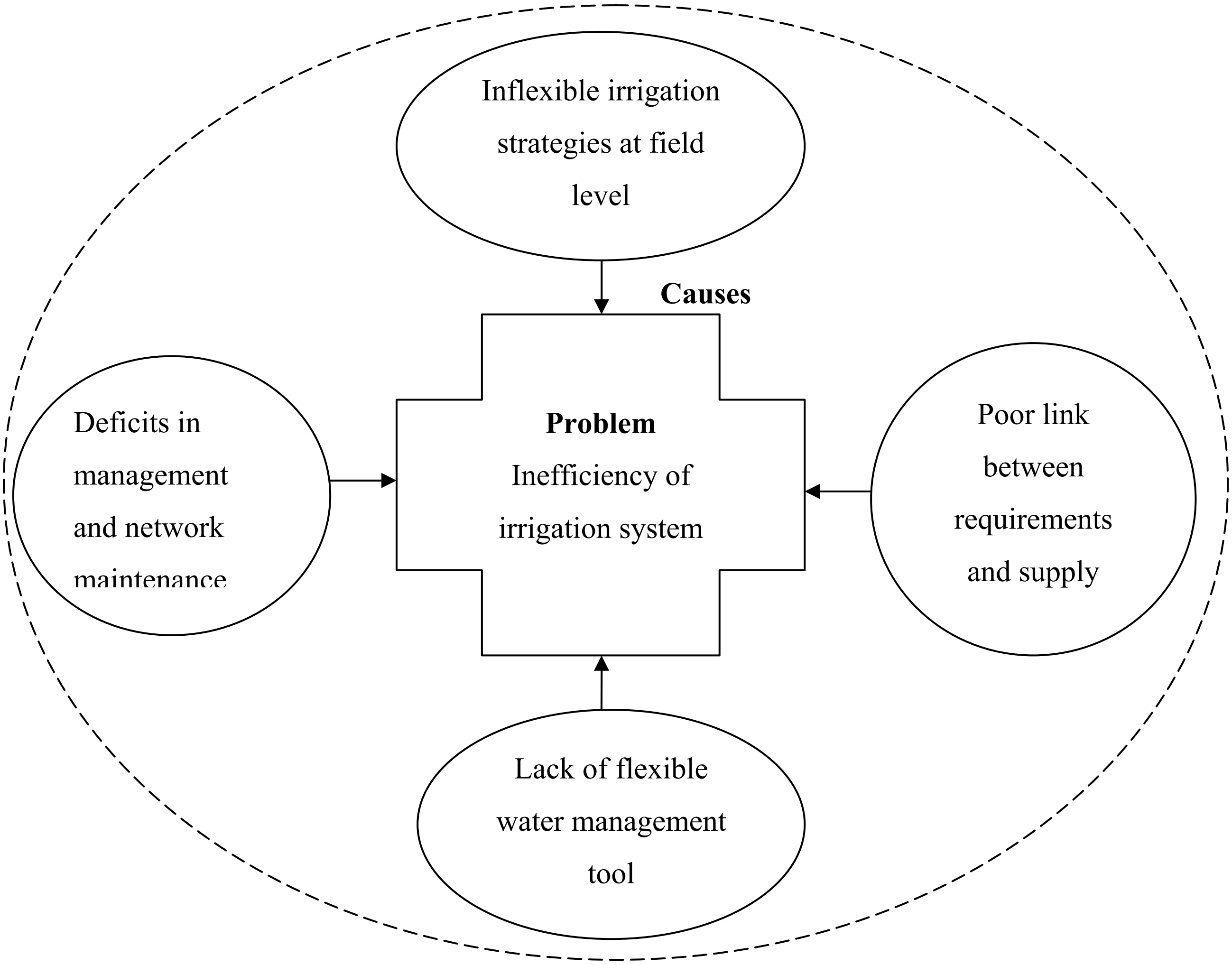


Figure 1.1 Causes of low irrigation efficiency in the irrigation system of the Khorezm region of Uzbekistan

This indicates a deficiency in the present water management tools and in turn a current lack of options to reduce the impacts on crops yields and food security by conceiving mitigation strategies in advance. Based on an analysis of the resource potential of shallow groundwater (Ayars et al., 2006; Forkutsa, 2006), integrating the use of surface and groundwater resources seems a promising approach (IWMI, 2005), particularly when taking long-term impacts of conjunctive use into account (Qureshi et al., 2004).

Therefore, a hydrological tool considering the dimensions of both surface and groundwater that is temporally and spatially highly detailed and can be used for addressing the current water deficits is an urgent need in the area. This tool should also allow developing scenarios that cope with the deficit water supply more efficiently and thus raise the income and food security of the farmers.

1.4 Objective of the study

The main objective of this study is to establish and introduce a hydrological tool by integrating surface and sub-surface irrigation that is based on satellite remote sensing and hydrological models to support the managerial decisions at the water users' association level.

The specific research objectives are:

- Develop an irrigation scheduling model for Shomakhulum Water Users Association (WUA) that is spatially and temporally highly detailed for improved system operation in the WUA (spatial resolution is to be achieved through developing an approach based on site- and soil-specific hydrological response units);
- Develop management scenarios of optimized system operation with the goal of maximizing the farmers' objectives under system- and water-resource limitations while minimizing impacts on the environment.

The conceptual framework to achieve these objectives is presented in the following section.

1.5 Conceptual framework

1.5.1 Development of a hydrological tool

To develop a hydrological tool that operates at a high temporal and spatial resolution, CROPWAT model was used as a basis. CROPWAT can develop irrigation schedules at high temporal resolution. It can be used to develop optimal irrigation schedules considering both sufficient water supply and reduced supply. In the first case, the optimal schedule allows avoiding water stress, and in the second case, the impact of water stress on yield reduction can be minimized and the yield losses under reduced water supply can be quantified. It has a shortcoming, however, as it is not able to compute the contribution of capillary rise to crop water use. To fill this gap, the HYDRUS-1D model was used; it has been parameterized for Khorezm and provides reliable quantifications of capillary rise (Forkutsa, 2006). We used HYDRUS-1D to compute capillary rise on a daily basis, and the values were introduced to CROPWAT. However, the GW levels are dynamic in nature and can vary significantly following surface water interventions. Therefore, the tool was further integrated with hydrological models to simulate improved irrigation efficiency scenarios. Remote sensing techniques (determination of actual and potential evapotranspiration using SEBAL) and real-time hydrological measurements (field experiments for application efficiency, rating curves for inflows and outflows from the WUA, ponding experiments for conveyance losses) were used to determine the overall irrigation efficiency of the WUA. Possible improvements in irrigation efficiency were taken from the literature and combined with the current values to develop improved irrigation efficiency scenarios. The effects of improved irrigation efficiency scenarios on GW levels were determined using the FEFLOW-3D model. Recharge as an important input for this model was determined using the water balance model. The dynamics of GW levels for four irrigation efficiency scenarios simulated by the FEFLOW-3D model were then introduced in the HYDRUS-1D model to calculate the capillary rise contribution. This value was used for all improved irrigation efficiency scenarios in the CROPWAT model to optimize the water use in the Shomakhulum water users association. Linking the CROPWAT, HYDRUS-1D, FEFLOW-3D, SEBAL and water balance model with high spatial and temporal resolution by the input and output is the novelty of this approach (Figure 1.2). Figure 1.3 illustrates the parameters used in the development of the hydrological tool.

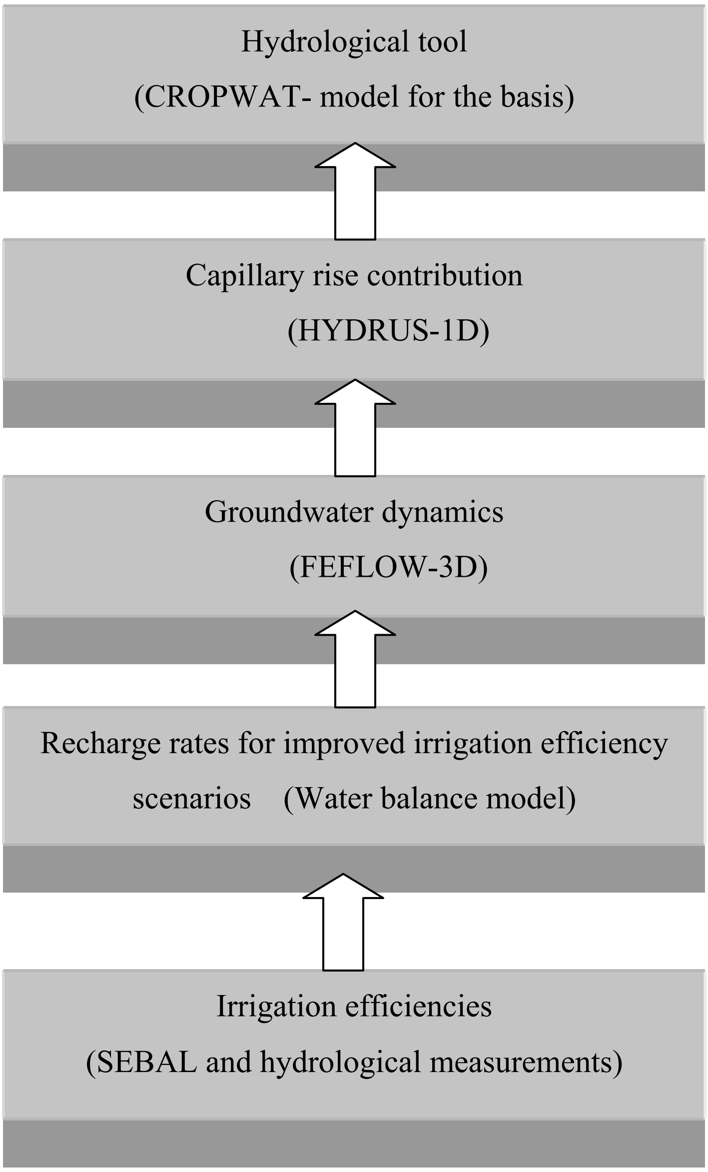


Figure 1.2 Conceptual framework of the hydrological tool

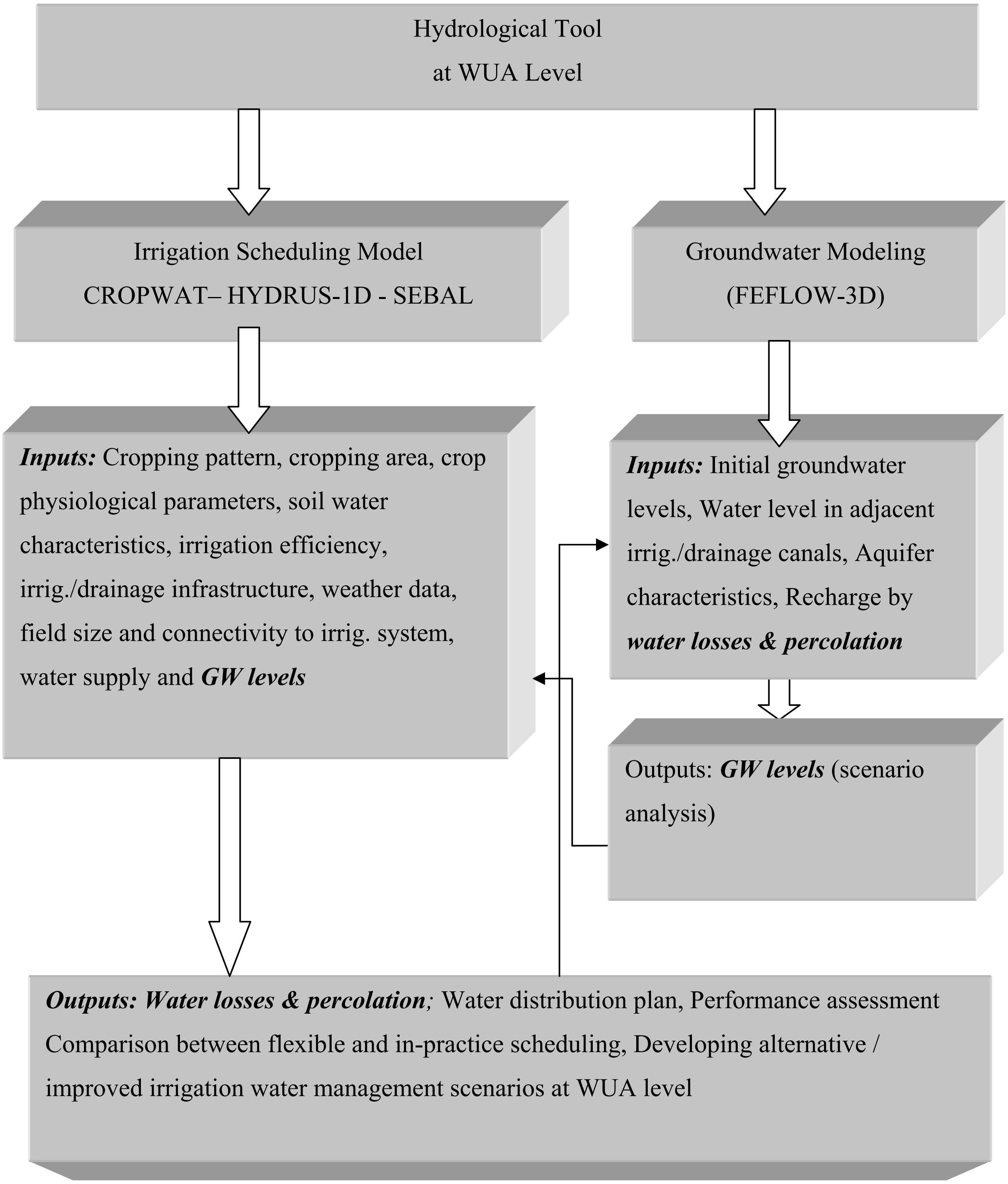


Figure 1.3 Input and output for the hydrological tool

1.5.2 Operational performance in the study area

To assess the operational performance of the irrigation system in the study area in general and field and application ratios in particular, remote sensing techniques (Surface Energy Balance Algorithm for Land (SEBAL) for potential and actual evapotranspiration rates) were used in combination with real-time hydrological measurements (inflow and outflow from the study area, ponding experiments for conveyance ratio and field experiments for field application ratio). Delivery performance ratio (DPR), relative evapotranspiration (RET), depleted fraction (DF), drainage ratio (DR), overall consumed ratio (OCR), field application ratio (FAR) and conveyance ratio (CR) were selected as performance indicators.

The irrigation scenarios investigated here refer to improvements of the FAR and CR towards target values derived from the literature. Irrigation efficiency by definition is the product of the FAR and CR. Target values of FAR were taken from Bos and Nugteren (1990, 1974a) and target values of CR were taken from Jurriens et al. (2001). By using the current and target values of FAR and CR, one baseline and three improved irrigation efficiency scenarios were developed:

- Scenario A: baseline business-as-usual (BAU),
- Scenario B: improving CR,
- Scenario C: raising FAR, and
- Scenario D: improving FAR and CR together.

1.5.3 Recharge estimates and development of hydrological response units

Irrigation efficiency strongly influences the recharge rates. Recharge rates in this study for the four irrigation efficiency scenarios were determined by the water balance approach under the assumption that the difference between gross and net irrigation requirements feeds the aquifer. However, recharge rates at field level depend on several factors, e.g., climatic conditions, soil texture, cropping pattern and GW levels. These factors can vary significantly in any irrigation canal command area. Thiessen polygons (on the available point data of GW wells and soil texture) were drawn in Arc GIS to capture the spatial variability of GW levels and soil texture, which determine the capillary rise and in turn, the water balance and hence the recharge. Satellite remote sensing was used for the land-use classification in the area. Areas of similar GW and soil texture in the WUA were defined as hydrological response units (HRUs).

1.5.4 Quantifying the GW dynamics

The spatial and temporal behavior of groundwater levels largely depends upon the recharge rates. The FEFLOW 3D model (Diersch, 2002a), which has successfully been tested for a number of benchmark examples in variable density flow, was selected for this study. FEFLOW uses recharge rates to simulate the GW dynamics on a daily basis. The daily changes in GW levels were simulated for four different irrigation efficiency scenarios.

1.5.5 Quantifying capillary rise and optimizing irrigation schedule with hydrological tool

With the daily GW levels, the HYDRUS-1D model (Simunek et al., 2005) was used to compute the capillary rise contribution for the four efficiency scenarios and for key crops (cotton, wheat and vegetables). These values were then entered into the CROPWAT model. Capillary rise was introduced into the CROPWAT model through the *user defined irrigation* option to develop the various scenarios, e.g., develop the optimal irrigation schedule for cotton, wheat and vegetables under the BAU scenario, develop the optimal irrigation schedule for cotton for the above-mentioned irrigation efficiency scenarios, compare the current and flexible irrigation scheduling, derive the options for water saving (change in cropping plan, leaving marginal locations out or for alternative crops), and develop the strategies for situations with low water availability.

1.6 Outline of the thesis

Chapter 2 describes the study area, where water use is regulated by the Shomakhulum water users association (WUA). Furthermore, irrigation and drainage system, hydrology, land use and soil types of the study area are described. Important issues related to the present irrigation norm, development of norms, hydromodules and hierarchical approach of water demand are also discussed.

Chapter 3 presents the methodology for assessing the operational performance of the irrigation scheme in the WUA Shomakhulum for the year 2007 and provides recommendations for the strategic planning prior to implementation of interventions. A set of performance indicators is selected taking into consideration the advantages of satellite remote sensing (determination of actual evapotranspiration), and then the parameters required to determine the performance indicators are received from both remote sensing techniques and (preliminary real-time) hydrological measurements. The derived performance assessment indicators and application and conveyance ratios are used to determine the recharge rates at different irrigation efficiency scenarios (Chapter 4).

Chapter 4 presents the methodology for modeling the recharge rates at field level by developing the water balance model and a GIS-based approach to upscale from field level to hydrological response units and then to the WUA level. Recharge is determined by following the water balance model concept, i.e., the fraction of the difference between gross and net irrigation contributes to recharge the aquifer. The difference between net and gross irrigation is driven on the irrigation efficiency as gross irrigation reduces with the improvement of application and conveyance efficiency. Current irrigation efficiency determined from the chapter 3 is used in conjunction with the target values reported in literature for establishing the four irrigation efficiency scenarios to determine the four corresponding recharge rates. Along with efficiencies, recharge rates at field level also depends upon several factors, e.g., climatic conditions, soil texture, cropping pattern and GW levels and these factors can vary significantly in any irrigation canal command area. Using the Thiessen polygons, GW and soil texture maps were drawn in Arc GIS to capture the spatial variability of GW levels and soil texture which determine the capillary rise (and in turn the water balance and hence the recharge). Based upon these maps, the identified subunits of the WUA having the homogenous conditions (GW and soil texture) are considered as hydrological response units (HRUs). The recharge rates are used to capture the changes in GW levels against the four different recharge rates (Chapter 5).

Chapter 5 focuses on modeling the GW situation in the presence of a complex open-drainage system using the FEFLOW-3D model. The model is calibrated using the groundwater (GW) level from April to June 2007, and then validated on the data set from July to September 2007. After calibration and validation, GW levels are simulated for the four different recharge rates. The simulated GW levels are used to determine the impact of different GW levels on capillary rise (Chapter 6).

Chapter 6 presents the methodology for modeling the capillary rise at field level by using the HYDRUS-1D model and a GIS-based approach to upscale from field level to hydrological response unit and then to WUA level. After determining the capillary rise in each HRU and in WUA, four different GW levels scenarios (Chapter 5) are used to compute the capillary rise. The computed capillary rise is the basis for developing optimal irrigation schedules (Chapter 7).

Chapter 7 presents the procedure for the development of the hydrological tool. After developing the irrigation scheduling model with CROPWAT as a base model, an optimal irrigation schedule is calculated and then different managerial scenarios are simulated for the best water management practices for the area.

Chapter 8, presents the general discussion on the management tool, and shows how the different models applied are linked together, how the efficiency scenarios are used, and the general outcomes of the model.

Chapter 9 presents the summary and conclusions.

2 STUDY AREA

2.1 Study area and water users association

The study was conducted in the Khorezm province, a region situated in the northwest of Uzbekistan and which has an arid continental climate (Suslov, 1961). The annual long-term average precipitation is 92 mm whereas the reference evapotranspiration (ET_o) is 950 mm (Mukhammadiev, 1982). Due to the arid climate, the difference between the crop water demand and precipitation needs to be covered by irrigation. The Amu Darya River is the sole source of irrigation water.

The land and water management reforms in Uzbekistan between 1996 and 2006 resulted in a shift of the agricultural production from large-scale *shirkats* (joint stock enterprises with 2000 ha and more) to smaller farms of on average 15.6 ha managed by individual farmers (Djanibekov, 2006). To supply farmers with irrigation water, 113 Water Users Associations (WUA) were established in the Khorezm region until 2006, which operate on the scale of the former *shirkats*. The WUAs are not only responsible for the water distribution, but also for socio-technical interventions.

For the present study, the Shomakhulum WUA in the southwest of Khorezm (Figure 2.1) was selected, since its environmental conditions are representative for the irrigated areas in Khorezm with respect to GW table and salinity, soil characteristics, cropping patterns and climate. In addition, the Shomakhulum WUA has distinct hydrological boundaries, which facilitates water monitoring, accounting and modeling. This WUA, together with the Tura-Vakil WUA in the Yangiarik district, had been chosen by the agricultural management authorities of Uzbekistan in 2005 for testing the introduction of water pricing.

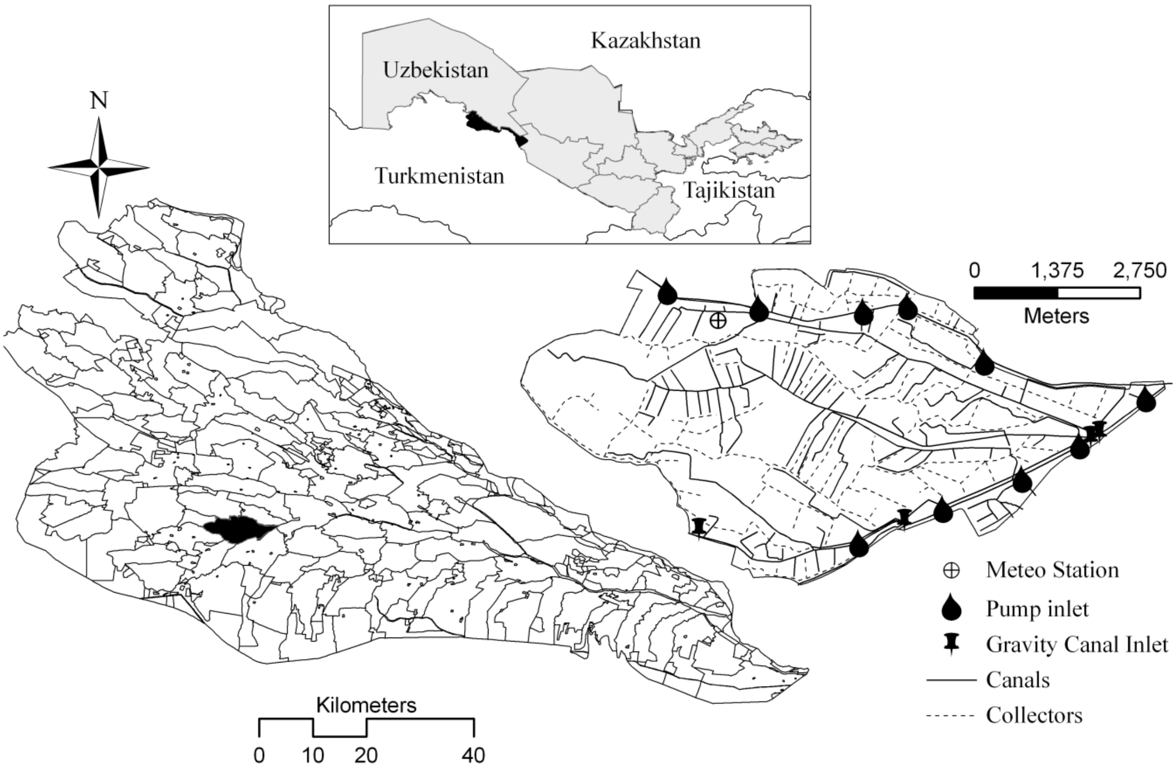


Figure 2.1 Shomakhulum Water Users Association, Khorezm region, showing irrigation and drainage system

2.2 Irrigation and drainage management in the Shomakhulum WUA

Water is provided to the WUAs by a network of irrigation canals. As canals are dug-in, the water needs to be pumped up into the main distributor canals of the WUA. However, depending on the topography, some farms receive the water directly from the dug-in canals. For example, about 66 % of the total water supply into the Shomakhulum WUA originates from the 10 lift irrigation schemes (pumps), whereas the remaining 34 % has surface water supply through gravity canals. The total length of the irrigation canals in Shomakhulum is around 156 km, and the density of the irrigation network is 83 m ha^{-1}.

An open horizontal drainage network is used to remove excess surface and groundwater from the area along with the salts, the latter especially stemming from leaching events prior to the vegetation season. The drainage network consists of laterals and collectors. The total length of the drainage system in the WUA is 101 km (drainage network density: 54 m ha^{-1}). Soils in the WUA are predominantly loamy to sandy loam according to USDA classification (GIS lab of ZEF/UNESCO project in Urgench). The GW level in the study area is shallow and ranges from 1.0–1.2 m below surface during leaching and irrigation events (Ibrakhimov et al., 2007). For monitoring the GW levels and salinity, the national authorities have installed 15 GW wells in the WUA. The so-called "Hydromelioration Expedition (*OGME*)" of the district is responsible for collecting the GW data of which copies are provided to the WUA office and Irrigation System Authority (*TEZIM)*.

The dominant irrigation mode is furrow irrigation. Cotton (cultivated on more than 50 % of the irrigated area) and wheat (22 % of the irrigated area) are the dominant crops in the WUA. Maize, vegetables and fruits are also grown. Before the irrigation season, the WUA officials determine the water demand of the entire irrigation scheme on decadal and seasonal bases. The crop water requirements (CWR) result from norms for different crops developed during Soviet times. These norms were established based on the so-called hydromodule zones. Hydromodules were established based on the characteristics of the factors that influence the net crop water requirements: climate, soil texture and groundwater levels. The reference evapotranspiration in the whole Khorezm region is considered uniform, and therefore soil texture and GW levels were the dominant factors for developing a total of nine (I-IX) such zones. This is a generalized approach for the rough estimation of the GW contribution to crop water requirements. Forkutsa (2006) showed that variations of GW levels of a few centimeters can significantly affect the net crop water requirements. However, in this approach there is always a range of GW levels. For example, the hydromodule zones VII-IX show a range of GW levels from 1-2 m, which shows that the GW contribution at 1 m is similar to that at 2 m.

The objective of developing such zones was to provide a rough indication of potential water withdrawal from the main source (river and main canals). Moreover, GW levels during the last decades have changed from the levels in the 1960's (Ibrakhimov et al., 2007). Therefore, the water norms are outdated and need to be revised to improve the water use efficiency and irrigation schedules. This hydromodule zone approach has similarities to the approach of hydrological response units used today. To capture the spatial variability of soil texture and groundwater levels, i.e., factors that influence capillary rise and eventually net irrigation requirements, the hydrological response unit approach was used in this study. In this concept, detailed information on the dynamics of GW levels and soil texture with high temporal and spatial resolution were extracted. For this purpose, the more sophisticated tool ArcGIS was implemented (see Chapter 4).

Table 2.1 Groundwater levels in different hydromodule zones in Khorezm

Hydromodule zone	Groundwater level
I-III	Deeper than 3 m
IV-VI	2-3 m
VII-IX	1-2 m

Source: SAYUzNihi, 1992

Hydromodule zones VII and VIII were established. In the Shomakhulum WUA, these two zones correspond to sandy loam to heavy loam soils and 1-2 m GW levels (Table 2.1). The average crop water requirement (CWR) values based on the hydromodules for each crop in the WUA are used for determining net water requirements. The gross water requirement is then determined by summarizing the information related to cropping area, crop type, and irrigation efficiency. The gross water requirement is prepared by the officials working in the WUA office and reported to the sub-UIS (Irrigation System Management Organization), which is responsible for regulating the water entering into the WUAs. The sub-UIS reports the water requirements for the WUA to the UIS. The UIS is responsible for collecting the water requirements for all sub-UISs and for regulating the water in the magisterial canals that supply water to the canals. Finally, BUIS (Basin Management Department of Irrigation System) reports the water requirements for the whole irrigation system to the Ministry of Agriculture and Water Management and then regulates the water allocated by the ministry to the irrigation system.

3 IRRIGATION PERFORMANCE ASSESSMENT

3.1 Introduction

The Khorezm region of Uzbekistan is facing an increasing spatial and temporal water scarcity (section 1.2). The increasing unavailability of water is not only a problem in the region but also a growing issue worldwide. Bos et al. (2005) reported that until 2025, food production must grow by at least 40 % to meet the needs of a population that will have increased by 33 % and to satisfy the trends for improved nutrition. As land and water resources are finite, meeting the increasing demands sustainably depends on raising the efficiency of water use rather than increasing water withdrawals (Batchelor, 1999; Perry, 1996). Thus, quantifying the efficiency of water is a key to understanding the water availability, establishing appropriate strategies, reducing possible constraints in water resources and eventually to provide additional food and fiber for a growing and more affluent population (Bouwer, 2002; Hillel, 2000; Perry, 1999).

The scientific approach to evaluate irrigation schemes has undergone various modifications during the last decades. However, two aspects have been focused on since the late 1980's. Firstly, the use of a comprehensive assessment framework and secondly the necessity of quantification of spatio-temporal comparisons within an irrigation system, so-called compound measures (Small and Svendsen, 1990) or indicators (e.g., Gorantiwar and Smout, 2005). Irrigation performance indicators mainly cover the key aspects of equity, productivity, adequacy, reliability, and ecological sustainability with which the water is delivered to and used within the irrigation scheme (Bos et al., 1994; Murray-Rust and Snellen, 1993; Wolters, 1992). Different approaches, possibilities and challenges of using performance indicators were recently summarized by Bos et al. (2005), who distinguished between strategic and operational irrigation performance. Based upon the results of the operational irrigation performance, irrigation performance indictors facilitate developing the long-term strategic planning.

Developments in the application of remote sensing make it possible to extract information related to land and water resources management (Bastiaanssen, 1998; Menenti, 1990; Vidal and Sagardoy, 1995). While traditional methods formerly did not allow determining the water consumption parameters required for assessing irrigation performance, water consumption parameters across a region can now be calculated.

However, as some of the parameters required to assess the irrigation performance, e.g., irrigation and drainage water inflow and outflow, cannot yet be extracted through remote sensing, researchers are relying on secondary data (inflow and outflow needs to be measured) for irrigation performance assessment (Ahmad et al., 2009; Bastiaanssen and Bandara, 2001; Karatas et al., 2009).

The Khorezm region of Uzbekistan is geographically located at the lower reach of the Amu Darya River and can be seen as a model region for the irrigated Amu Darya lowlands (Martius et al., 2009). Since the collapse of the Soviet Union, there have been changes in the managerial infrastructure and management of land and water resources in Uzbekistan (Veldwisch, 2007), including the transformation of the former *kolkhozes* (collective farm enterprise) to new water user associations (WUA). The WUAs are not only responsible for the water distribution, but also for socio-technical interventions. These comprise the redistribution of land to families, increases in wheat area for food security, implementation of a quota system for cotton and wheat, changes in agricultural subsidies, and the dismantling of large collective farms (Abdullaev et al., 2008). The water allocation in the region is demand oriented, and hence the total water withdrawals from the Amu Darya River are based on the total water requirements of all WUAs. In this bottom-up water supply approach, WUAs are important. There are huge withdrawals of water from the Amu Darya River. However, the adequacy, equity and reliability of water allocation and water distribution in these subunits are always questionable.

The objective of the research was to develop an effective methodology for irrigation performance assessment of WUAs in Central Asia. Such methodology was developed for the irrigation scheme of one WUA in Khorezm i.e., Shomakhulum WUA, and can support strategic planning of interventions in the WUA. To increase the effectiveness of performance assessment and to reduce the errors, primary data were collected through remote sensing. To determine the actual inflow and outflow from the WUA, flow measuring stations were installed. The discharge from these stations was determined using discharge rating curves. Field-water balances were established to quantify losses from the field. Losses from canals were measured by ponding experiments. Water consumption variables, ET_a and ET_p were extracted through satellite remote sensing.

3.2 Materials and methods

3.2.1 Study area

The irrigation water in the region is supplied to the WUA through a network of 14 canals. Out of the 14 canals, 10 are ‘pump schemes’ (water needs to be pumped in order to flow from dug-in channels to fields higher up), and the remaining 4 are gravity canals (water flows following a gravity gradient; Figure 3.1).

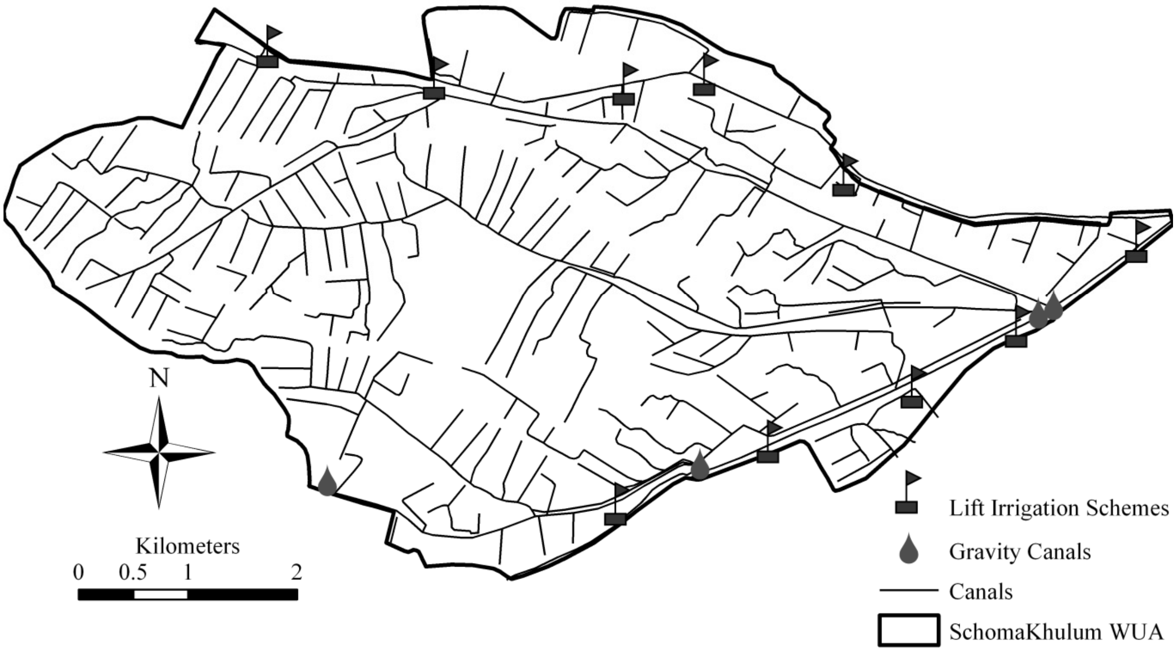


Figure 3.1 Water inflow points for lift irrigation schemes (pumps) and gravity canals in the WUA Shomakhulum, Khorezm, Uzbekistan

3.2.2 Monitoring the water balance components for the WUA Shomakhulum

Actual flow of water (V_c)

Irrigation water is supplied to the WUA through a network of 14 irrigation canals (4 gravity canals, 10 pump schemes). Daily seasonal inflow data at the inflow points of these 14 canals were provided by the WUA office. To cross-check the inflow data with the official information, four flow measuring stations were installed in major canals (Shomakhulum canal, Pakhtakiyar, Pump-1 and Pump-2), which supply more than 70 % of the irrigated area (Figure 3.2).

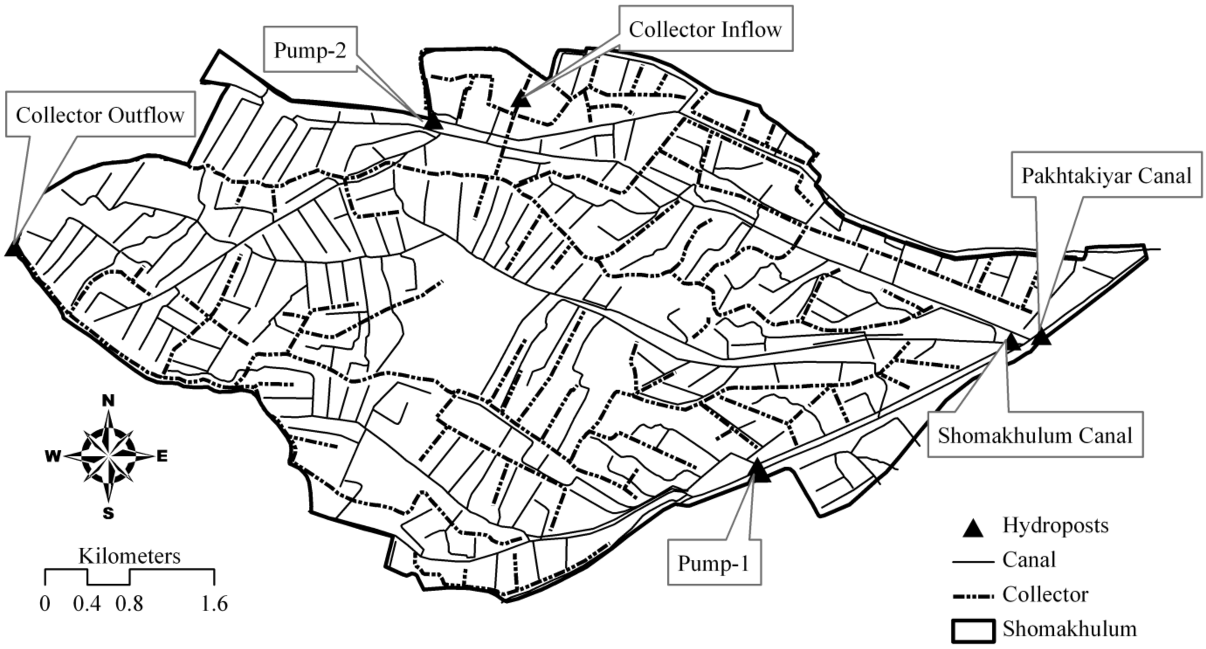


Figure 3.2 Flow measuring stations installed for determining the water balance in the WUA Shomakhulum

Stream-gauging technique was used to measure the actual flow of water from these canals. With this method, the height of water in a canal, known as stage or head, is used to determine the discharge or equivalent volume for the given period. To measure the head, automatic water level sensors (http://www.ecotech-bonn.de/en /produkte/hydrologie/pdlr-pdla.html) were installed in these canals. For different stages, the corresponding value of discharge was calculated from a discharge-water level function (rating curve).

Establishment of rating curves

As described above, rating curves are based on simultaneous measurements of water level and discharge covering the full range of discharge variation. The velocity-area method, which is the most practical method for measuring stream discharge, was applied in this study. Here, discharge is equal to the product of the cross-sectional area and the velocity. The cross sections were measured at all flow measuring stations from an assumed benchmark (a point of known elevation) before and after the vegetation season to determine the amount of sedimentation, which can disturb the relationship between the head values and the discharge. The width of the canals at the stations was divided into a number of subsections, each containing no more than 5% of the total discharge. For each subsection, canal depth and average velocity were measured. The current meter was placed at a depth where average velocity was expected to occur. Water depths lower than 1 m were multiplied by 0.6 times the total depth of the canal, and the current meter was placed at this depth to measure the average velocity. When depths were larger, the current meter was placed at a distance of 0.2 and 0.8 times the total depth of the canal (Buchanan and Somers, 1969). The product of velocity, depth and width of the section is the discharge through the respective subsection. The sum of the discharge amounts in the subsections equals the total discharge of the canal. As the main objective of the rating curve is to calculate the discharge for the stages that are not captured by a current meter, the equation for the best-fit-line was used for further discharge calculations. After knowing the discharge for each head and the time for which the canal operated at that head, the volumetric inflow was calculated. The volume of water was aggregated on a half-hourly, daily, monthly, and seasonal basis.

The officials of the WUA record water inflows on a daily basis and, therefore, the total volume of the water was also calculated on a daily basis and then compared to the official data. As actual inflows measurements were taken in the main canals, so these data were supplemented with secondary data contributed by the Shomakhulum WUA. The total discharge was calculated by adding the actual volume of water from all 14 inflow points.

Intended flow of water (Vi)

Intended flow of water or the amount of water supposed to be delivered to the irrigation system from the main canals for the 2007 vegetation season was determined from the dataset of the Shomakhulum WUA.

Actual and potential evapotranspiration using satellite remote sensing (ETa and ETp*)*

The quantification of actual evapotranspiration (ET_a) and potential evapotranspiration (ET_p) from irrigated schemes is important for water resources planning and regulation. Due to the restrictions in measuring ET_a and ET_p with traditional methods, it was almost impossible to measure the irrigation performance indicators involving ET_a and ET_p until a few years ago (Karatas et al., 2009). The development of remote sensing energy-balance models has made it possible to measure these parameters at different temporal and spatial resolutions. For this study, the Surface Energy Balance Algorithm for Land (SEBAL; Bastiaanssen et al., 1998) was selected for modeling ET_a and ET_p. The accuracy of the model was successfully validated by the use of lysimeters, scintillometers, Bowen ratio towers and eddy covariance systems (Bastiaanssen et al., 2005). The evaporative fraction (Λ) which is output of SEBAL is determined by the following equation:

$$\Lambda = \frac{\lambda E}{(Q^* - G_0)} = \frac{(Q^* - G_0 - H)}{(Q^* - G_0)} \qquad (3.1)$$

where Λ is evaporative fraction, Q* is the instantaneous net radiation (W/m2), G_0 is instantaneous soil heat flux (W/m2), H is instantaneous sensible heat flux (W/m2) and λE is instantaneous latent heat of vaporization (W/m^2). The actual evapotranspiration (ET_a) is calculated by converting the daily net radiation (Rn24) from W/m^2 to mm per day using the T_0 dependent latent heat of vaporization:

$$\mathrm{ET_a} = \Lambda \times Rn24 \times 86400 \times 10^3 [(2.501 - (0.002361 \times T_0)) \times 10^6]^{-1} \qquad (3.2)$$

where ET_a = evapotranspiration (mm per day), Rn24 = average daily net radiation (W/m^2 per day) and T_0 is the surface temperature (K).

The potential evapotranspiration of a crop can be achieved when there is no restriction due to either biological control or soil water content, which in practice corresponds to the well-watered condition of a crop (Bandara, 2003). Here, ET_p was estimated using the Penman-Monteith equation (Allen et al., 1998; Monteith, 1965; Rijtema, 1965; Smith, 1992) and 24-h net radiation values derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) data (Bastiaanssen and Bandara, 2001).

SEBAL applications require thermal remote sensing data. In principle, sensors exists that record thermal information at high resolution such as Landsat 7 (60 m) or ASTER (90 m), which allow ET_a modeling at field level. However, multi-temporal data are necessary for estimates of seasonal ET_a, but these were not available for 2007. To cover the entire season, imagery recorded by MODIS on NASA's Terra satellite with a spatial resolution of 1 km was used. Beside thermal overpass data, MODIS products representing 8- and 16-day periods were downloaded from the LPDAAC website /https://lpdaac.usgs.gov. The products used for SEBAL included MOD11L2 (land surface temperature, overpass data), MOD13A2 (normalized difference vegetation index), MOD15A2 (leaf area index), and MOD09Q1 (surface reflectance) (Table 3.1). Using the HDF-EOS to GeoTIFF Conversion Tool (HEG), these products were re-projected and gridded into 1 km resolution. However, only seven images free of clouds were available for the study area in the whole vegetation period (2007).

Table 3.1 Overview over the satellite overpasses selected for modeling ET_a and ET_p using SEBLA

Data set	Layer	Spatial Resolution	Temporal resolution	Linear interpol.
MOD11L2	LST	1 km	overpass	No
MOD13A2	Vegetation Indices	1 km	16day	Yes
MOD15A2	LAI	1 km	8day	Yes
MOD09Q1	Surface Reflectance	250 m	8day	Yes

Total drained water from the area (V_{dr})

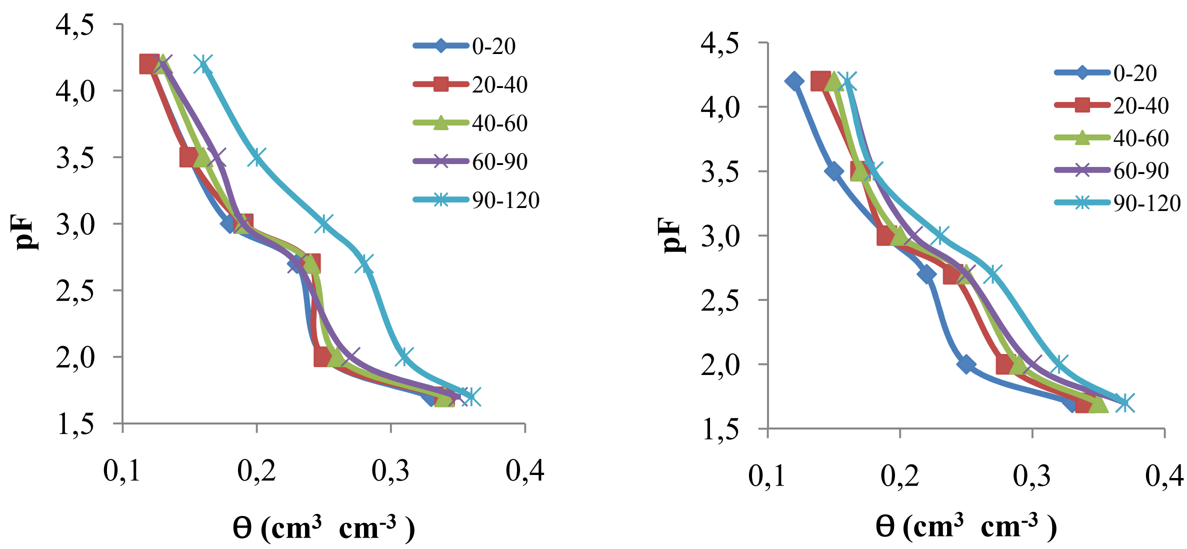
A network of open field drains exists in the study area. The water from these open drains is collected in a large collector that takes the drainage water out of the area. However, the drainage water from one collector outside the WUA enters into this large collector. Therefore, to determine the total water drained out from the WUA, it was necessary to also determine the discharge from this inflow collector. For this purpose, two flow measuring station were established, i.e., one at the inflow collector and another at the outflow collector. The volume of water from these stations was measured in the same way as the inflow of water into the area through the irrigation canal (described above).

Field experiment for identifying field application ratio (FAR)

Two farms in Shomakhulum having different but representative GW levels, soil textures and cropping patterns were selected to measure FAR. Farm-1 had a total area of 13 ha, where cotton and different sorts of vegetables were grown on 9 and 4 ha, respectively. On Farm-2 (10.1 ha), cotton and wheat were cultivated on 6 and 4.1 ha, respectively. Five irrigation events were monitored to determine FAR. At the main inflow point of each farm, 2-m-long uniform concrete cross sections with a width of 1 m were constructed to facilitate the discharge measurements. Inflow was measured using the stream gauge technique as described above.

The required amount of water for each irrigation event was measured using the water balance approach. The required amount of water is equal to the difference between the field capacity and the soil moisture prior to irrigation.

To establish the characteristic soil moisture curve for determination of field capacity and permanent wilting point, two pits of 1 m^3 volume were dug in the middle of each farm. From these pits, soil samples were taken from 0-20, 20-40, 40-60, 60-90 and 90-120 cm depths. The samples were analyzed to establish the retention curve for soil moisture characteristics using the Richards pressure membrane method (Klute, 1986b). Soil bulk density was determined according to the method by Blake and Hartge (1986). The analyses were carried out by the Central Asian Scientific Research Institute of Irrigation (SANIIRI) laboratory in Tashkent (Figure 3.3). The average bulk density at Farm-1 was 1.5 g cm^{-3} and at Farm-2 it was 1.46 g cm^{-3}.



(a) (b)

Figure 3.3 Soil retention curve for (a) Farm-1 and (b) Farm-2

Soil texture was measured using the gravimetric method (Loveland and Whalley, 2001) from the same depth at 16 spatially distributed locations. The dominant soil texture at Farm-1 is loamy and at Farm-2 sandy loam. Samples for soil moisture, determined by the gravimetric method on a dry basis, were taken one day before and 4 to 6 days after the irrigation events depending on the soil moisture status on the farms. In the center of each farm, wells were installed to monitor the changes in GW. The GW level at Farm-1 and Farm-2 ranged from 1.5 to 2 m and 2 to 3.5 m, respectively.

Ponding experiments to determine the conveyance losses in the irrigation network

During the monitoring program, three hierarchies of canals (inter-farm, farm and field canals) in the WUA Shomakhulum were observed. Therefore, the losses in the whole irrigation network of the WUA can be mathematically expressed as:

$$TLIN = LIFC \times LFC \times LFdC \tag{3.3}$$

where TLIN is total losses in the irrigation network (%), LIFC is losses in inter-farm canals (%), LFC is losses in farm canals (%), and LFdC is losses in field canals (%). Values in % refer to the design discharge for each hierarchy.

The ponding method was used to estimate the conveyance losses through seepage of six different canals. Two experiments were conducted in inter-farm canals (Site-1 and Site-2), three in farm canals (Site-3, Site-4 and Site-5) and one in field canals (Site-6). The selection of canals was based mainly on the hierarchy of the canals. However, another important factor affecting canal seepage is the permeability of the soil immediately below the wetted perimeter of the canals (Rohwer and Stout, 1948). To classify the soil texture, soil samples were taken from three different locations near the canals from 0-15, 15-30, 30-60, 60-90 and 90-120 cm beneath the soil surface till the GW level was reached. Therefore, the replication within one canal hierarchy was performed where soil texture was found to be different.

Experiments were conducted in accordance with the guidelines suggested by Rohwer and Stout (1948). In each canal reach, uniform canal segments were selected for the experiments. The length of the ponds varied from 40-120 m depending on the hierarchy of the canals, water filling capacity, easiness of dam construction, and uniform lengths. Nevertheless, the ponds were long enough to make the sum of the pond end areas a very small percentage (not more than 3%) of the total wetted area. After selecting the segments, embankments were built on both sides of the canals. Using an excavator, spades and wooden sticks, barriers were constructed, compacted, lined with plastic sheets and covered with soil to prevent seepage. After filling the pond with water, a survey was done to determine whether there was any seepage.

In earthen canals, it is difficult to find a classic cross section with a typical geometric shape. To describe the geometry of the canal segments, a relatively complicated approach was applied for all the ponding sites in this study to obtain more accurate results. With this approach, the most representative cross section in the ponds was selected. To describe the shape of the cross sections, elevation points were taken at each 25 cm segment. A best-fit trend line was added to the surveyed points to find the polynomial equation for calculating the geometric components of the pond. Using the coordinates (x,y) of the polynom developed for the cross sections of all the ponding sites, the wetted perimeter was determined for each 1-cm depth with the aid of Pythagoras theorem, and the results were added together.

Data loggers were installed in the middle of each test reach to record changes in water levels in 5-min intervals. In areas with shallow GW tables, confirmation of the GW level is very important because GW levels have a direct influence on seepage rates (Bouwer, 1969). Therefore, three observation wells about 20 m, 5 m and 10 m apart were installed to monitor GW fluctuation.

To determine the longitudinal slope of the canals, profile surveys were taken with an engineering level. Observation wells, data loggers in the middle of the pond, cross sections of the pond and longitudinal slope were surveyed in one local system of elevation. Using this information, losses were determined for each canal reach and used to adjust the evaporation and rainfall for net seepage measurements. The seepage rates were then related to wetted area. Brockway and Worstell (1968), ICID (1967), Kraatz (1977), Byrnes and Webster (1981), Wachyan and Rushton (1987), Frevert and Ribbens (1988) and McLeod (1993) recommended representing seepage findings with respect to wetted area.

3.2.3 Calculation of performance indicators

To assess the operational performance of the irrigation scheme, first the targets of the performance assessment need to be formulated (Bos et al., 2005). Then the appropriate performance indicators need to be selected from comprehensive lists provided, e.g., in the ICID guidelines (ICID, 1978). The rationale for selecting these indicators includes the feasibility of taking measurements, the accuracy of measurements and the cost effectiveness (Bandara, 2003). In this study, the performance assessments mainly targeted water availability and water use efficiency at both systems and field scale. Furthermore, water distribution was investigated at different levels in the canal system. Therefore, delivery performance ratio (DPR), relative evapotranspiration (RET), depleted fraction (DF), drainage ratio (DR), overall consumed ratio (OCR), field application ratio (FAR) and conveyance ratio (CR) were selected as performance indicators. These indicators are based on the components of the water balance (see section 3.2.2). The following subsections define the indicators and then describe the methodology for determining the parameters used in these indicators.

3.2.4 Delivery performance ratio (DPR)

The delivery performance ratio (DPR) is an indicator used to assess the reliability of the water distribution in the irrigation scheme. Bos et al. (1991); Clemmens and Bos (1990) and Molden and Gates (1990) rated it as the most important indicator for the operational performance of the water distribution in the irrigation scheme. It is defined as:

$$DPR = \frac{V_c}{V_i} \tag{3.4}$$

where Vc is actual flow of water, and V_i is intended flow of water.

3.2.5 Relative evapotranspiration (RET)

Relative evapotranspiration (RET) is an indicator used to assess the reduction in ET and evaluate the adequacy of irrigation water delivery to a selected command area (Perry, 1996). It is defined as:

$$RET = \frac{ET_a}{ET_p} \tag{3.5}$$

where ET_a = actual evapotranspiration and ET_p = potential evapotranspiration.

3.2.6 Depleted fraction (DF)

The depleted fraction (DF) indicates the changes in actual crop water use in relation to the available water, and is useful for diagnostic purposes in water-scarce areas. It is defined as (Molden and Sakthivadivel, 1999):

$$DF = \frac{ET_a}{V_c + P_e} \tag{3.6}$$

Where ET_a is actual evapotranspiration of the gross command area (including uncultivated land within the hydrological boundaries of the observed irrigation system), Pe is effective precipitation (Dastane, 1978) within the gross command area, and Vc is volume of surface water flowing into the command area and is equal to the actual flow of water.

In poorly drained areas, DF furthermore indicates the risk of rising GW levels and soil salinity (Bos et al., 2005).

3.2.7 Drainage ratio (DR)

The degree to which the supplied water is consumed in an irrigation scheme is defined as drainage ratio (DR) and is also useful for diagnostic purposes. It is defined as (Bos et al., 1994):

$$DR = \frac{V_{dr}}{V_c + P_e} \tag{3.7}$$

where V_{dr} is the volume of water drained from the area.

During long-term observations of a catchment, DR and DF should sum up to 1 (Bos et al., 2005). In irrigation systems with shallow GW tables, this value can be used as an orientation to assess the variations of the GW level and therefore the risk of soil salinization.

3.2.8 Overall consumed ratio (OCR)

The overall (or project) consumed ratio (OCR) quantifies the degree to which the crop irrigation requirements are met by irrigation water in the irrigated area (Bos and Nugteren, 1974). The ratio allows, among others, evaluations of the overall system efficiency and is defined as:

$$OCR = \frac{ET_p - P_e}{V_c} \tag{3.8}$$

where ET_p is potential evapotranspiration (see section 2.2.1.), and Pe is effective precipitation.

3.2.9 Field application ratio (FAR)

The field application ratio (FAR) is the measure of water losses in the field. This efficiency indicator is defined as (ICID, 1978):

$$FAR = \frac{ET_p - Pe}{Volume\ of\ water\ delivered\ to\ the\ field} \tag{3.9}$$

where ET_p is the volume of water required by a specific crop.

3.2.10 Conveyance ratio

The classical definition of conveyance ratio is the water balance of a canal (Bos et al., 2005). The water delivered to the canal either reaches the field or is lost through evaporation and seepage and eventually by overflow into the drainage system.

3.3 Results and discussion

3.3.1 Water balance of the WUA Shomakhulum

For assessing the operational performance of the WUA, the water balance components actual inflow, intended inflow, total outflow, actual and potential evapotranspiration and precipitation were used (Table 3.2).

Table 3.2 Water balance components for Shomakhulum water users association during the 2007 vegetation season

Month	Actual inflow (mm)	Intended inflow (mm)	Total outflow (mm)	Actual ET (mm)	Potential ET (mm)	Precipitation (mm)
April	94	84	101	35	85	41
May	246	148	154	118	138	4
June	245	242	115	191	175	9
July	451	308	247	104	164	1
August	456	255	219	124	140	0
September	97	110	45	89	102	0
Seasonal	1589	1147	881	661	804	55

Actual inflow of water

Flow of water is a product of the cross-sectional area of the canal and the velocity with which water is passing through this cross-section (Figure 3.4). The uniform cross section of the Shomakhulum canal at Pump-1 and Pump-2 is due to the fact that flow measuring stations were established where water management authorities had constructed the concrete trapezoidal infrastructure to facilitate the discharge measurements. The irregular shape of the Pakhtakiyar canal is due to the earthen cross section at this flow measuring station.

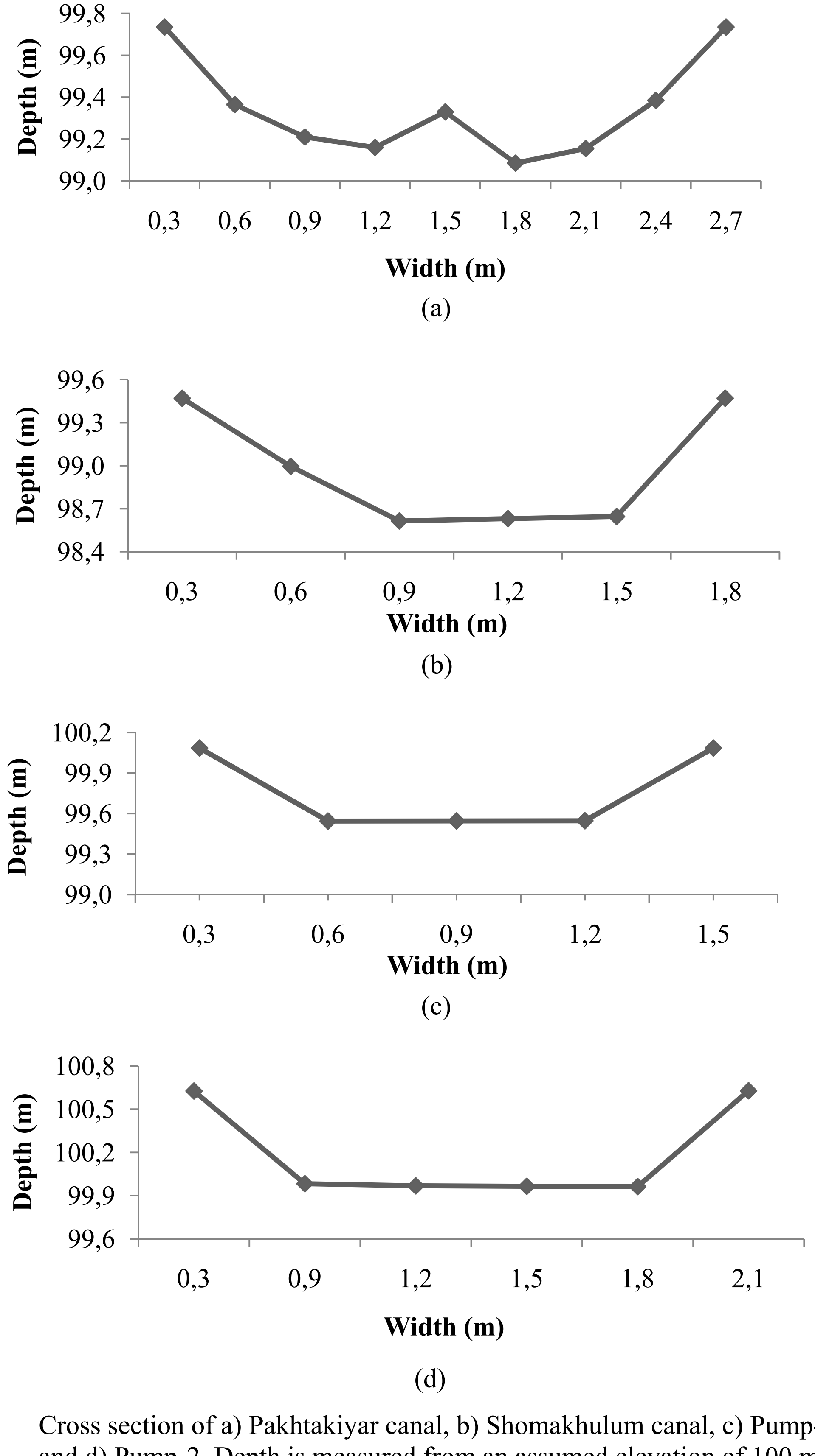


Figure 3.4 Cross section of a) Pakhtakiyar canal, b) Shomakhulum canal, c) Pump-1 and d) Pump-2. Depth is measured from an assumed elevation of 100 m a.s.l

For the Pakhtakiyar canal, Shomakhulum canal and Pump-1, the logarithmic curve was selected as the best-fit line with coefficient of determination (R^2) as 0.71, 0.9 and 0.84, respectively. The polynomial equation of power 4 was used as the best-fit line for Pump-2 (Figure 3.5).

The rating curves of the Pakhtakiyar and Shomakhulum canals show a typical trend, whereas the curves for Pump-1 and Pump-2 are much smoother. The small variation in the discharge values for Pump-1 and Pump-2 is due to the fixed discharge capacity of the pumps. For example, the discharge capacity of Pump-1 is 0.4 m^3 s^{-1}. The graph shows that the pump mostly operated near to full capacity. However, the variation in discharge values for these pumps is due to the low water levels in the main canals. During the field measurements, it was also observed that the condition of most of the pumps was very poor. The metallic tubes were rusty and had holes that allowed air to enter the suction chamber. Farmers use mud and cloths to prevent this, but are not always successful, thus the lower discharge values.

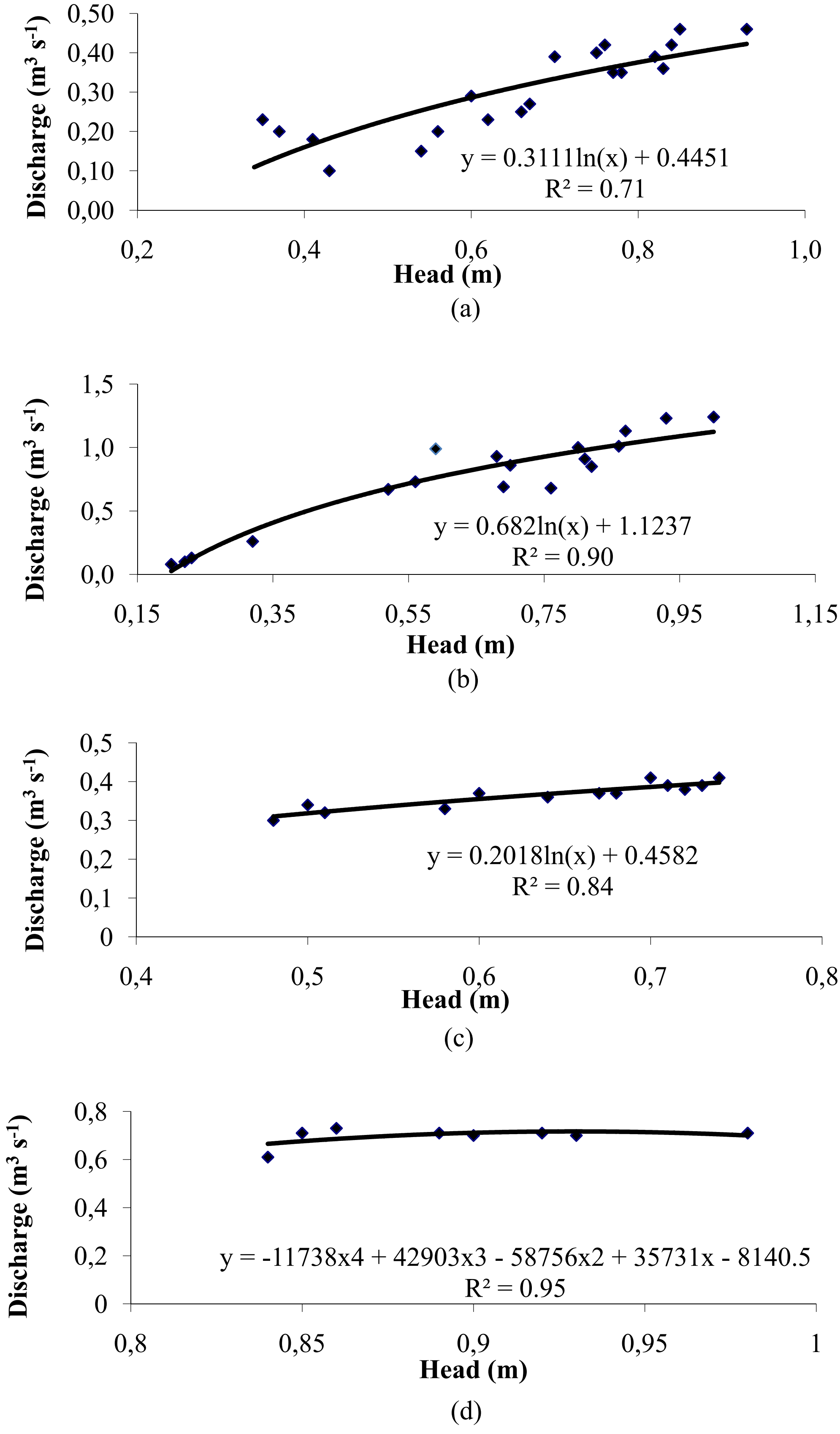


Figure 3.5 Discharge versus head relationship for a) Pakhtakiyar canal, b) Shomakhulum canal c) Pump-1, d) Pump-2

The rating curves show that the months of July and August are the peak season of irrigation with the highest water inflows, while the low discharge values in April and September are due to low crop water requirements (Table 3.2).

The monthly comparison between the monitored volume and the official figures of the total amount of water entered in the WUA during the 2007 vegetation season shows clear discrepancies (Figure 3.6). For the whole season, the WUA officials recorded 29 % less water than actually entered the WUA. Similar observations were made by Conrad et al. (2007).

To compare the inflow of water on a daily basis at the flow measuring station and the inflow reported by the officials of the WUA, the Shomakhulum canal, i.e., the main gravity canal providing water to around 460 ha of the irrigated area, was selected (Figure 3.7). August was selected as an example because the water withdrawals from the canal are highest during this month. Here also clear discrepancies were observed. The WUA officials recorded 43 % less water than actually entered the WUA. The trend is the same for the other months.

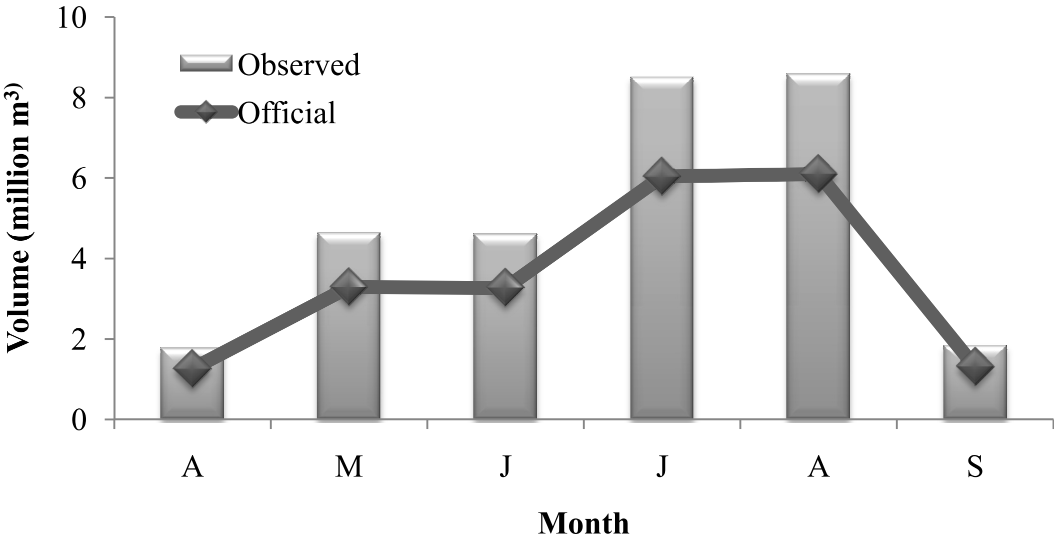


Figure 3.6 Total daily inflow into the WUA (million m^3) during the 2007 vegetation season as reported by the WUA compared to measurements at the installed flow measuring station

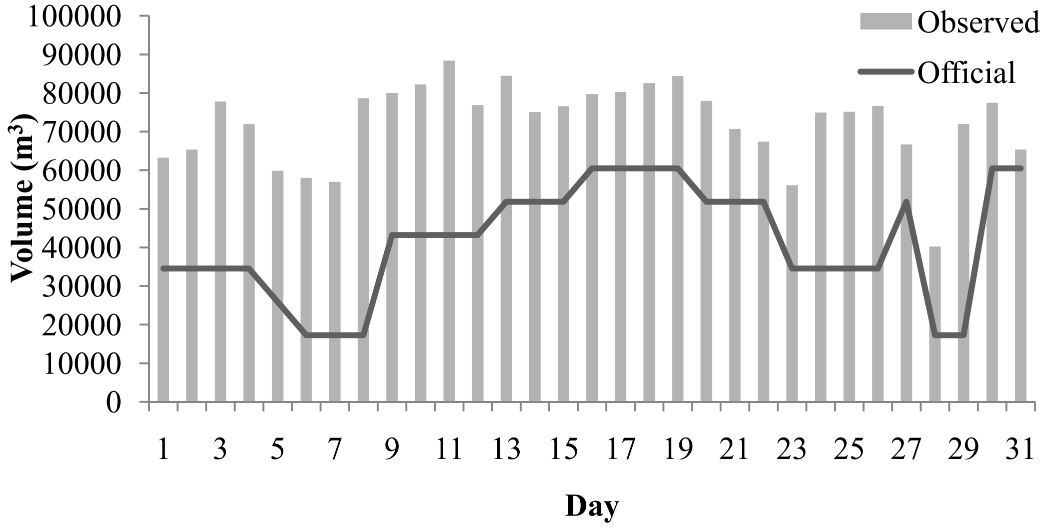
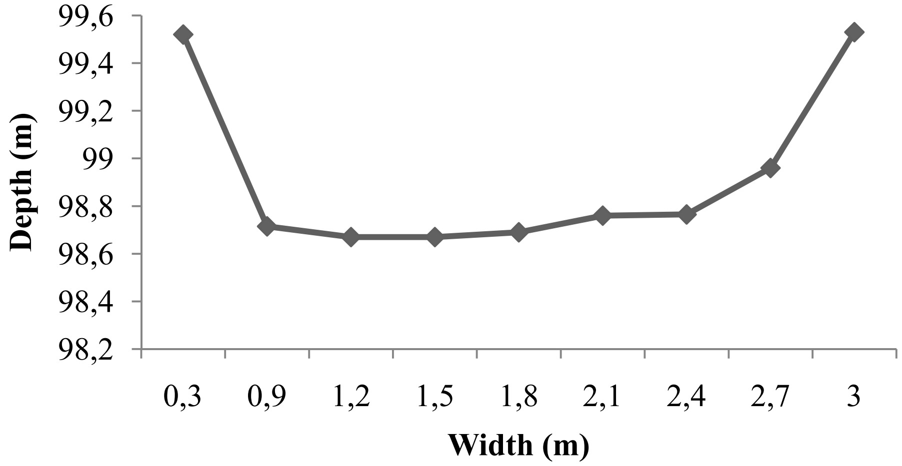


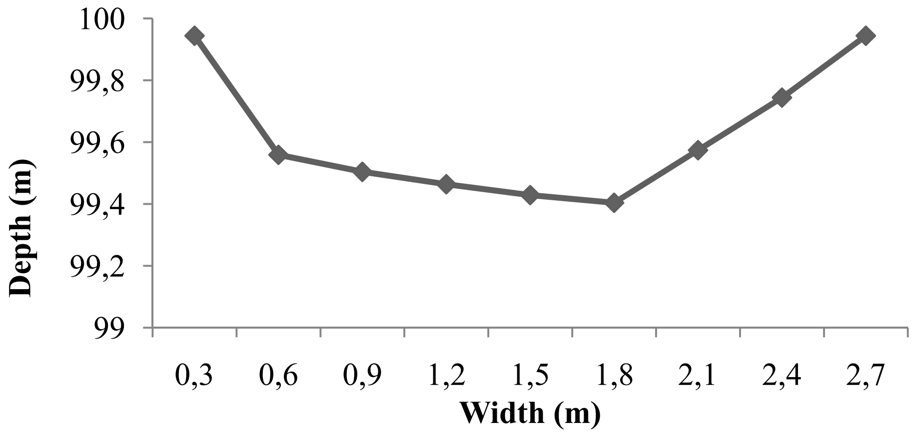
Figure 3.7 Daily inflow (m^3) for Shomakhulum canal in August as reported by the WUA compared to measurements at the installed flow measuring station

Total outflow from the WUA

Figure 3.8 depicts the cross section of the outflow and inflow collectors. These are both irregular in shape. The outflow collector is quite deep with approximately 85 cm, whereas the inflow collector is only 50 cm deep.



Outflow collector



Inflow collector

Figure 3.8 Cross-section of outflow and inflow collectors. Depth is measured from an assumed elevation of 100 m a.s.l.

Figure 3.9 represents the rating curves for both collectors. The logarithmic curve describes the best-fit line with coefficients of determination (R^2) of 0.93 and 0.77 for the inflow and outflow collector, respectively.

By using these rating curves, the volumetric outflow (subtracting the inflow of drainage water from the total outflow) for the vegetation season 2007 was determined (Table 3.2). Results show that the maximum outflows are during the months of July and August due to the peak season of irrigation (see section 3.3.4).

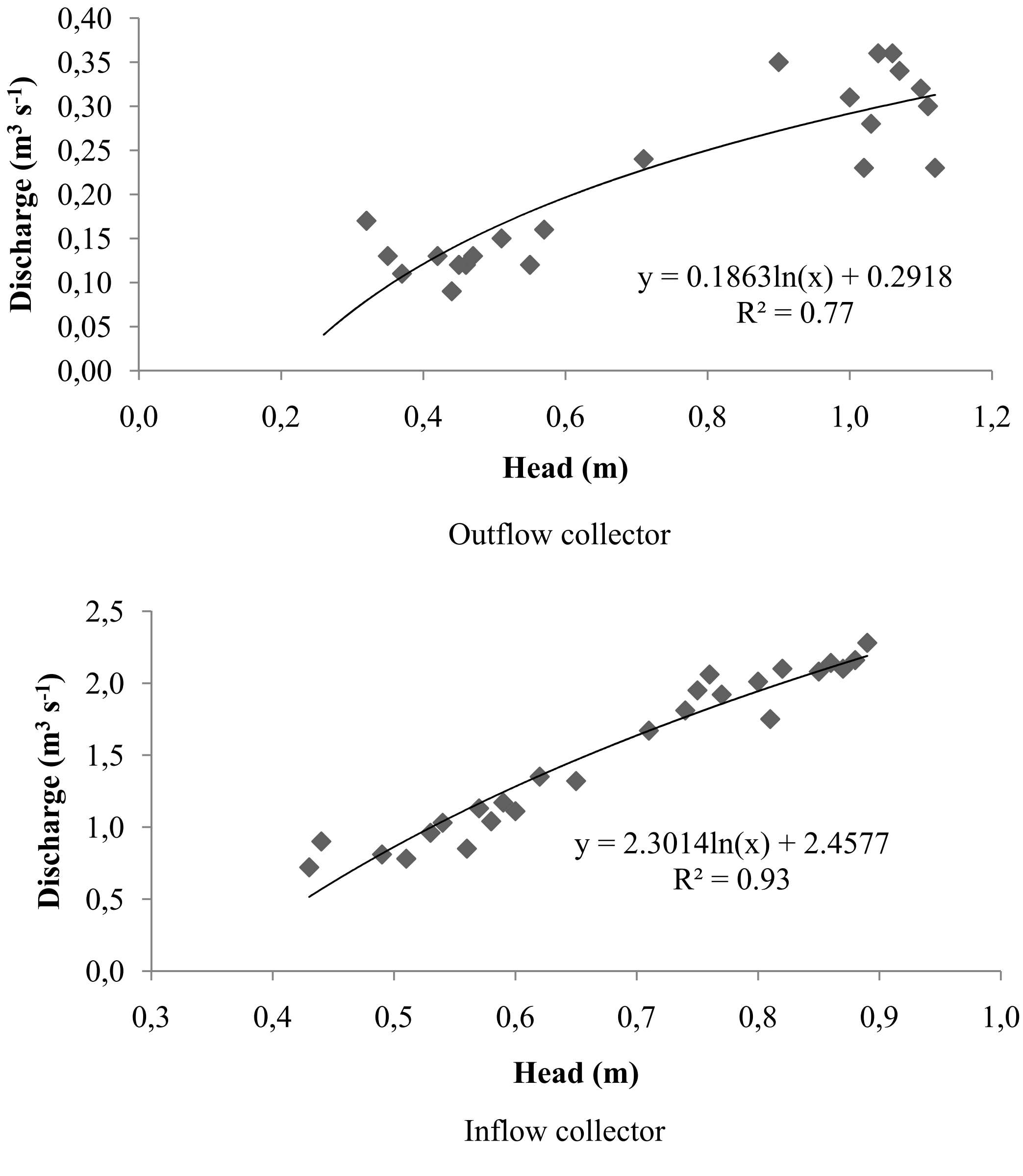


Figure 3.9 Discharge versus head relationship for outflow and inflow collector

3.3.2 Irrigation performance assessment indicators

The performance assessments for the Shomakhulum WUA focused on i) water availability at system boundaries and at field level, ii) water distribution within the system, and iii) water use efficiency at both field and system level.

Relative evapotranspiration (RET), which is an indicator for the adequacy and equity of water delivery, is discussed below using information on the supply of water delivered from the source against the intended delivery performance ratio (DPR).

High efficiency of water distribution is usually accompanied by low losses from the system and vice versa. The depleted fraction (DF) describes the overall efficiency of the irrigation project, while drainage ratio (DR) is a measure of the losses from the irrigation project. Thus, DR and DF were analyzed together (section 3.3.4).

Overall consumed ratio (OCR) as the product of field application ratio (FAR) and conveyance ratio (CR) cannot be assessed correctly without tracking FAR and CR (section 3.3.4).

3.3.3 Relative evapotranspiration and delivery performance ratio

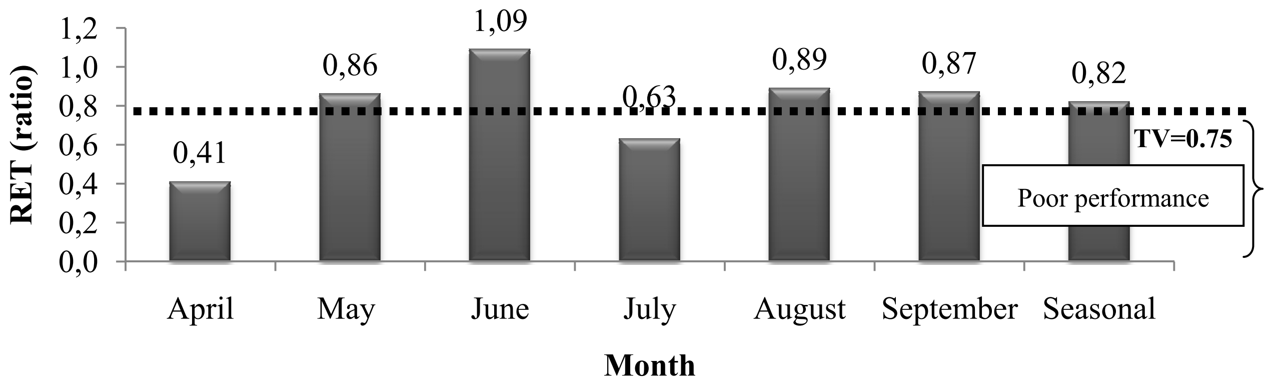
Bandara (2006) suggested starting the evaluation of an irrigation scheme with an analysis of the RET to reveal the status of the current water situation in the field in relation to the potential water needs. The RET in the study area, calculated on a monthly basis for the vegetation season 2007, in general meets the target value for all the months except April and July (Figure 3.10a). The RET exceeding the value of 1.0 in June indicates that the actual evapotranspiration is higher than the potential evapotranspiration, which is not possible in reality. The error can be due to canals in the pixels. The low RET values in April and July may have been caused by a relatively low water supply at the system boundaries in contrast to on-field crop water requirements. Therefore, the DPR was critically reviewed.

The DPR (Figure 3.10b) shows that the water supply generally exceeds the demand, as monthly DPR values are always above the target value except in September. One of the reasons for higher DPR during almost the whole season could be the shift of the cropping plan from low-water-demand crops to the high-water-demand crops. This shift can underestimate the intended flow of water and thus lead to a higher DPR.

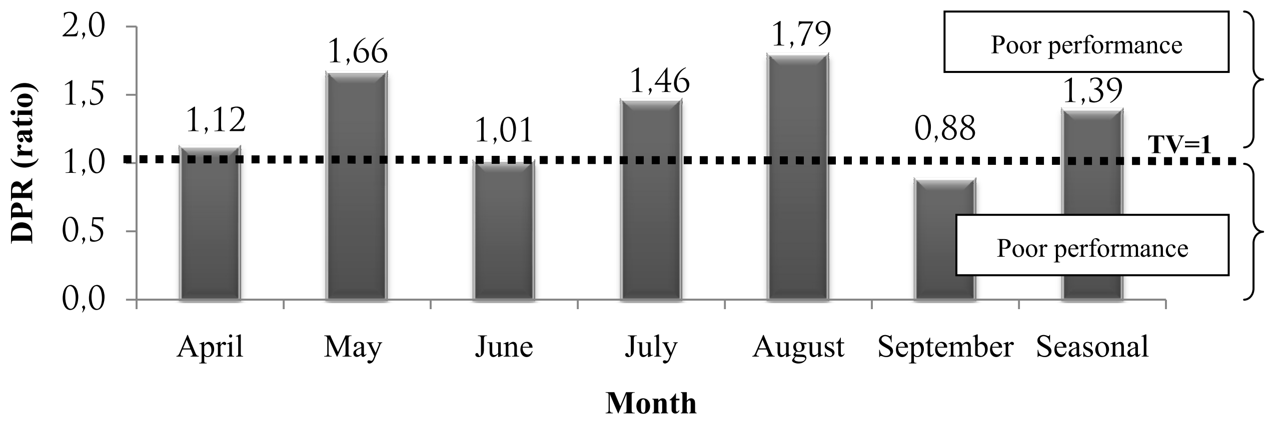
However, when the cropping plan and the water demand data were checked with the officials, there was no such shift of water demand throughout the season.

Therefore, despite a sufficient water supply, the low RET as reported mainly for April and July can be due to three reasons (Bandara, 2006): i) part of the delivered water is drained out from the canal system during the vegetation season (by direct linkages between the irrigation canals and drainage collectors), ii) part of the delivered water retained in the cropped area is discharged into the drains during application, and iii) low application efficiency.

All these cases have been observed in Khorezm, as in other parts of the world, e.g., in Sri Lanka (Bandara, 2006). In Khorezm, the farmers drain the water out from the rice fields to decrease the temperature of the soil and water and to reduce the risk of infection of the rice stem by fungi. The survey of several canals during the vegetation season revealed that most of the canals end in drains, which is a clear indication that fresh water may be directly channeled to the saline drainage collector. The reasons for directing the canal water into the drains is both poor operational and technical problems. The water supply through the pumps is not flexible, with an average discharge of 0.5 m^3s^{-1}. A group of 4-5 farmers is supposed to share this water. But conversations with the farmers revealed that collective use of water is hardly implemented in Khorezm. A group of farmers seldom agrees to irrigate their neighboring fields at a specified time. Thus, given the fixed pump discharge parameter, more water than needed is pumped into the canal. In addition, inappropriate canal design forces the farmers to discharge the water into the drains to protect the earthen canals against the high discharge. Abdullaev (2009) reported that water distribution approaches should be revised with greater consideration of water users' demands to make water use more efficient, i.e., technical solutions should be integrated in the social context. By improving the marginal factors such as pump capacity, freshwater losses can be avoided, and thus efficiency increased.



(a)



(b)

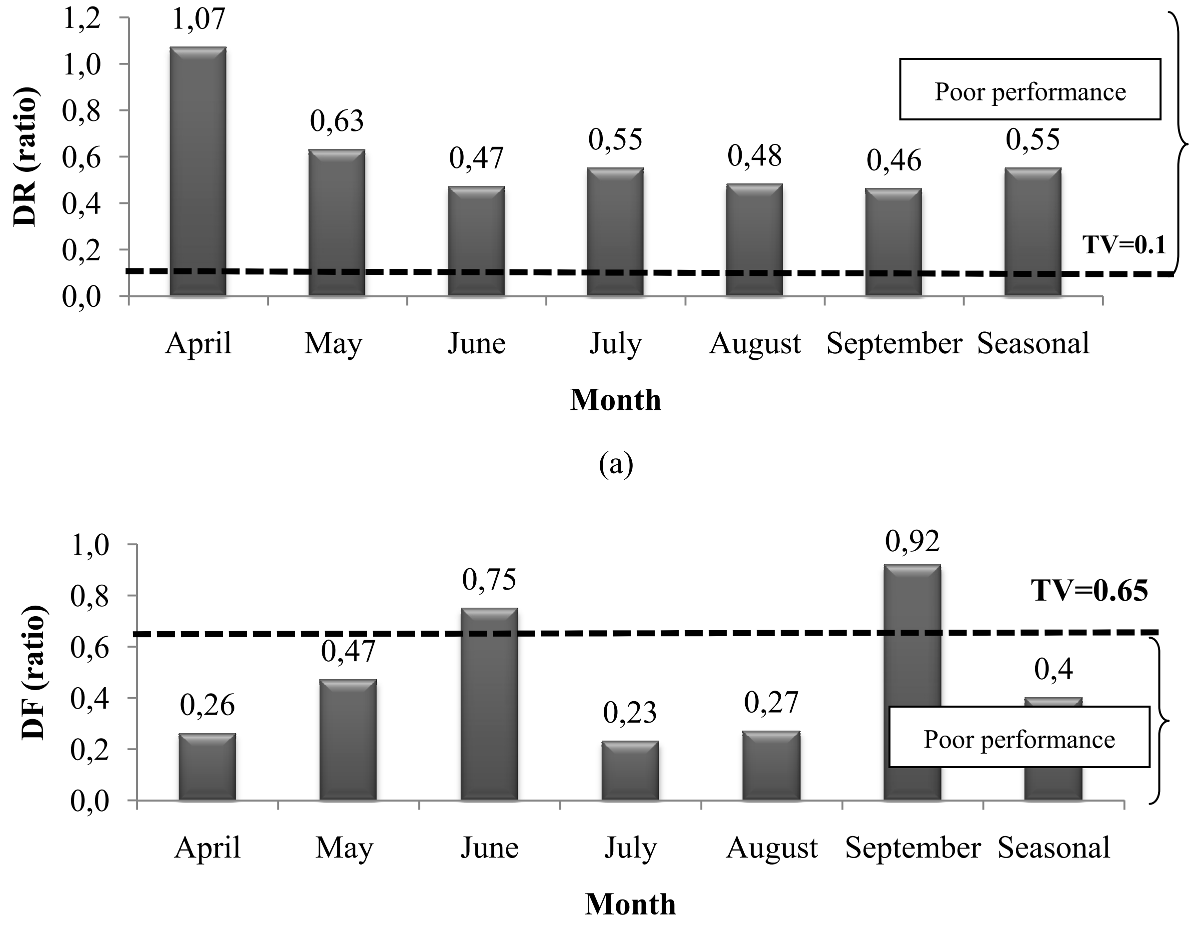
Figure 3.10 Behavior of performance indicators during the 2007 vegetation season in Shomakhulum WUA: a) relative evapotranspiration (RET) and b) delivery performance ratio (DPR)

3.3.4 Drainage ratio and depleted fraction

As described above, RET and DPR indicate discrepancies in water availability at the levels of system boundaries and fields. Especially the RET in April and July (Figure 3.10a) shows inefficient water distribution. The performance indicators DR and DF were also calculated to track and assess the water distribution (Figure 3.11a and Figure 3.11b). The DR in the beginning of the season is much higher than the target value, especially in April. The excessive leaching before the season increases the GW level and hence the outflows. This corresponds with the results of research at higher water distribution levels in Khorezm (Conrad et al., 2007). Both the delay of GW flow to the drains and the relatively low velocities in the drainage system reduce the drainage outflow from the scheme. Relating the delayed drainage discharge to the low irrigation inflows in April explains why the DR exceeds the value of 1. During July and August, again high amounts of water are supplied to meet the crop water requirements. In this 2-month period, actual water inflows are almost the same, but the DR is higher in July than in August. Surveys of the drains revealed that farmers start blocking the drains in periods of high water demand to retain soil moisture in the root zone, and therefore the drainage outflows decreased in August. The drains are blocked by dams either in the field drains or in the collector. The increased drainage amount against a low water supply recorded in September confirms this situation (blockage of drains). The situation in September underlines the role of GW contribution for irrigation in Central Asia, which was also reported by Forkutsa (2006), Forkutsa et al. (2009) and Conrad et al. (2007) for the Khorezm region, and by Pereira et al. (2009) for irrigation systems in the upstream region of the Syr Darya River. Obviously, the aforementioned management problems at farmers level and an inadequate infrastructure are responsible for low RET and simultaneously high DR in July.

Depleted fraction (DF) also reflects the underestimation of the GW contribution (Figure 3.11b). The DF is below the target value most of the season, which indicates the wastage of water. Decreasing DR will lead to rising GW tables, which increase the risk of soil and GW salinity (Bos et al., 2005). The latter has been reported for the Khorezm region by Ibrakhimov et al. (2007). The DF is only satisfactory in June and September because of the low inflow during these months. Moreover, low DR and high DF show that water was efficiently used in June. But the higher DF and DR found for September shows that the excessive water accumulated in the system during July and August either by excessive water supply or by blockage of drains is released in this month from the system. Altogether, the DR and DF perform poorly during the vegetation season and highlight the necessity of restructuring water distribution and adapting the infrastructure to the situation after the land reforms.

The sum of the DR and DF should be near to 1.0 to close the water balance. Over the entire vegetation period, the DF and DR sum up to 0.95, which is close to the target value 1. On the other hand, the values indicate an increased amount of water in the system after the vegetation season. However, only long-term observations (summer and winter season) and quantification of lateral flows would reveal a complete view of the drainage situation in the WUA.



(a)

(b)

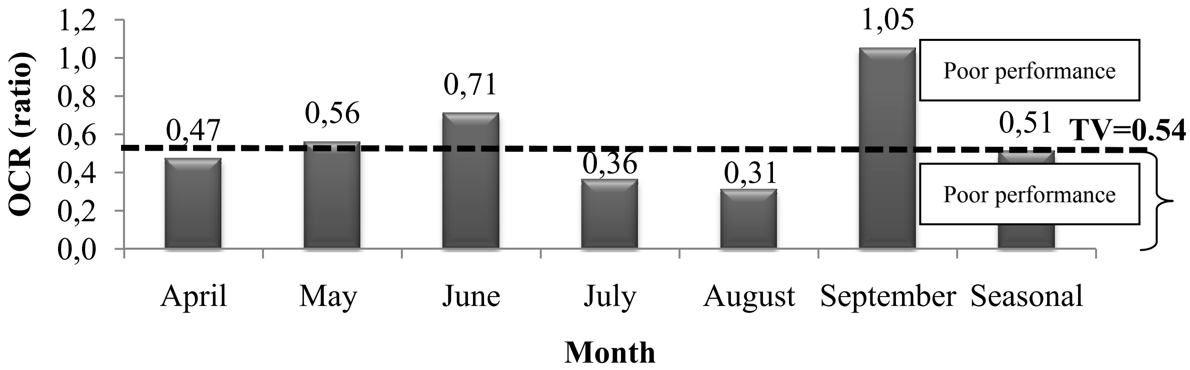
Figure 3.11 Behavior of the performance indicators during the 2007 vegetation season in Shomakhulum WUA: a) drainage ratio (DR) and b) depleted fraction (DF)

3.3.5 Overall consumed ratio, field application ratio and conveyance ratio

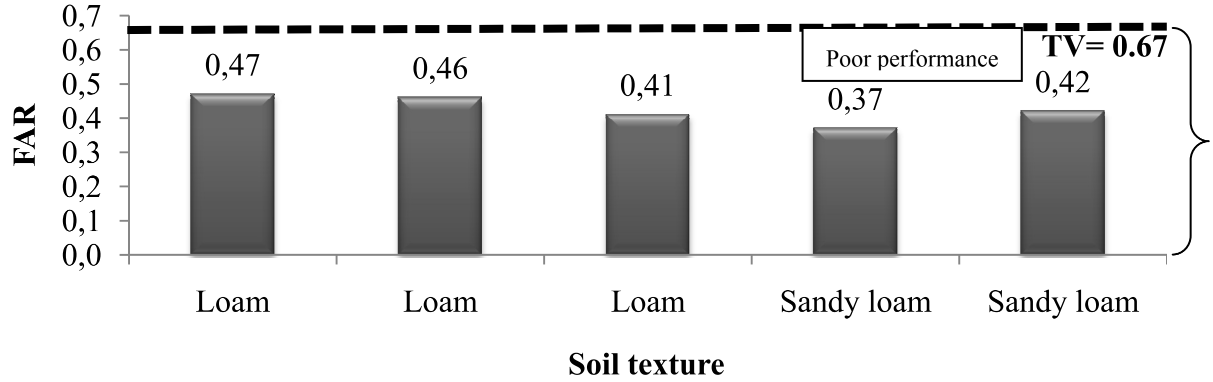
Throughout the season, the overall consumed ratio (OCR) is below the target value except in June and September (Figure 3.12a). The increased OCR in these two months results in higher DF and hence lower DR, Thus, an increase in the OCR would improve both the DF and DR. OCR is therefore an important strategic indicator (Bos, 1997). As it is the product of FAR and conveyance ratio, the study was further expanded to track the parameters used for formulating a target value for this indicator.

Field application ratio

FAR is not close to the target value (0.67) in any of the irrigation events (Figure 3.12b), which shows that the farmers applied much more water than required. On sandy soils, an average of 55 % of the entire water was lost during the application. Large field sizes and irregular leveling, but especially the farmers' strategy to use more than the required water amounts whenever available to cope with the unreliable water supply in the canal system result in the low efficiency. It was observed and also discussed with the farmers that whenever they have the opportunity to irrigate the fields, they neglect considerations on water requirements and try to irrigate as much as possible. Furthermore, there is a lack of flow measuring devices which means that there is no proper control of the used irrigation water. A reliable water supply and measurement infrastructure, double-sided irrigation (Paluasheva, 2005) and laser leveling (Masharipova, 2009) are among the solutions to increase the FAR in Khorezm. For furrow irrigation, which is practiced on more than 98 % of the irrigated area in the region, Horst et al. (2005) proposed different inflow rates than currently practiced to improve the application ratio. In the same study, best performances were obtained by adopting the inflow rate of 1.8 ls^{-1} for silty loam soils, which increased FAR and distribution uniformity. This led to seasonal water savings from 200 to 300 mm when compared with actual water use in every furrow.



(a)

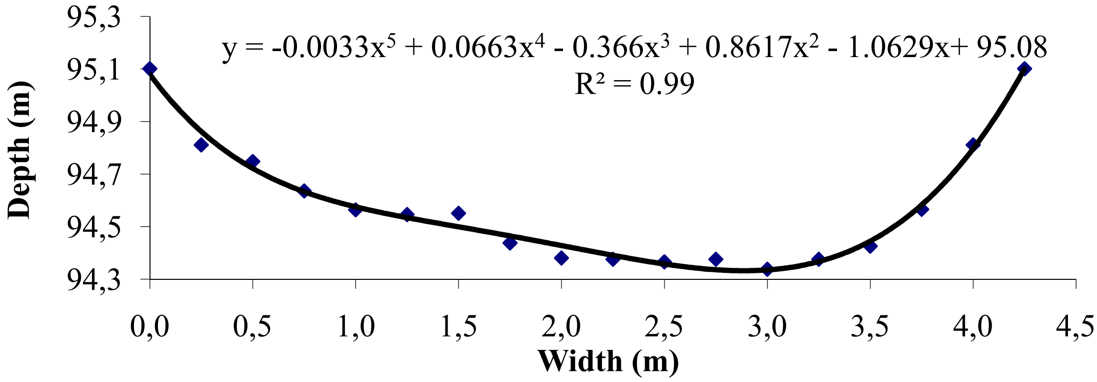


(b)

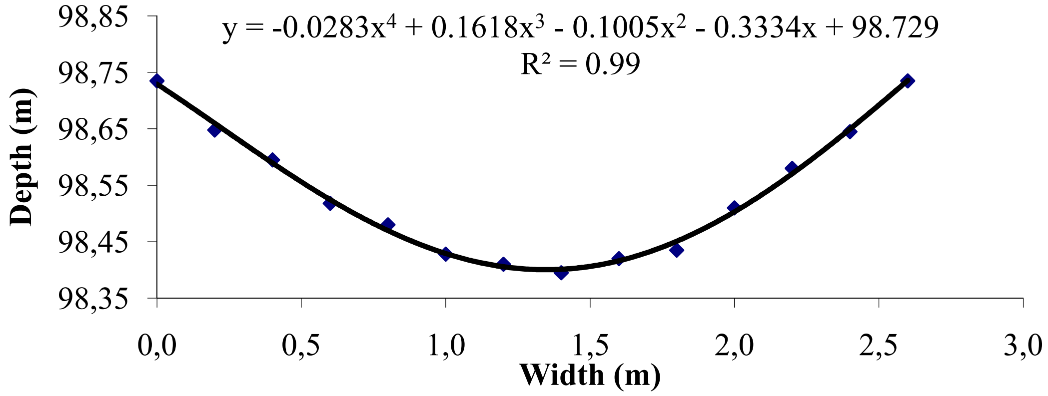
Figure 3.12 Behavior of the performance indicators during the 2007 vegetation season in Shomakhulum WUA: a) overall consumed ratio (OCR) and b) field application ratio (FAR)

Conveyance ratio

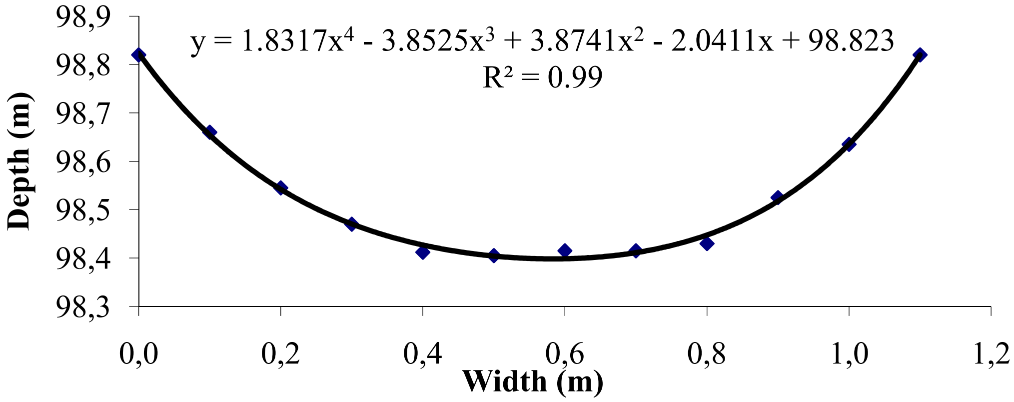
The experiment at Site1 in the inter-farm canal was discarded due to the interference of the GW level with the full supply level (FSL) of the canal. The shallow GW conditions not only restricted the seepage of the water from the canal, but also caused the ex-filtration of the shallow GW into the canal. Depths and widths in the cross sections depend upon the hierarchy of the canals. Pakhtakiyar canal (Site-2) being the inter-farm canal has a maximum width and depth, while the field channel (Site-6) has the smallest cross-sectional area (Figure 3.13 a - e). The cross-sectional areas for the sites 3, 4 and 5 (farm channels) range from 0.3 m^2 to 0.5 m^2.



(a) Site 2 (inter-farm canal)

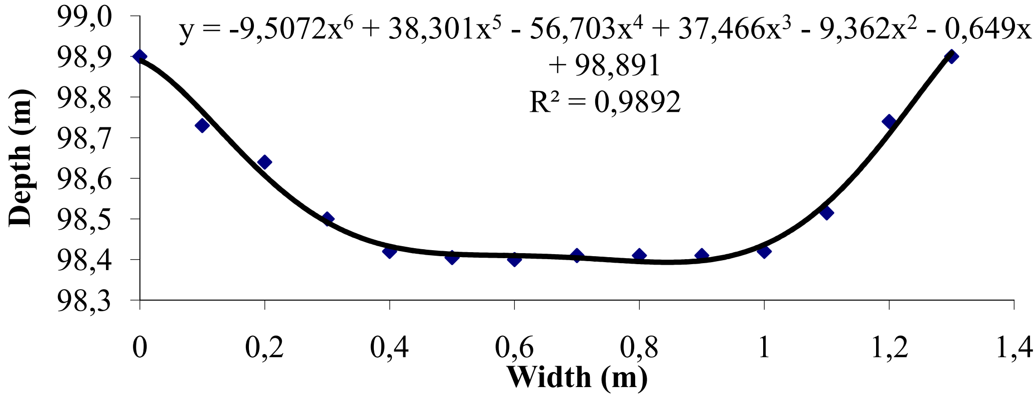


(b) Site 3 (farm channel)

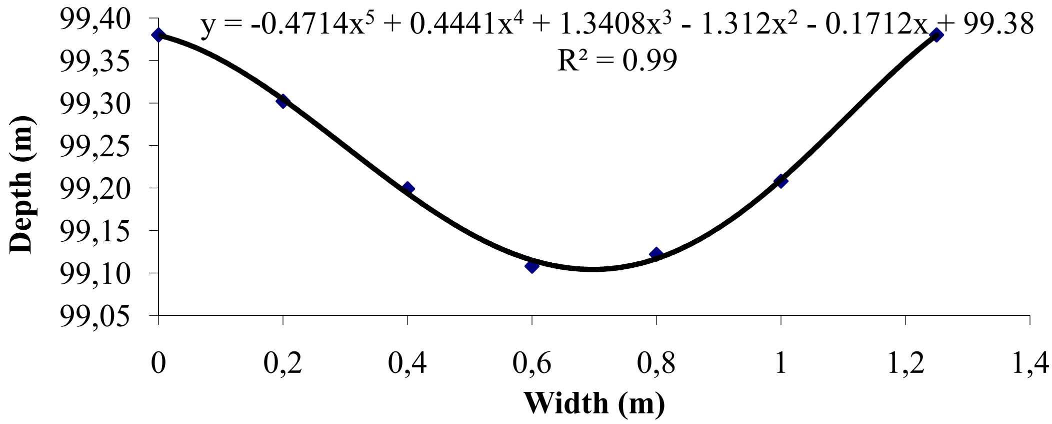


(c) Site 4 (farm channel)

Figure 3.13 Cross sections of canals in ponding experiments at different sites in Shomakhulum WUA. Depth is measured from an assumed elevation of 100 m a.s.l



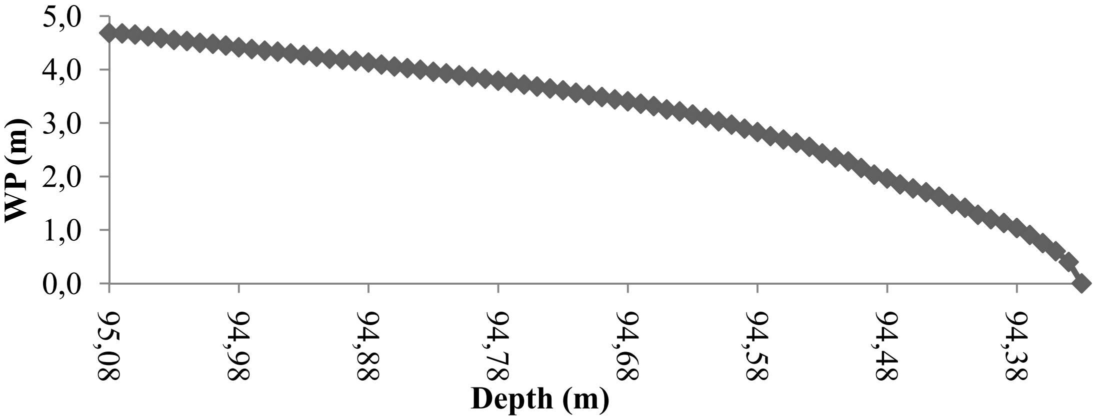
(d) Site 5 (farm channel)



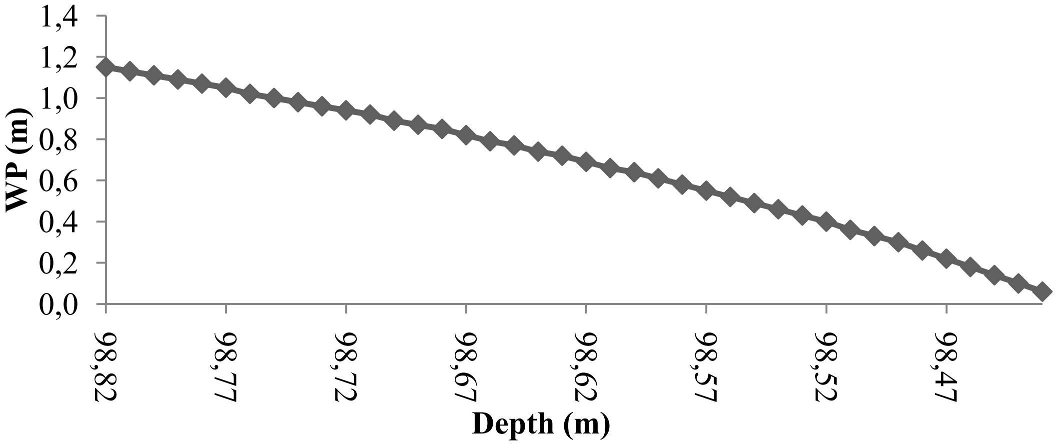
(e) Site 6 (field channel)

Figure 3.13 continued

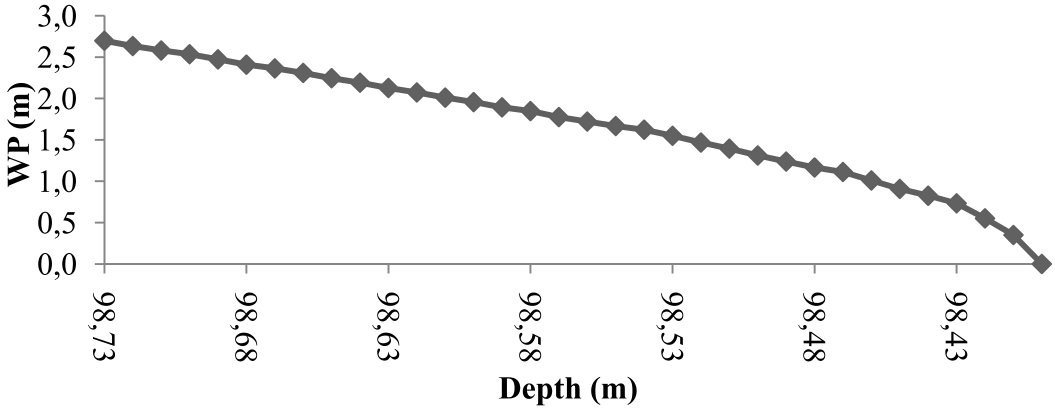
Most of the ponding sites follow the typical trend of the wetted perimeter (WP) curve, i.e., gradual decrease in WP in the upper depths and rapid decrease during the lower half of the canal segment (Figure 3.14).



(a) Site-2 (inter-farm canal)

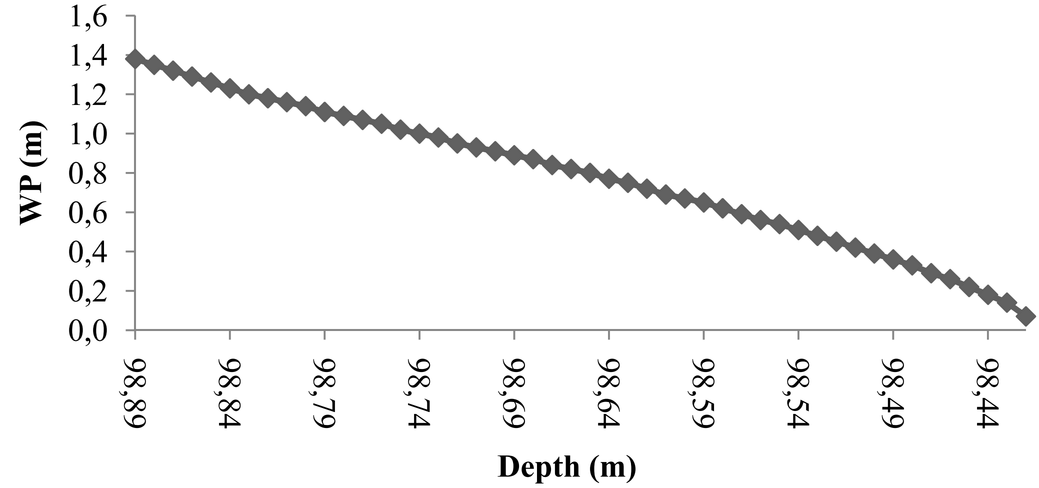


(b) Site-3 (farm channel)

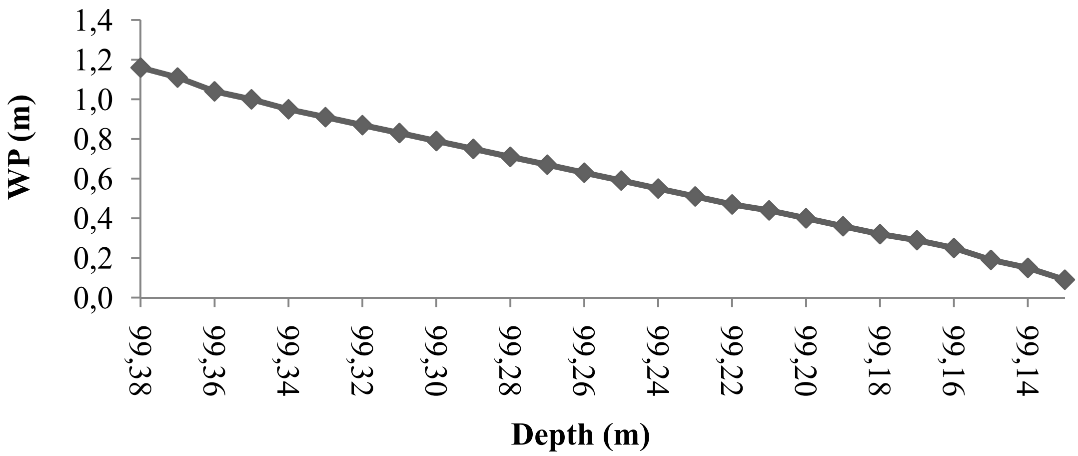


(c) Site-4 (farm channel)

Figure 3.14 Relationship between wetted perimeter (WP) and depth in pondingexperiments at different sites in the WUA Shomakhulum. Depth is measured from an assumed elevation of 100 m a.s.l.



(d) Site-5 (farm channel)



(e) Site-6 (field channel)

Figure 3.14 continued

The low seepage rates in almost all canals can be explained by silt deposits at the canal bottom and shallow GW conditions particularly in the inter-farm canals. The total losses in the irrigation network of the WUA Shomakhulum (eq. 3.1) ranged from 23-26 % (Table 3.3).

Table 3.3 Conveyance losses in the irrigation network of Shomakhulum WUA

Canal hierarchy	Soil type	Losses in the canal (%)
Inter-farm canal	Sandy clay loam	Negative
Inter-farm canal	Sandy clay loam	2
Farm channel	Sandy clay loam	6
Farm channel	Loam	3
Farm channel	Sandy clay loam	4
Field channel	Loam	18

The average value of 0.76 for the conveyance ratio was calculated for the irrigation network in the WUA Shomakhulum. Jurriens et al. (2001) reported that a CR of 0.84 can be achieved for an irrigation network with well-managed earthen canals. Although the CR for the WUA Shomakhulum is close to the target value of 0.84, there is still room for improvement. The losses in inter-farm and farm channels are quite low. However, the losses in the field channels need to be reduced. An improvement in CR in field channels can be attained either by restructuring the shape of the canals or by lining. However, for the WUA Shomakhulum, lining is not generally recommended due to the shallow GW. Maintenance costs for lined canals under fluctuating GW conditions would also be very high.

3.3.6 Conclusions and recommendations

The developments in remote sensing (determination of actual evapotranspiration, which is not possible using traditional methods) made it possible to monitor the operational performance in one WUA on a decadal basis. The results of this study can provide guidance for water distribution planners, researchers, policy makers and the national and international organizations working in the region before they implement any interventions in the present transitional period.

Oversupply of water and occasional crop water stress with huge outflows from the drains reflected by DPR, RET and DR indicators, respectively, shows the inadequacy, inequity and unreliability of the system. These indicators also point to the bottlenecks in water distribution. The OCR, FAR and CR are below the target values, which shows the inefficiency of the system at all levels. To improve the efficiency of the system and to reduce the drain losses, proper planning for distribution of water within the WUA is required. In particular, there is a need to reduce the operational losses, which can be possible by institutionalizing the involvement of farmers (not all that active at the moment) in water distribution planning.

Abstract: *Remote sensing and on-ground real-time hydrological measurements to assess the irrigation performance in a sub-unit of the Khorezm irrigation and drainage system in the lower Amu Darya River basin, Uzbekistan*

The Khorezm region of Uzbekistan, geographically located at the lower reach of the Amu Darya River, is typical for the large-scale irrigation systems in Central Asia. After the collapse of the Soviet Union, infrastructure has deteriorated in the entire region. In Uzbekistan, the agricultural production system has changed, and management of land and water resources has been modified in response to this (e.g., establishment of Water Users Associations). Water Users Associations (WUA) are now responsible for water distribution, a task formerly performed by the state. Water distribution is a fundamental activity in agriculture in the region due to the arid climate. Hence, the objectives of the study were to assess the operational performance of the irrigation scheme in one WUA, Shomakhulum, for the year 2007 and to provide recommendations for strategic planning. Relative evapotranspiration (RET), delivery performance ratio (DPR), drainage ratio (DR), depleted fraction (DF), overall consumed ratio (OCR), field application ratio (FAR) and conveyance ratio (CR) were used as performance indicators. The required water balance components were obtained through the application of remote sensing techniques and hydrological measurements in the field.

The surface energy balance algorithm for land (SEBAL) was applied to MODIS satellite data to derive actual and potential evapotranspiration. Inflows and

outflows (discharge rates in m^3 s^{-1}) were quantified with field measurements in the irrigation and drainage network using discharge rating curves. Ponding experiments were performed to determine canal seepage losses. Water balances were established at field level for application efficiency estimations. The indicator values were then compared to target values taken from literature in order to assess the operational capabilities of the irrigation scheme.

The general performance of the irrigation system is very poor. DPRs exceeding 1.0 indicate that more water is delivered to the system than is demanded. The seasonal DF of 0.4 is lower than the target value of 0.6. Losses during the field application averaged at 57 %, 24 % higher than the target value. Seasonal DR, OCR, and RET are 0.55, 0.51 and 0.82 against the target values of 0.1, 0.54, and 0.75, respectively. We conclude that the distribution mechanism can be considerably improved. Besides improving water distribution (timing and equity) in the network, another recommended intervention would be to increase the DF, particularly by interventions at field level that raise the FAR, which in turn will result in improvements of DR and OCR. This can be achieved by introducing modern water management approaches such as laser leveling, double-sided irrigation, control of inflow through flow-measuring devices installed at farm gates, and adequate water pricing. The other option can be to introduce a flexible irrigation scheduling model integrating surface and groundwater, which can provide advanced site-specific irrigation information (including impact of water stress and capacity for simulation) with respect to timing and amount.

4 MODELING RECHARGE RATES AT DIFFERENT SPATIAL SCALE

4.1 Introduction

Recharge, i.e., percolation that crosses the uppermost water table of a perched lens or an unconfined aquifer (Stephens, 1996) to groundwater (GW), is an important component of the water balance, as GW levels largely depend upon it (Freeze and Cherry, 1979). The quantification of recharge is the basis of surface water management strategies and policy development that not only protect from adverse effects, e.g., soil water logging, but also from future stresses, e.g., climate change (Lerner et al., 1990). Sophocleous (2002) pointed out that GW and surface water are not isolated components of the hydrological system but that recharge is an important link between these two resources. The knowledge on recharge is not only important for this reason but also because it is needed for the assessment of the impacts from surface water management on the GW system.

Estimation of recharge is a complex process and requires understanding of the interaction between the important processes in hydrological cycles such as infiltration, surface runoff evapotranspiration and GW level dynamics (Jyrkama and Sykes, 2007). Among the several methods available for estimating the recharge, e.g., direct measurement (lysimeters), water balance approach (Grindley, 1969 and Hough and Jones, 1998), hydrological models, Darcian and tracer methods (Simmers et al., 1997). Lerner et al. (1990) ranked the water balance model first, especially when it comes to individual irrigation events. However, accuracy of the water balance model depends on the accurate conceptualization and parameterization of the modeling inputs at different temporal and spatial scales. The computerized water balance models at field scale and the studies on these models (e.g., Khan et al., 2008) provide the recharge on a seasonal basis, which gives limited or no information for strategic planning during the season. The spatial scale of recent water balance studies was either a canal command area (Shirahatti et al., 2001) or a larger region (Gebreyohannes, 2008), approaches that do not cover the complex field situations (Grayson and Bloschel, 2000). Another traditionally disregarded process is the upward flow, i.e., capillary rise from GW in response to surface drying driven by evapotranspiration. The recent developments in modeling now enable us to quantify the capillary rise (Sharma, 1989). The focus of this study was (a) to adopt the water balance model to local conditions at a field scale taking into account the capillary rise and relevant variables and processes and hence to obtain more accurate recharge estimates, and (b) to upscale the model results to a region of interest using GIS techniques.

Research was conducted in the Khorezm region of Uzbekistan. This region is located at the lower reach of the Amu Darya River, and is seen as a model region for the irrigated Amu Darya Lowlands (Martius et al., 2009). The Shomakhulum WUA situated in the southwest of Khorezm was selected for the study (see Chapter 2). In the 1960's, the Soviet planners decided to convert the desert land in the Aral Sea Basin into irrigated agricultural areas, which increased from 4 million ha to 8 million ha. This area includes former desert land in Khorezm. To fulfill the water requirement for crops, most specifically cotton, an intensive network of irrigation systems was installed all over the region. The huge withdrawals from the Amu Darya and Syr Darya rivers to the established irrigation systems resulted in the shrinking of the Aral Sea (Ressl and Micklin, 2004), and ultimately led to the Aral Sea Syndrome (WBGU, 1998). After independence from the Soviet Union, the overexploitation of water resources continued on a regional (Conrad et al., 2007) and scheme level (see Chapter 3). Although there is a temporal and spatial shortage of water in the study area, the seasonal values of the delivery performance ratio are well above the target value (see Chapter 3). This wasteful use of surface water is not sustainable (Gupta et al. 2009). As 80% of Uzbekistan's water supplies come from neighboring countries, primarily via the rivers Amu Darya and Syr Darya (Mirzaev, 1996), agriculture and agricultural policies in Uzbekistan have significant international dimensions. Along with this, competition for water between the local water users has increased substantially (Abdullaev et al., 2008a). Several studies have been conducted in the region to promote a more efficient water use on the field level (Paluasheva, 2005) and on a regional scale (Conrad et al., 2007) in order to cope with the expected future shortage of surface water supply. Improved efficiency would result in lower recharge and hence directly influence the GW resources.

4.2 Materials and methods

4.2.1 Study area

The study was conducted in the Shomakhulum WUA situated in the southwest of the Khorezm region in Uzbekistan. Cotton (cultivated on more than 50 % of the irrigated area) and wheat (22 % of the irrigated area) are the dominant crops in the WUA. Maize, vegetables and fruits are also grown (Figure 4.1; see also Chapter 2).

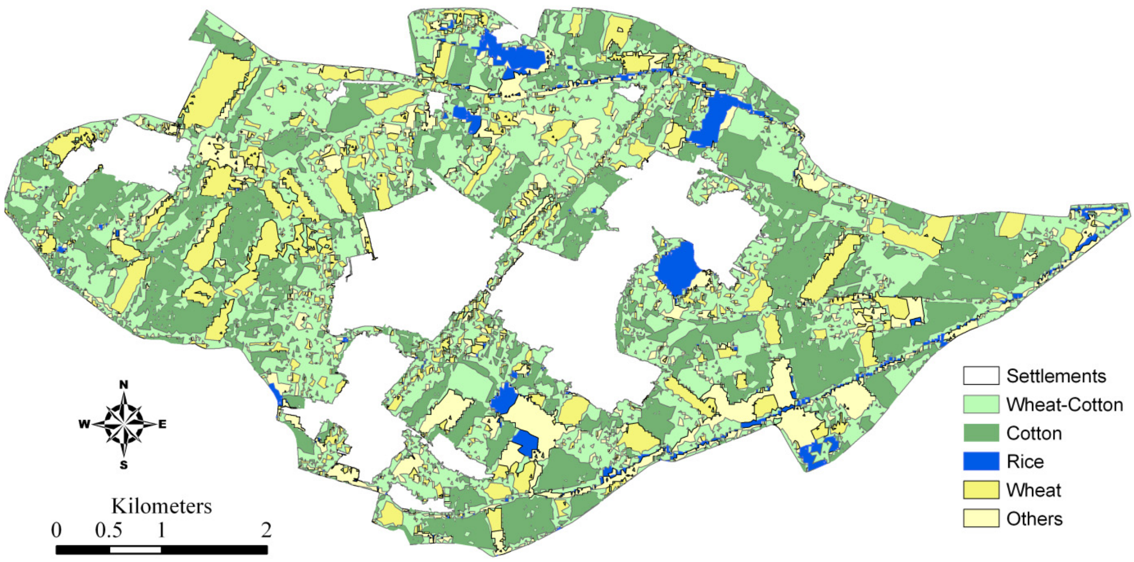


Figure 4.1 Land use in 2007 in the WUA Shomakhulum, Khorezm, Uzbekistan

4.2.2 Hydrological response units

To represent the spatial dynamics of groundwater (GW) levels and the soil characteristics, which determine capillary rise and in turn water balance and recharge, the WUA Shomakhulum was divided into smaller spatial units where these characteristics were uniform. The difference between the hydrological response unit approach used in this study and the hydromodule*s* developed by *TEZIM* is described in Chapter 2. These spatial units are named hydrological response units (HRUs). These units were created using the Thiessen polygons. The advantage of using Thiessen polygons were two folds: 1) interpolation techniques such as Kriging (Cressie, 1992) and Inverse Distance Weighted (Nalder and Wein, 1998) creates the surfaces whereas Thiessen polygons creates the polygon – the requirement for creating the HRUs, 2) it is the only interpolation technique which can work with sparse data sets - a practical limitation in study region due to sparse soil texture and GW level data sets.

For creating the HRUs, soil texture data from five profiles at different depths (0-30, 30-60, 60-90, 90-120 and 120-150 cm) were taken from a secondary source (ZEF/UNESCO GIS center in Urgench). Four profiles have a dominantly silt loam soil texture and one a silty clay loam. Thiessen polygons were drawn using a GIS to distribute the soil texture attributes spatially (Figure 4.2). GW level data for the 15 observation wells present in the WUA were taken from the *TEZIM* office (Irrigation System Authority). The WUA was divided into polygons on the basis of these wells (Figure 4.2). A well was taken as the center point for each polygon, and the GW level measured at the well considered representative for the area of land included in the respective polygon.

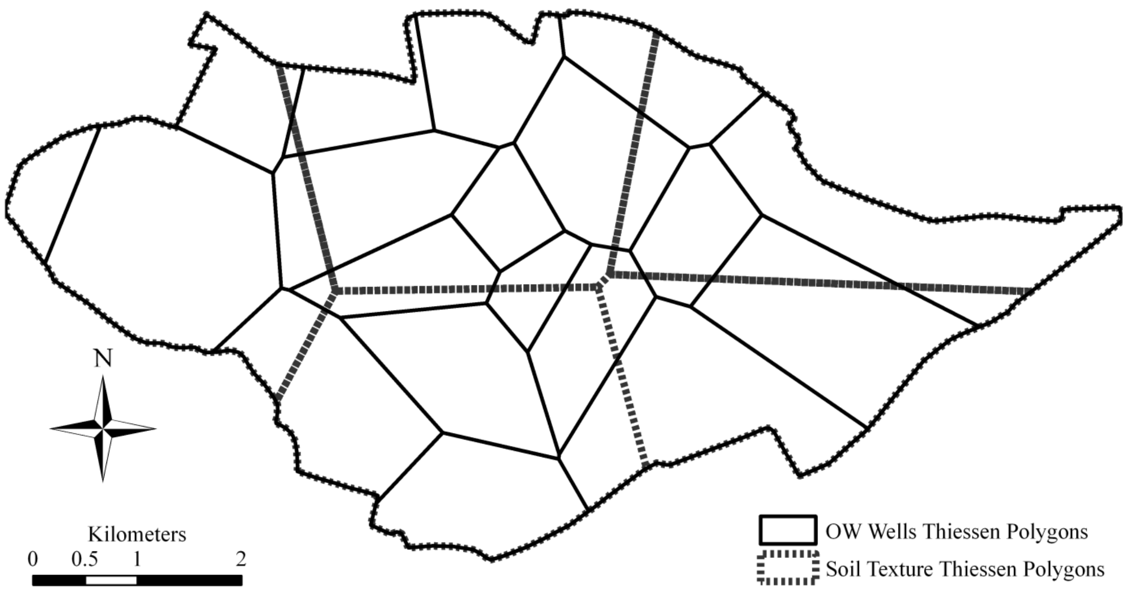


Figure 4.2 Thiessen polygons for soil texture and groundwater levels in the WUA Shomakhulum

The GW levels in the polygons were classified as shallow, medium and deep ranging from 0-100 cm, 100-150 cm and more than 150 cm below ground, respectively, during the peak irrigation season June to August (Figure 4.3).

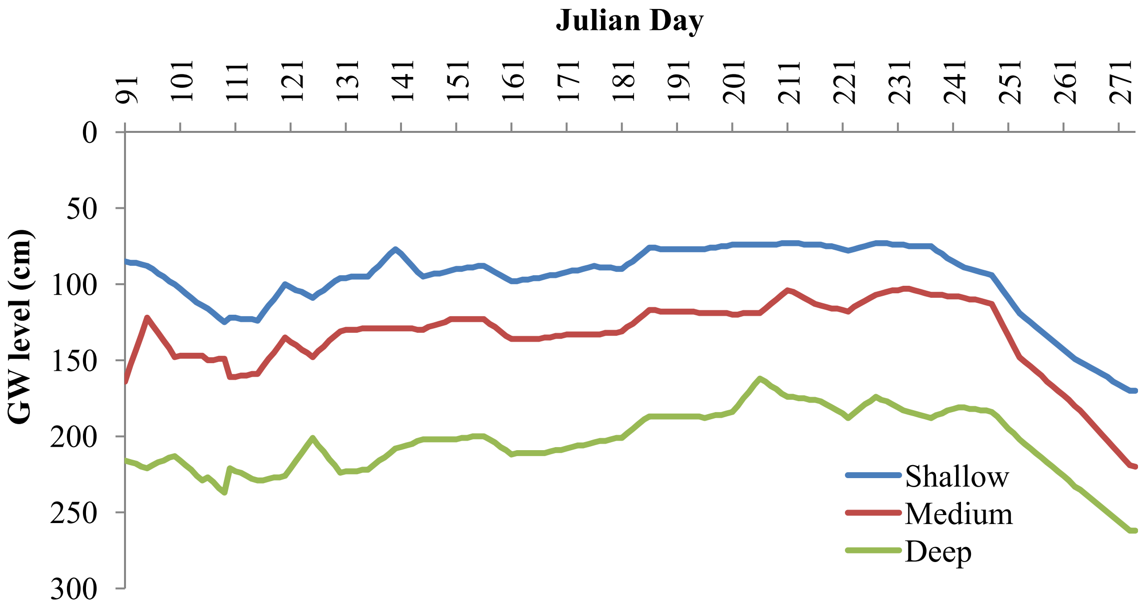


Figure 4.3 Average daily groundwater levels for shallow, medium and deep groundwater level zones in the WUA, 2007

The polygons around the GW observation wells were combined with the soil texture polygons (Figure 4.4). Thus, each HRU represents the same GW level and soil texture value (Table 4.1). The HRUs with shallow GW levels and silt loam soils are named S-SL, those with medium GW levels and silt loam soil texture M-SL, and those with deep GW levels and silty clay loam soil texture D-SCL.

Table 4.1 Characteristics of hydrological response units (HRU) in the WUA Shomakhulum

Hydrological response unit	GW level	Soil texture	Resulting HRU type
HRU-1	Shallow	Silt loam	S-SL
HRU-2	Shallow	Silt loam	S-SL
HRU-3	Shallow	Silt loam	S-SL
HRU-4	Deep	Silty clay loam	D-SCL
HRU-5	Medium	Silt loam	M-SL
HRU-6	Medium	Silt loam	M-SL

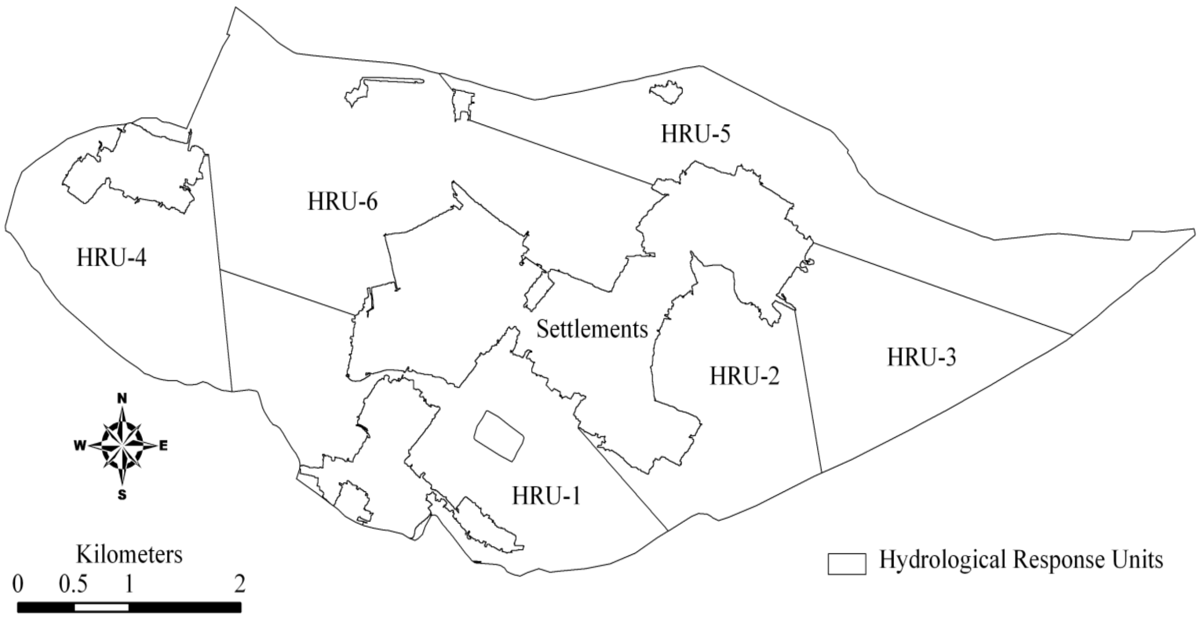


Figure 4.4 Hydrological response units in the WUA Shomakhulum

4.2.3 Cropping pattern in WUA and HRUs

The cropping pattern in the region is regulated through a state quota system. In this system, farmers sign a contract with semi-state organizations regarding the supply of pre-determined amounts of wheat and cotton. The quota for each individual farmer is determined by the local government (hakimyat) using land quality (bonitet) grades (Abdullaev et al., 2008b). The state also provides land for commercial crops such as rice, vegetables and fruits of around 1 ha and less. Cotton and wheat being the state quota crops provide low profits to the farmers, and therefore farmers use their social network and connections to grow more rice than the quota (Müller, 2006). These additional amounts are not mentioned in the official cropping plan. Therefore, remote sensing was used to identify the actual rice, cotton and wheat cropping areas.

Two ASTER satellite images (1 June 2007, and 3 July 2007) were used for land-use classification (Abrams, 2003). Out of the three different spectral bands (visible and near infrared, short-wave infrared and thermal infrared), the visible and near infrared bands recommended by Rowan and Mars (2003) for acquiring vegetation information with a spatial resolution of 15 m were used. In order to avoid the scattering and absorption effect of atmospheric gases and aerosols on the electromagnetic radiation (EMR) signals received by the satellite sensors (Jensen, 2005), atmospheric corrections were made by converting radiance values to top-of atmosphere (TOA) reflectance (Song et al., 2001). Supervised classification was used for land-use mapping. For this, spectral signatures were collected from specified locations (training sites) covering a wide range of land use during the field work in 2007. These were then used to classify all the pixels in the images. Supervised classification was followed by knowledge-based expert classification to improve the accuracy of the classification process (Berberoglu et al., 2007). The settlements were classified using the knowledge-based classifier. Cotton, wheat and rice were classified in both the images separately, and the accuracy was improved using the engineer classifier in the ERDAS imagine software.

The other crops include vegetables, maize, and perennial plants, e.g., fruit trees. These crops are difficult to classify by remote sensing, as they are grown on small fields and sometimes in the backyards of houses. The data on these crops were provided by the officials (Table 4.2).

Table 4.2 Share (%) of different crops in six hydrological response units (HRU) and WUA for the year 2007

Crop	HRU-1	HRU-2	HRU-3	HRU-4	HRU-5	HRU-6	WUA
Cotton	30	66	66	51	21	58	50
Wheat	21	22	20	25	44	15	18
Vegetables	25	8	7	13	14	10	16
Perennial	19	3	6	12	7	13	12
Maize	3	0	0	0	9	2	3
Rice	2	0	0	0	4	3	1

4.2.4 Recharge at field level

Recharge at the field level was estimated by adopting the water balance model to the local conditions. This was done by quantifying the difference between the amount of water entering into the root zone and the amount of water leaving the zone.

Penman (1950) defined the root zone budget where the recharge was associated to precipitations as:

$$P - ETa = d\Theta + R \tag{4.1}$$

where P is precipitation, ET_a is actual evapotranspiration, dΘ is change in soil moisture storage, and R is subsequent recharge.

This equation calculates recharge by assuming precipitation as the driving force. Precipitation provides part of the crop water needs to satisfy its transpiration requirements. In humid climates, this is sufficient to satisfy these requirements. However, agriculture in arid regions depends on an artificial water supply by irrigation. In Khorezm, an enormous surface water supply via the intensive irrigation network is the main driving force recharging the aquifer, while rainfall contribution remains very low (about 92 mm annual rainfall; see Chapter 3). Irrigation is supplied to the system based upon the net irrigation requirements. These are determined by subtracting the capillary rise and rainfall from the potential evapotranspiration for a specific crop:

$$NIR = ET_p - C - P \tag{4.2}$$

where NIR is net irrigation requirements, ET_p is potential evapotranspiration, C is capillary rise, and P is rainfall

To include the irrigation network losses and losses in the field, gross irrigation requirements will be:

$$GIR = \frac{ET_p - C - P}{AR \times CR} \tag{4.3}$$

where GIR is gross irrigation requirements, AR is application ratio, and CR is conveyance ratio.

The fraction of the difference between the gross and net irrigation requirements is recharge and is described as:

$$R = \left(\left(\frac{ET_p - C - P}{AR \times CR}\right) - \left(ET_p - C - P\right)\right) \times K \tag{4.4}$$

where R is recharge in mm and k is a fraction (0.9) of the difference between gross and the net irrigation which recharge the aquifer.

The variables in the brackets of the left side of eq.4.3 are the difference between gross and the net irrigation (and therefore the losses), whereas recharge is a fraction of the difference. This fraction is assumed to be in the range of 10 %. It was estimated that around 7 % of the irrigation water goes directly into the drains (referred to as operational losses), while 3 % of the irrigation water evaporates (pers. communication with Dr. Bernhard Tischbein).

The application ratio (measure of water losses in the field) was determined using the methodology proposed by Bos et al. (2005), while ponding experiments were used to determine the conveyance ratio (measure of water losses in canals; see Chapter 3). The results show an average field application ratio of 0.43, with ranges from 0.37 to 0.47 for silt loam and silt clay loam soils, respectively, and averaged conveyance ratio for the scheme of 0.74. Net irrigation requirements when divided by the product of these two ratios give the gross irrigation requirements.

4.2.5 Net irrigation requirements

Net irrigation requirements were calculated by subtracting the sum of capillary rise and rainfall from potential evapotranspiration for all crops grown in each HRU. In Khorezm, the annual long-term average precipitation is 92 mm, an amount that certainly contributes only insignificantly to aquifer recharge.

Potential evapotranspiration (ET_p)

The CROPWAT program developed by the FAO was selected for this study. Procedures for calculation of the crop water requirements and irrigation requirements are based on methodologies presented by Allen et al. (1998). The required weather data (relative humidity, minimum and maximum air temperature, wind speed and solar radiation) to calculate the (potential) reference evapotranspiration (ET_o) were collected with an automatic weather station installed in the WUA. ET_o was converted to crop ET_c using crop-physiological parameters (development stages and crop coefficients, rooting depths), which were obtained from the Central Asian Scientific Research Institute of Irrigation (*SANIIRI*), Uzbekistan (Table 4.3).

Table 4.3 Monthly potential evapotranspiration (mm) for different crops in the Shomakhulum WUA calculated with the CROPWAT model for the year 2007

Crop	April	May	June	July	August	September	Season
Cotton	11	49	101	191	160	84	596
Wheat	98	161	103	0	0	0	363
Vegetables	52	133	169	43	0	0	397
Perennial plants	86	133	154	157	128	70	830
Maize	0	25	119	189	11	0	397
Rice	0	375	70	159	154	70	728

Capillary rise

In the presence of a shallow GW table, the upward water movement by capillary rise from the water table to the root zone is an important incoming flux at the bottom of the root zone. The capillary rise for different crops in each HRU was calculated using the HYDRUS-1D model (Table 4.5; see Chapter 6).

4.2.6 Up-scaling the recharge fields to WUA level

Up-scaling the recharge from field to hydrological response unit level

After quantifying the required parameters of the water balance model, recharge for six different crops (cotton, wheat, vegetables, alfalfa, maize and rice) at field level was calculated. Using the recharge value for these crops at field level and knowing the area of the particular crop, the recharge was up-scaled to the six HRUs using the following equation:

$$RHRUi = \sum_{j=1}^{6} (RF)j \times (Area\ of\ the\ field)j \qquad (4.5)$$

where $RHRU_i$ is recharge for hydraulic response unit i (m^3), and RFj is recharge from field j ($m^3\ ha^{-1}$).

Up-scaling recharge from hydrological response units to WUA

To determine the recharge occurring across the WUA, the recharge calculated for the six HRUs was up-scaled using the following equation:

$$RWUA = \sum_{i=1}^{6} (RHRU)i \tag{4.6}$$

where RWUA is recharge from WUA (m^3), and $RHRU_i$ is recharge from HRUi ($m^3\ ha^{-1}$)

4.2.7 Scenarios

This study aims not only to monitor and model the recharge for the vegetation season 2007 but also to investigate the impact of future improvements in application and conveyance ratios on the GW recharge of the WUA. Therefore three different irrigation efficiency scenarios were developed and compared to the business-as-usual baseline scenario.

The irrigation scenarios investigated here refer to improvements of the field application (FAR) and conveyance (CR) ratios to reach the target values (Table 4.4). Target values of FAR are taken from Bos and Nugteren (1990, 1974a), and those of CR are taken from Jurriens et al. (2001). Irrigation efficiency by definition is the product of CR and FAR. The reference situation is based on the product of the current values of FAR (0.43) and CR (0.76). This scenario is the business-as-usual (BAU) scenario, and represents low irrigation efficiency. In Scenario B, the target value of CR (0.84) was multiplied by the current value of FAR (0.43). In this scenario, the improvement in the irrigation efficiency is caused by increasing the CR. However, this improvement is not so marked, as the CR is already close to the target value. In scenario C, the target value of FAR (0.67) was multiplied by the current value of CR (0.76). This scenario shows that an improvement in FAR can significantly improve the irrigation efficiency. Scenario D is the product of the target values of FAR and CR. This scenario represents the maximum irrigation efficiency, which can be achieved by improving both the FAR and CR.

Table 4.4 Improved irrigation efficiency scenarios

Scenario	Application ratio	*Conveyance ratio	Irrigation efficiency ratio
S-A (BAU)	0.43	0.76	0.33
S-B	0.43	0.84	0.36
S-C	0.67	0.76	0.51
S-D	0.67	0.84	0.56

* *Conveyance ratio considers percolation/seepage (and evaporation), but not the operational losses (which can hardly be measured)*

4.3 Results and discussion

4.3.1 Quantification of the recharge components

Gross irrigation requirements are higher from June to August than in the other months (Table 4.5). The main reasons for the higher values during this period are (1) higher potential evapotranspiration (ET_o) driven by climatic parameters and (2) cotton-specific requirements (highest crop coefficients in the period of highest ET_o). This makes the crop-specific evapotranspiration (ET_c) during these 3 months higher than that of all other crops grown in the region (Table 4.3). Along with the high ET_p of cotton, the share of cotton is higher than 50 % in the WUA, which contributes to the high gross irrigation requirements (Table 4.2). Total rainfall measured at the Shomakhulum meteorological station for the year 2007 during the peak irrigation season (June to August) was only 1 mm, which provides no contribution during this season. Seasonal rainfall (April to September) is also less than 5 % of the gross irrigation water applied during the 2007 vegetation season.

In the shallow-silt loam (S-SL) hydrological response units, capillary rise contributed 28 % of the crop-specific evapotranspiration of cotton (Table 4.5). This reduced to 23 and 16 % in the medium-silt loam (M-SL) and deep-silt loam (D-SCL) units, respectively. Similarly, 12 % of the ET_c of vegetables was met in the S-SL units, which reduced to 5 % and even to 0 % in the M-SL and D-SL units, respectively. The GW contribution under wheat from April till the harvest in October in the S-SL units is only 9 % of the ET_c, which reduced to 6 % and even 0 % in the M-SL and D-SL units, respectively.

Table 4.5 Monthly values of different water balance model components in the Shomakhulum WUA for the year 2007

Month	*Gross irrigation mm	Rainfall mm	**Capillary rise (mm)								
			Cotton			Wheat			Vegetables		
			S-SL	M-SL	D-SCL	S-SL	M-SL	D-SCL	S-SL	M-SL	D-SCL
April	75	41	7	9	0	4	9	0	1	0	0
May	105	4	54	32	13	24	6	0	17	3	0
June	270	9	43	20	32	6	5	0	12	6	0
July	355	1	49	51	34	0	0	0	17	11	0
August	419	0	7	28	14	0	0	0	0	0	0
September	65	0	4	0	4	0	0	0	0	0	0
Seasonal	1289	55	164	140	97	34	20	0	47	20	0

* *Gross irrigation values determined by the water balance model*

** *Represents the capillary rise for different crops in shallow-silt loam (S-SL), medium-silt loam (M-SL) and deep-silt clay loam (D-SCL) hydrological response units (Source: Chapter 6)*

4.3.2 Recharge estimates at field, HRU and WUA level

Field level

The monthly and seasonal recharge rates were determined by the water balance model at field level for the S-SL, M-SL and D-SCL hydrological response units for different crops (Table 4.6). The maximum values for the rice fields are due to percolation from the permanently flooded fields (Table 4.3). Due to the continuous flooding of the rice fields during the whole rice growing season, the recharge rates for different months do not differ much. GW contribution also has no influence on rice fields, as the fields are always flooded, thus the higher infiltration amounts suppressed the capillary rise (Thomas, 2003). Recharge rates are also high for perennial plants and cotton. For cotton, the rates are almost similar on M-SL and D-SCL soils. Although the seasonal capillary rise difference between S-SL and M-SL is 24 mm, the monthly variation of capillary rise caused the same seasonal recharge rates (Table 4.5). The capillary rise contribution during the month of August (month with high cotton crop water requirement) for S-SL is less than for M-SL, which increased the recharge rates for S-SL as compared to M-SL and eventually resulted in the same seasonal values. Higher recharge rates for perennial plants as compared to cotton are due to the long irrigation season of perennial plants. Although monthly recharge values for perennial plants are

lower than for cotton during the peak irrigation season, higher irrigation requirements for the perennial plants caused the higher seasonal recharge rates.
Seasonal recharge rates from wheat and maize are lowest. The trend of variation in seasonal recharge rates is similar for both cotton and wheat. The lowest recharge rates are for S-SL due to lower gross irrigation requirements but increased under M-SL and D-SCL.

Seasonal recharge rates from vegetables are 606, 626 and 657 mm for S-SL, M-SL and D-SCL, respectively. Due to low capillary rise contribution, the gross irrigation requirements for vegetables are higher, which caused high recharge rates. The monthly trend for vegetables does not vary much due to almost similar monthly net irrigation requirements.

Table 4.6 Monthly and seasonal recharge (mm) determined from the water balance model at field level for different soil and groundwater characteristics and different crop types

(a) Shallow GW-silt loam

Month	Cotton	Wheat	Vegetables	Perennials	Maize	Rice
A	0	132	0	126	0	0
M	0	161	0	109	0	0
J	119	184	188	119	0	349
J	333	0	193	123	109	363
A	409	0	225	198	184	365
S	0	0	0	203	189	365
Season	861	477	606	878	482	1442

(b) Medium GW-silt loam

Month	Cotton	Wheat	Vegetables	Perennials	Maize	Rice
A	0	123	0	123	0	0
M	0	193	0	147	0	0
J	160	186	198	160	0	349
J	330	0	203	119	105	363
A	372	0	225	161	147	365
S	0	0	0	210	196	365
Season	862	502	626	920	448	1442

(c) Deep GW-silt clay loam

Month	Cotton	Wheat	Vegetables	Perennials	Maize	Rice
A	0	139	0	139	0	0
M	0	203	0	181	0	0
J	139	195	209	139	0	381
J	360	0	223	149	135	397
A	396	0	225	186	172	379
S	0	0	0	203	189	369
Season	895	537	657	997	496	1526

Hydrological response unit level (HRU)

Table 4.7 presents the monthly averages of daily recharge rates (mm d^{-1}) for six hydrological response units and for the WUA determined using equation (4.5) and equation (4.6), respectively, for the year 2007. Recharge rates are higher from June to August in all HRUs. July and August are the peak months of irrigation for cotton, which explains why recharge is so high during that period. Average recharge is 4 mm d^{-1}, which represents 57 % of the average gross irrigation amount.

Table 4.7 Monthly averages of daily recharge rates (mm d^{-1}) for different hydrological response units in the Shomakhulum WUA for the year 2007

	April	May	June	July	August	September
HRU1	1.7	1.7	5.0	5.9	7.4	1.7
HRU2	1.1	1.3	4.6	7.8	9.6	0.2
HRU3	1.2	1.3	4.6	7.8	9.6	0.4
HRU4	1.7	3.8	5.4	7.4	8.2	0.8
HRU5	2.0	3.0	5.7	4.4	5.0	1.6
HRU6	1.1	1.5	5.7	7.7	8.7	1.3
WUA	1.4	2.0	5.2	6.6	7.7	1.2

The characteristics of HRU-1, HRU-2 and HRU-3 are similar (S-SL), but the recharge rates of HRU-1 differ substantially from those of HRU-2 and HRU-3. Although the cropping patterns of the latter two do not differ much (Table 4.2) and the share of cotton is the same in both HRUs. The same share of cotton resulted in similar recharge rates during the peak irrigation season of cotton (June-August). Slightly higher recharge rates for September in HRU-3 are due to a higher share of perennial crops in this HRU. In contrast, HRU-1 has a less than 50 % share of cotton compared to HRU-2 and HRU-3, which resulted in the different recharge rates. The higher recharge rates for HRU-1 during the early season (April and May) and even at the end of season (September) are due to the larger share of perennial plants compared to HRU-2 and HRU-3.

The characteristics of HRU-5 and HRU-6 are similar (M-SL), but both have different recharge rates. In HRU-5, wheat is the dominant crop providing higher recharge rates during April and May, whereas HRU-6 has a higher share of cotton, providing higher recharge rates during July and August. However, it is clear that the recharge rates in HRU-5 for April and May are much lower than those in HRU-6. This is due to higher recharge rates for cotton at field level as compared to wheat.

The characteristics of the HRU-4 (D-SCL) are different from all other HRUs, and therefore recharge rates cannot be compared to those in the other HRUs. Cotton is a dominant crop in this HRU (more than 50 % of the total cropped area), which leads to higher recharge rates from June to August.

Water users association level

After determining the recharge rates at HRU level, recharge was up-scaled from this level to the WUA level using equation (4.6) The monthly recharge rates at the WUA level show that the recharge rates in April, May, and September are 1.4, 2 and 1.2, respectively, which is quite low compared to June (5.2 mm d^{-1}), July (6.6 mm d^{-1}) and August 7.7 (mm d^{-1}). The recharge rates increase almost linearly, and maximum is during August, while they are reduced substantially during September (Figure 4.5). Monthly trends of recharge rates in most of the HRUs do not differ much, i.e., most show higher recharge rates from June to August due to the higher share of cotton in the WUA, and lower recharge rates in April, May and September due to low irrigation supplies against the low irrigation water demand (Table 4.3).

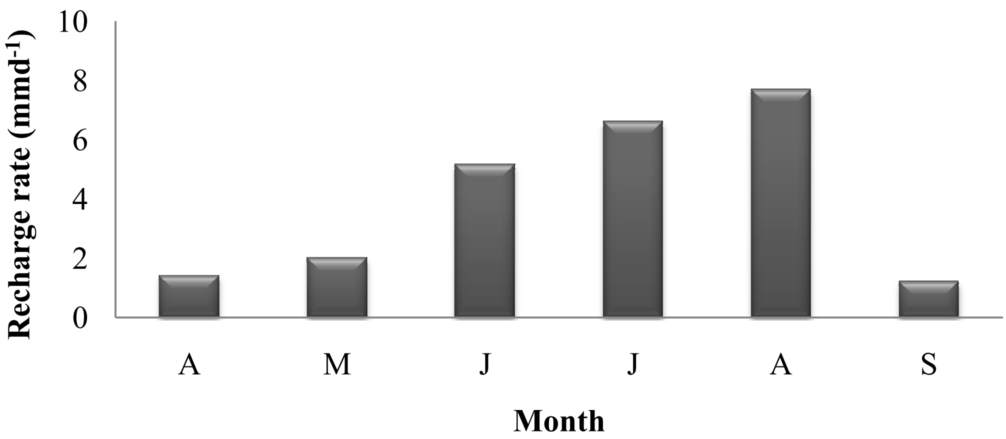


Figure 4. 5 Recharge rates determined from the water balance model at WUA level during the vegetation season 2007

4.3.3 Recharge with different application and conveyance ratios

Once recharge rates under the existing irrigation efficiency (baseline scenario) were determined, the impact of increased efficiency was quantified for the WUA and for the six HRUs (Figure 4.6). In the baseline scenario (A), the water managers delivered higher amounts of water in the absence of sufficient rainfall to compensate for lower

FAR and CR, which resulted in higher percolation and eventually higher recharge rates (Figure 4.6). The declining trend of the gross irrigation curves from scenario A over scenarios B and C to D is due to an improvement in the FAR and CR.

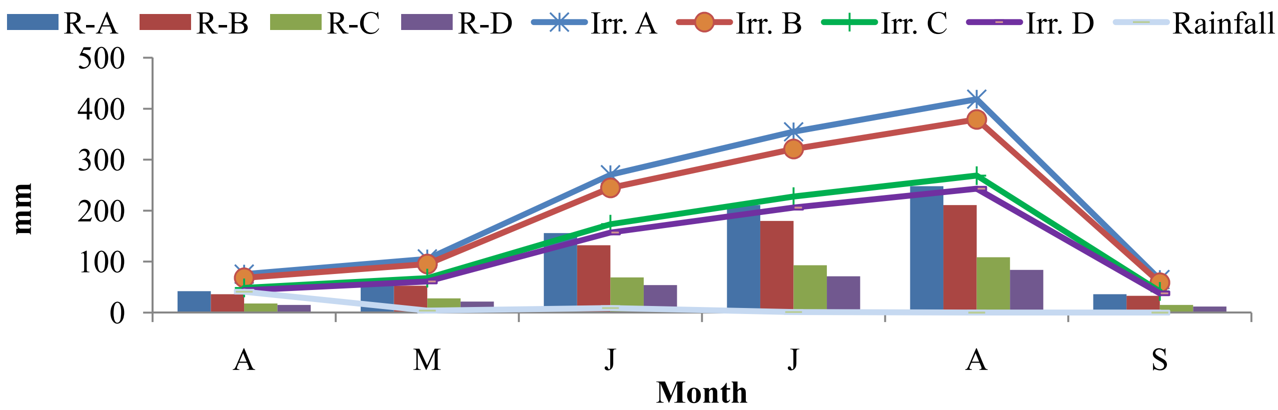


Figure 4.6 Monthly recharge (R), gross irrigation (Irr.) and rainfall for the WUA Shomakhulum for different scenarios (S-A = baseline or business-as-usual, S-B = improving conveyance ratio, S-C = raising field application ratio, S-D = improving field application ratio and conveyance ratio). Recharge (mm) is indicated by bars; gross irrigation and rainfall are indicated by lines.

The maximum gross irrigation is during August for all scenarios. The reason for high gross irrigation during this month is the high crop water requirements (Table 4.3). The gross irrigation curves for scenarios A and B are quite close to each other as are the curves for scenarios C and D. As FAR and CR are the driving forces for the establishment of these curves, a critical review of the data shows that the difference between the existing CR (0.76) and the target value (0.84) is very small. Therefore, by improving the CR (scenario B), the impact on the gross irrigation compared to the baseline scenario is not so prominent, and therefore these curves are so close to each other. In contrast, the increase in FAR (scenario C) from the existing value of 0.43 to the target value of 0.67 considerably lowers the gross irrigation amounts. The gross irrigation amounts are lowest in scenario D, where both the application and conveyance ratios are equal to target values.

As shown in the water balance equation, recharge is driven by the gross irrigation amounts. Therefore, the trend of variation in recharge values is similar to the gross irrigation curves. During August (peak irrigation month), the recharge for scenario A was 248 mm and reduced to 211 mm in scenario B. Due to the substantial decrease in gross irrigation curves. During August (peak irrigation month), the recharge for scenario A was 248 mm and reduced to 211 mm in scenario B. Due to the substantial decrease in gross irrigation from scenario A to Scenario C, recharge also reduced in scenario C (109 mm). The lowest recharge was 84 mm in scenario D, due to the lowest gross irrigation amount.

To capture the effect of any increase or decrease in irrigation efficiency on recharge rates, the empirical relationship between recharge and four irrigation efficiency ratio scenarios (S-A: 0.33, S-B: 0.36, S-C: 0.51, S-D: 0.56) at the WUA level was established by fitting the determined rates of recharge and the corresponding values of irrigation efficiency (Figure 4.7). An exponential curve fitted successfully (coefficient of determination is 0.9).

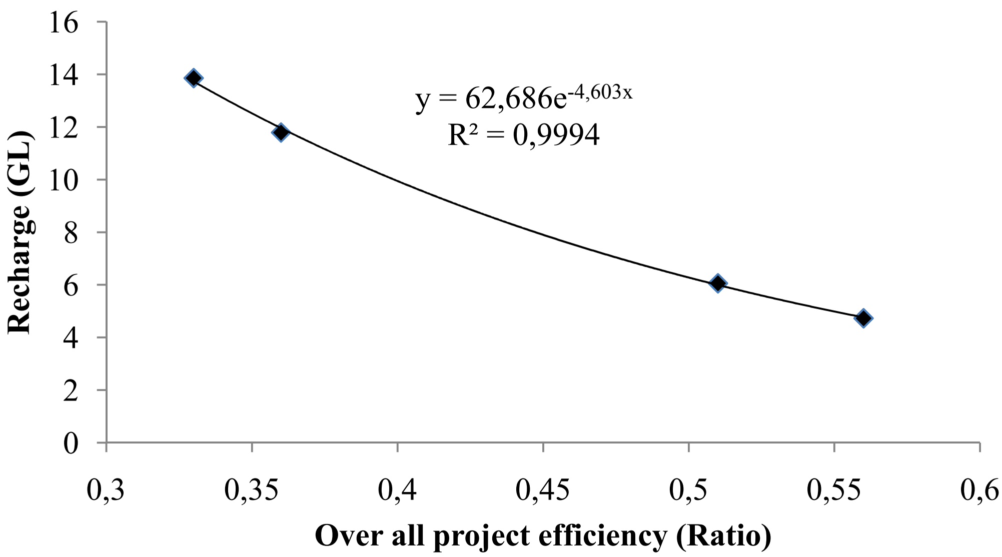


Figure 4.7 Recharge-irrigation efficiency relationship for the WUA Shomakhulum

The equation derived from the exponential curve can be used to determine the recharge for any value of irrigation efficiency. The equation also indicates that recharge is not a constant fraction of irrigation, but rather the fraction increases as the water inputs increase. It can also be derived that recharge is almost zero when the irrigation efficiency ratio is 1, whereas recharge increases to maximum when the irrigation efficiency is reduced. The equation can be used as a guideline for policy makers for managing the recharge rates, i.e., the groundwater situation, as recharge directly influences the GW levels.

4.4 Summary and conclusions

The water balance model adapted to the local conditions provided a useful tool for the management of recharge rates and thus GW resources. At field level, recharge rates are higher with deep GW levels and silt clay loam soil texture (D-SCL) than with shallow GW levels and silt loam soil texture (S-SL) and medium GW levels and silt loam soil texture (M-SL). The higher recharge under D-SCL is due to a smaller capillary rise contribution in this soil, which increases the net irrigation requirements and hence the recharge rates. For example, cotton has a 35 mm higher recharge under D-SCL than S-SL. In HRU-2 and HRU-3, with S-SL characteristics and larger share of cotton than all other HRUs, the highest recharge rate was 9.6 mm d^{-1} during the month of August. HRU-1 also has S-SL soils, but the maximum recharge during August was only 7.4 mm d^{-1}. The low recharge rate in this HRU-1 compared to HRU-2 and HRU-3 is consistent with the lower share of cotton. This shows that recharge rates are also under the strong influence of land use. At WUA level, the maximum recharge rate is 7.2 mm d^{-1} during the month of August, which is quite high compared to values in other studies, e.g., on the Indus basin. In the developed scenarios, the monthly trend of the recharge rates is similar to the baseline scenario, i.e., maximum in August and lowest in April, May and September. However, the recharge reduces with the increase in irrigation efficiency. This relationship was well described by creating the exponential function (coefficient of determination near to 1). The equation of the exponential curve shows that recharge rates decrease with the improvement of irrigation efficiency and come closer to zero with a maximum irrigation efficiency ratio of 1. The relationship can be used for managerial purposes by the water managers in the area to control the recharge.

Abstract: *Modeling groundwater recharge at field level and GIS-based approach to upscale from field to scheme level*

Accurate quantification of the rate of groundwater (GW) recharge is a pre-requisite for the sustainable management of GW resources. This study presents (1) a method to determine recharge at field level and (2) a procedure for up-scaling from field to scheme level. The field level investigations can capture the complex processes, e.g., upward flow of water under shallow GW conditions, which have been disregarded worldwide for years in the past when estimating the recharge at a larger scale. For this purpose, a

water balance model at field level was modified to suit the local conditions of the Shomakhulum Water Users Association (WUA) in the southwest of the Khorezm region in Uzbekistan. Recharge in this water balance approach is considered as a fraction of the irrigation water losses, which can be determined by estimating difference between net and gross irrigation requirements. Net irrigation requirements were calculated by subtracting the capillary rise (using the HYDRUS-1D) and rainfall from the potential evapotranspiration (using the FAO CROPWAT model) for the crops grown in the area. Determination of gross irrigation requirements was based on the efficiency concept. Recharge at field level depends on several factors, e.g., climatic conditions, soil texture, cropping pattern and GW levels. These factors can vary significantly in any irrigation canal command area. To capture the spatial variability of these factors, Arc GIS was used. Thiessen polygons were drawn in Arc GIS to capture the spatial variability of GW levels and soil texture, which determine the capillary rise and in turn the water balance and hence the recharge. Satellite remote sensing was used for land-use classification. Based on the GW and soil texture maps, the six subunits of the WUA with homogenous GW conditions and soil textures are considered as hydrological response units (HRUs). HRU-1, 2 and 3 have shallow-silt loam (S-SL) characteristics, HRU-4 has deep-silt clay loam (D-SCL) and HRU-5 and 6 have medium-silt loam (M-SL) characteristics. Recharge calculated at field level was first up-scaled for these HRUs and then for the whole WUA. To quantify the impact of improved irrigation efficiency scenarios on recharge rates, 4 irrigation efficiency scenarios were developed: 1) current irrigation efficiency (S-A), 2) improved conveyance efficiency (S-B), 3) increased application efficiency (S-C), and 4) improved conveyance and application efficiency (S-D).

Results show that GIS provides a useful environment to capture the spatial variability of physical factors (GW and soil texture) that influence recharge. During the monitoring year 2007, land use was identified as the driving force. The area under cotton has the highest recharge (895 mm under D-SCL) in the peak irrigation period after rice (2514 mm), but a very low share of rice (1 %) in the considered WUA is the reason for the rather small influence of rice cultivation on the recharge in the WUA. Due to higher recharge rates of cotton at field level, the HRUs with the highest share of cotton show a higher recharge (9.6 mm d^{-1} during August) than those with the lowest share of cotton

(4.4 mm d^{-1}), which shows that recharge is strongly influenced by the share of cotton. The high recharge rates in the cotton fields are not only due to the crop-water requirement but also due to special treatments the crop receives from the water management planners because of its strategic importance. For the different irrigation efficiency scenarios, it was found that by improving the irrigation efficiency, seasonal recharge reduced from maximum of 4 mm d^{-1} (S-A) to a minimum of 1.4 mm d^{-1} (S-D). The curve established for recharge and irrigation efficiency scenario can provide guidelines for the water planners in the region for regulating irrigation schemes keeping in mind the effect on recharge rates.

5 SIMULATING GROUNDWATER DYNAMICS WITH FEFLOW-3D

5.1 Introduction

In the Khorezm region of Uzbekistan, there have recently been intensive debates among the researchers from local (e.g., Urgench State University) and international (e.g., ZEF/UNESCO) institutes focusing on irrigation water use, especially on how to overcome overexploitation of surface water resources, implement water saving techniques, achieve improvements in irrigation and drainage infrastructure, shift the cropping pattern from high to low water demanding crops to save surface water, and cope with the reduced water supply due to climate change (Lerner et al., 1990), and on the introduction of water pricing in the region. These debates reflect the expectation that the irrigation planners in the region would be able to take effective water-saving measures, either by improved irrigation efficiency (modern irrigation techniques) or by introduction of water-saving crops. A reduced surface water supply would help to avoid the menacing twin problems of water logging and salinity in the area (Kahlown, 2005), but this would reduce the water contribution to crop water use that is currently provided by the shallow ground water (GW) tables. One can argue that GW levels should be deep to flush the salts out of the system and the water saved by improving the irrigation efficiency can be stored and used in water scarce periods. This can be the ideal condition for the management of surface and ground water resources but the region does not have a single infrastructure and even don't have intention to store the surface water for irrigation. Moreover such an infrastructure needs huge investment.The shallow GW level is a fundamental element of the current system management, even if it is not officially recognized or supported, which helps securing crop yields under the current inefficient water distribution system. Thus, any attempts at lowering the GW level would need to address the possible risk of reducing yields. Therefore, conjunctive use of surface and GW resources would save conventional irrigation water and could also mitigate the impacts of the outlet problems. Under the ideal condition, deep GW levels can the water saved by improving the irrigation efficiency can be used for the water scarce years.

The dynamic behavior of GW levels is greatly influenced by surface water (Sophocleous, 2002 and Rai et al., 2006) through the so-called recharge. Different analytical approaches have been developed to link recharge to GW resources. In theoretical studies on water table fluctuations, Rai et al. (2006) have shown that the variation in the recharge rate significantly affects the behavior of the water table. The time-varying nature of the recharge rate has also been discussed in detail by Abdulrazzak and Morel-Seytoux (1983) and Morel-Seytoux (1984).

The modeling techniques allow the surface water interventions by obtaining recharge as an output from the surface water model and feeding it to the GW models. The modeling approach has been used widely in three ways: (1) development of an integrated surface-groundwater model (Bouraoui et al., 1997; Jayatilaka et al., 1998 and Yu and Schwartz, 1998), (2) linking an existing groundwater model with a surface water model (Havard, 1995; Ramireddygari et al., 2000; Sophocleous and Perkins, 2000; Ross et al., 2005; Sarwar, 1999 and Rodriguez et al., 2008), or (3) using packages of existing groundwater models (Monninkhoff and Schaetzl, 2008; Pucci et al., 1995).

In the present study, the GW model was linked to the surface water model by the recharge from the surface water model. Estimating recharge is a complex process, and models used for recharge estimates sometimes do not precisely model the real-time local situation. Therefore, a surface water balance model adapted to the Khorezm region was applied and coupled with the existing GW model (approach 2).

The study was conducted in the WUA Shomakhulum, which is situated in the southwest of the Khorezm region in Uzbekistan. An intensive network of irrigation and drainage systems with densities of 68 and 31 m ha^{-1}, respectively, is spread over the WUA. The average GW levels for the last ten years (1997-2007) show that during the leaching and vegetation season, the GW levels range from 0.5 to 1.3 m and 1.1 to 1.5 m, respectively. These values are in the range of the overall average of the Khorezm region, i.e., GW levels ranged around 1.0 to 1.2 m below surface during leaching and irrigation events (Ibrakhimov et al., 2007). Soils in the WUA are predominantly loamy to sandy loam (USDA classification).

For the recharge estimates with the surface water balance model, the WUA was subdivided into six units (hydrological response units; HRUs) where the conditions influencing the recharge process are homogenous. A water balance model is a book-keeping process defining the inflow, outflow and change of storage. Recharge was first determined at field level by taking into account all complex processes, e.g., capillary rise, cropping pattern, soil characteristics, then up-scaling the recharge to the HRU level and linking this recharge to the efficiencies of the network and the field application, and finally linking these efficiencies to the overall system efficiency. Irrigation efficiencies monitored in the study area (see Chapter 3) were used in combination with the target values suggested by Bos and Nugteren (1990, 1974a) and Jurriens et al. (2001) to develop scenarios (section 2.2.4).

The recharge values calculated by the water balance model were then introduced into the GW model. For the present study, FEFLOW-3D (Version 5.1) was selected for simulations of groundwater levels. FEFLOW is a Finite Element Subsurface Flow & Transport Simulation System with a fully graphics-based and interactive user interface (Diersch and Kolditz, 2002), to allow the solution of the complex problems. The FEFLOW parameters for calculating the GW flow include the information on the horizontal and vertical (spatial) distribution of permeable and impermeable layers, parameters describing the characteristics governing GW flow and balance (hydraulic conductivity, porosity, etc.), and information on GW flow (rate of GW recharge, surface water level intersecting the GW at borders or within the system in the form of drains or canals). The attributes of these parameters are imported either as shape files prepared in ArcGIS or as ASCII files.

After parameterizing, calibrating and validating the model, GW fluctuations in the four different irrigation efficiencies scenarios (see Chapter 4) were determined. Information on these GW fluctuations can provide guidelines for policy makers for the management of GW resources.

5.2 Materials and methods

5.2.1 Study area

In Shomakhulum, there are a total of 15 observation wells for monitoring the GW levels, some of them are near to canals and drains (Figure 5.1 and Figure 5.2). The so-called “Hydromelioration Expedition (*OGME*)” of the district is responsible for collecting the GW data of which copies are provided to the WUA office and *TEZIM*. For details on the study area see Chapter 2.

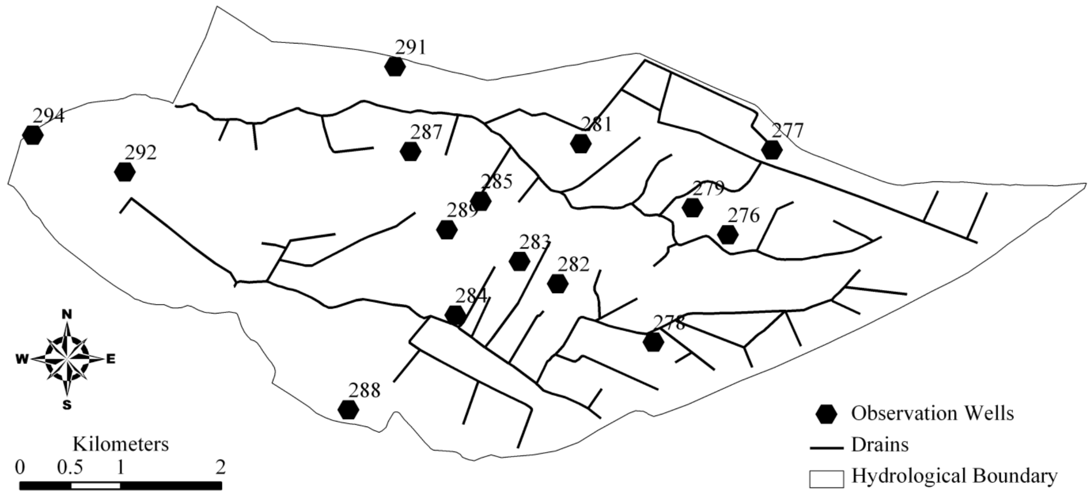


Figure 5.1 Drainage network and observation wells in the WUA Shomakhulum

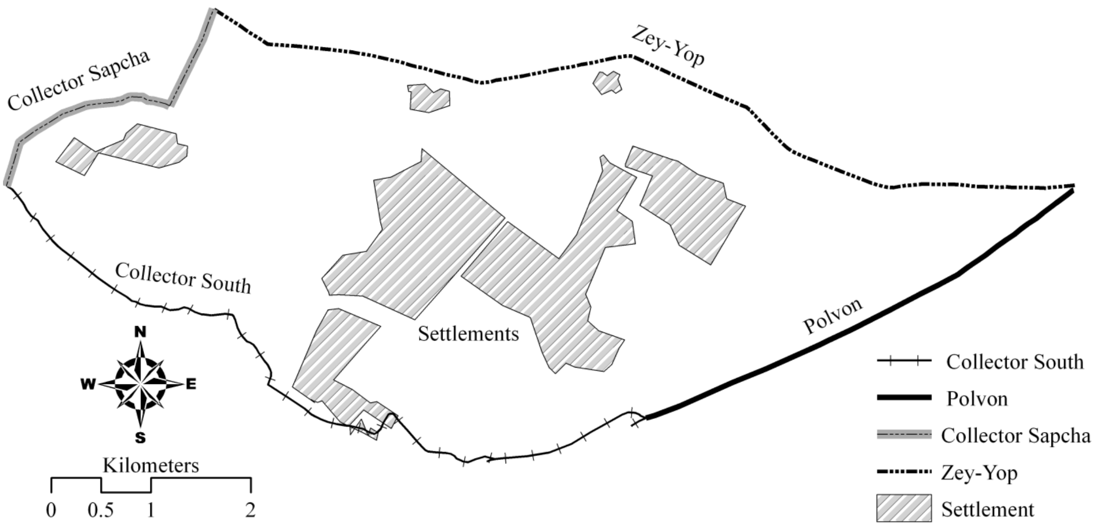


Figure 5.2 Location of the settlements, canals and collectors forming the hydrological boundary of the WUA

5.2.2 Basic modeling approach

Depending on the complexity of the problem and available datasets, there are several approaches to modeling the surface and GW interaction. The water management strategies for surface water are dynamic in space and time, and therefore a model that can capture all the site-specific conditions does not exist, whereas several GW models exist to capture the flow and material properties in saturated and unsaturated zones. The aim in this study was therefore to link an existing GW model (FEFLOW) with a developed surface water balance model. The surface and GW model was linked through the recharge rates.

5.2.3 Water balance model

For details on the water balance model and the determination of recharge at different spatial scales for the WUA Shomakhulum see Chapter 4. A summary of the methodology and adaptation to the context of the GW modeling is given below.

The WUA was divided into six spatial units (hydrological response units – HRU; (see Chapter 4). To capture the processes influencing the recharge rates, e.g., upward flow of water under shallow GW conditions, the recharge was first calculated in detail at field level and then up-scaled to the six HRUs. For this purpose, a detailed water balance model at field level was established:

$$R = \left(\left(\frac{ET_p - C - P}{AR \times CR} \right) - (ETp - C - P) \right) \times K \qquad (5.1)$$

where R is recharge, ET_p is potential evapotranspiration, C is capillary rise, P is rainfall, AR is application ratio, CR is conveyance ratio, and K is coefficient. The detail of the establishment of the water balance model is given in section 4.2.4

Using the CROPWAT model for potential evapotranspiration, HYDRUS-1D for capillary rise and rainfall from the meteorological station, net irrigation requirements were calculated. The losses in the field and in the irrigation network were introduced in the water balance model based on the irrigation efficiency concept. The fraction of the difference between the gross and net irrigation contributes to recharge aquifer.

After quantifying the required parameters of the water balance model, recharge for six different crops at field level was calculated. Using the recharge value for these crops at field level (m^3 ha^{-1}) and knowing the area of the particular crop (ha), the recharge was up-scaled to all the six HRUs by the following equation:

$$RHRUi = \sum_{j=1}^{6} (RF)j \times (Area\ of\ the\ field)j \tag{5.2}$$

where $RHRU_i$ is Recharge for hydraulic response unit i (m^3)and RFj is Recharge from field j (m^3 ha^{-1}).

5.2.4 Groundwater model

Numerical GW flow modeling was performed using FEFLOW (Diersch, 2002a), which has successfully been tested for a number of benchmark examples in variable density flow, such as the Elder problem, the Henry problem, the salt- dome problem and the salt- pool problem (Diersch, 2002b). The fundamental basis of FEFLOW is that it introduces the Darcy equation in the mass conservation equation of any phase.

The following equation represents the mass conservation of any phase (Diersch, 2002b):

$$\frac{\partial}{\partial t}(\varepsilon_\alpha \rho^\alpha) + \frac{\partial}{\partial X_i}(\varepsilon_\alpha \rho^\alpha V_i^\alpha) = \varepsilon_\alpha \rho^\alpha Q_\rho^\alpha \tag{5.3}$$

where t is time [T], $\mathcal{E}_\alpha$ is volume fraction of α-phase [–], ρ^α is density of α-phase [ML^{-3}], X_i is Eulerian spatial coordinate vector [–], V_i^α is velocity vector of α-phase [LT^{-1}], Q_ρ^α is mass supply of α-phase [T^{-1}].

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Further, the equation was modified for conservation of fluid mass:

$$\frac{\partial}{\partial t}(\varepsilon \rho^f) + \frac{\partial}{\partial X_i}\left(\rho^f q_i^f\right) = \rho^f Q_\rho \tag{5.4}$$

The term qi^f is known as the Darcy velocity flux, and FEFLOW uses the following density-dependent formulation of the Darcy law (Diersch, 2002b) to calculate this flux:

$$q_i^f = -K_{ij} f_u \left(\frac{\partial h}{\partial X_j} + \frac{\rho^f - \rho_o^f}{\rho_o^f} e_j\right) \tag{5.5}$$

where Kij is tensor of hydraulic conductivity of fluid phase [LT-1], fu is viscosity relation function [–], ρof is reference density of fluid phase [ML-3] , ρf is fluid density [ML-3], and ej is gravitational unit vector [-].

5.2.5 Parameterization of FEFLOW model

The FEFLOW parameters for calculating the GW flow include the information on the horizontal and vertical (spatial) distribution of permeable and impermeable layers, parameters to describe the characteristics governing groundwater flow and balance (hydraulic conductivity, porosity, etc.), and information on groundwater flow at the interface to surface water (rate of groundwater recharge, surface water level intersecting the GW at borders or within the system in the form of drains or canals (see sections 5.2.6 to 5.2.9). The attributes of these parameters are imported either as shape files prepared in ArcGIS or as ASCII files. The interpolated values of the parameters for the whole model domain were achieved by Akima interpolation. The details of these parameters are presented in a sequence representing the set-up of FEFLOW, i.e., top- to down-menu-based parameterization of the model.

5.2.6 Creating the finite element mesh

To define the model area and to construct the superelement mesh, the background map of the hydrological boundary of the WUA (Figure 5.2) was imported as an ArcGIS shape file. Shallow GW levels (Ibrakhimov et al., 2007) and a high DR ratio in the range of 0.55 (see Chapter 3) in the presence of a dense drainage system play important roles in the overall water management of the system. Therefore, the geo-referenced and digitized map of the drains and collectors in the WUA was introduced into the model domain (Figure 5.1). Observation wells were used not only for setting the flow initials as a groundwater surface at the beginning of the transient simulation run, but also as observation points for reference flow data. Therefore, GW levels and collectors/drains were introduced as add-ins, lines or points which FEFLOW used as focal points to create finite element nodes in the mesh generator in the FEFLOW domain. A triangular mesh was used as a mesh generator around the GW levels and collectors with 1000 element numbers (Figure 5.3). The domain is divided into 1476 triangular meshes and 794 total nodes.

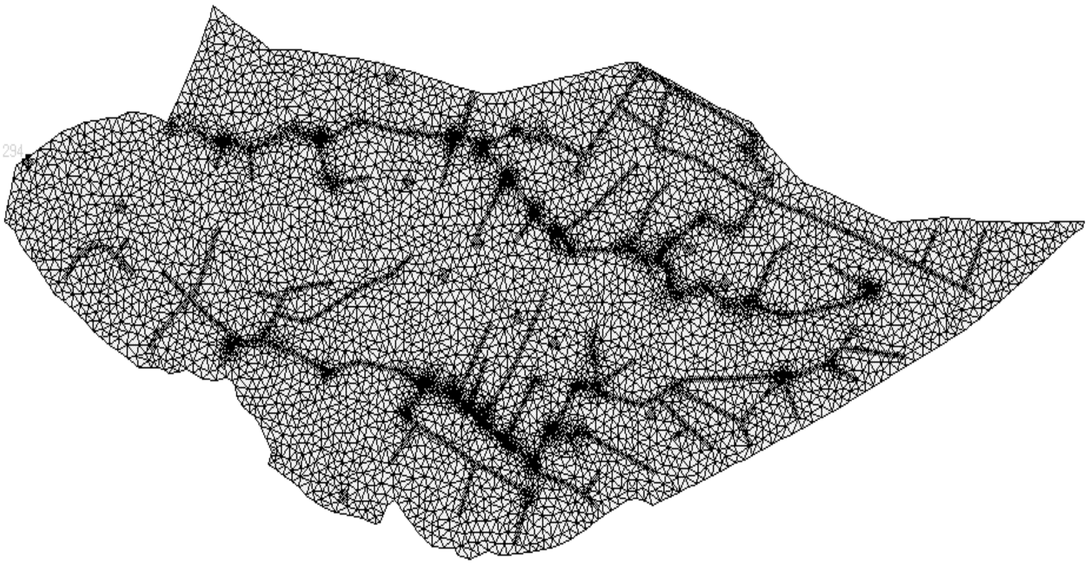


Figure 5.3 Finite element mesh (triangle) with high refinement around the collectors and observation wells

5.2.7 Problem class and temporal and control data

Due to the dynamic nature of GW levels, fluctuating water levels in canals and drains and varying recharge rates during the simulation period, the transient flow model for an unconfined phreatic aquifer with the top slice as a free and movable surface (GW level) and bottom as a fixed surface (impermeable layer) was set as a problem class. For the temporal approximation, the forward Adams-Bashforth/backwards trapezoid rule predictor-corrector scheme with adaptive time stepping (error tolerance 10^{-05}, initial time step length 0.001 days, maximum time step length 0.1 days) was used (Diersch, 2002b), which helped to eliminate numerical oscillations (i.e., it is a stable computational tool) that may have otherwise occurred.

5.2.8 3D-slice elevation

A geomorphological-lithological map of the Khorezm region and Turtkul oasis (Pre-Aral Hydro-Geological Expedition, 1982) covering Khorezm at a scale of 1:100,000, which contains information on the geometry of strata, was obtained from the hydrogeological Station of Khorezm and introduced in a 3D-slice elevation menu of FEFLOW. Among the available maps for four hydrogeological cross sections (I-I, II-II, III-III and IV-IV; Figure 5.4 and Figure 5.5), the cross section IV-IV in northeast-southwest direction is the closest section near the WUA Shomakhulum.

In the simulation area, the depth of the phreatic aquifer is 48 m, and the elevation of the bottom barrier (impermeable layer) of the aquifer is 50 m a.s.l. The thickness of the top layer (loam to sandy loam) is 1.5 m over a 31.5 m deep sandy layer. Between the sandy layer and the impermeable layer, the thickness of the sandstone layer is 15 m. Based on this layer information, the vertical discretization corresponds to 3 layers and 4 slices.

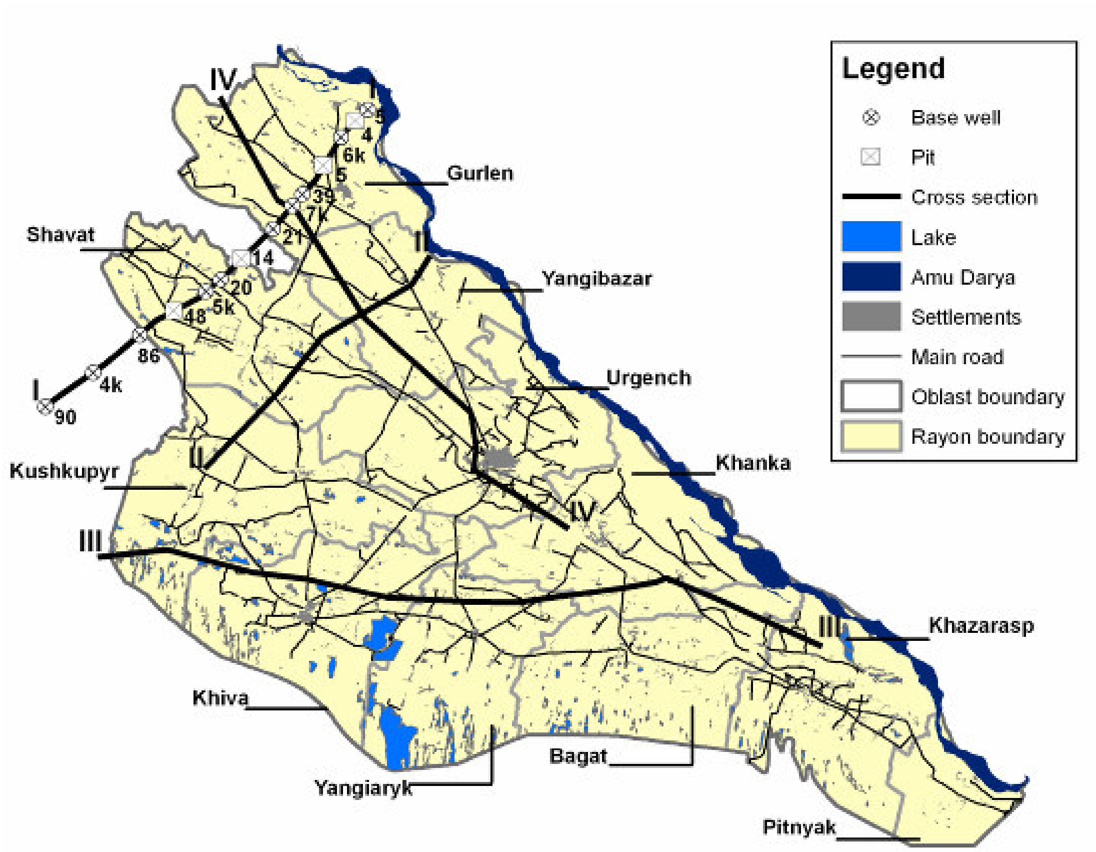


Figure 5.4 Location of the four different hydrogeological cross sections in Khorezm. The cross section IV-IV passes near the WUA Shomakhulum (Pre-Aral Hydro-Geological Expedition, 1982)

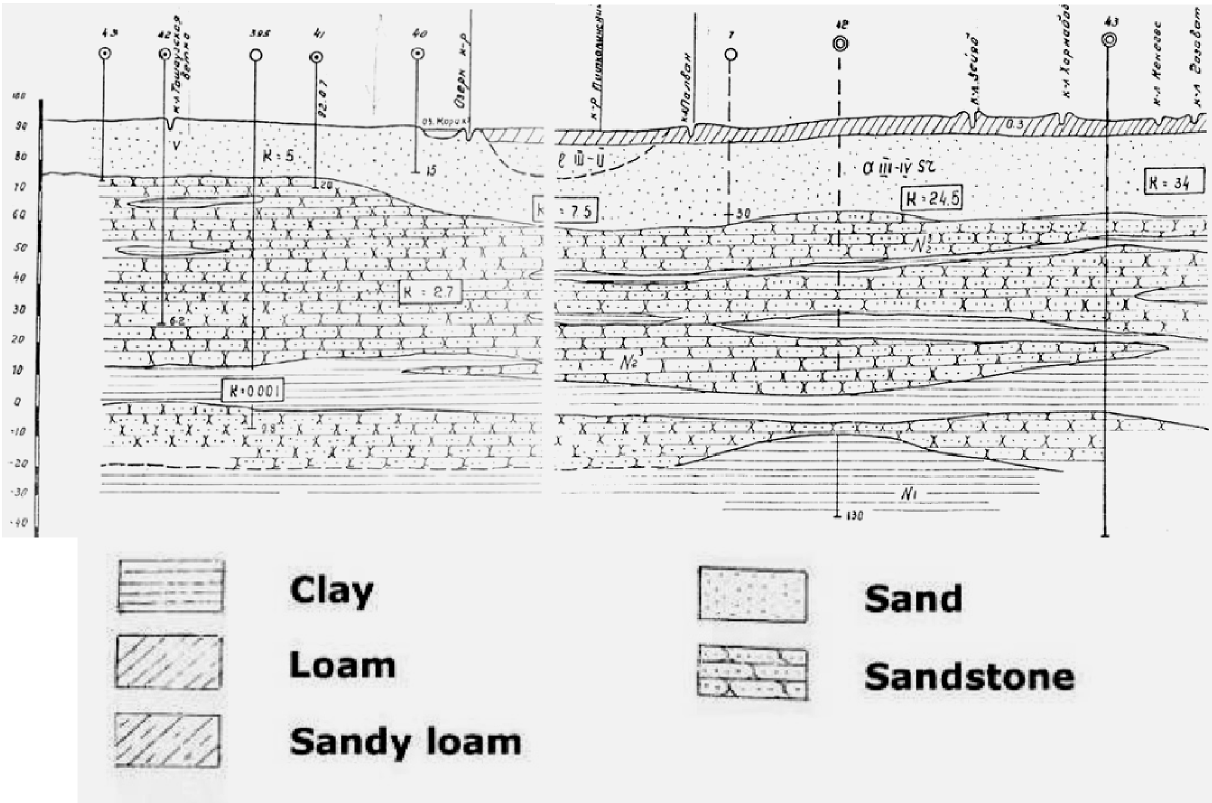


Figure 5.5 Material properties of different strata for IV-IV hydrological cross section

5.2.9 Flow data

Flow initials

A total of 15 monitoring wells was available in the WUA for perennial measurements of the GW level (Figure 5.1). The GW levels in the beginning of April were attached as an attribute table to the shape file of the observation well and directly transferred into the database of FEFLOW to set an initial groundwater surface of the WUA. The equation used for defining the initial values of water surface for the domain (Ω) of the simulated scope is given as:

$$h(x_i, 0) = h_I(x_i) \quad \text{in } \Omega \qquad (5.6)$$

where h_I is the spatial varying function of initial distribution.

Data regionalization for hydraulic heads over the study area was carried out using Akima interpolation.

Flow boundaries

The 1st- kind or Dirichlet- type boundary condition describes a hydraulic potential at a node. The Dirichlet boundary condition was set by inputting head values of the canals and collectors around the simulated area (Figure 5.6). The domain of the model is surrounded by the Zey-yop and Polvon canals and coincides with the groundwater flow lines on the northern and eastern border, respectively, while the Gauk Canal and collector intersect the GW surface in the southern to western part of the WUA, respectively.

$$h(x_i, t) = h_1^R(t) \qquad \text{on } \Gamma_1 \ t(0,\Theta) \qquad (5.7)$$

where h_1 is Prescribed boundary values of hydraulic head h, and Γ_1 the boundary of the first type.

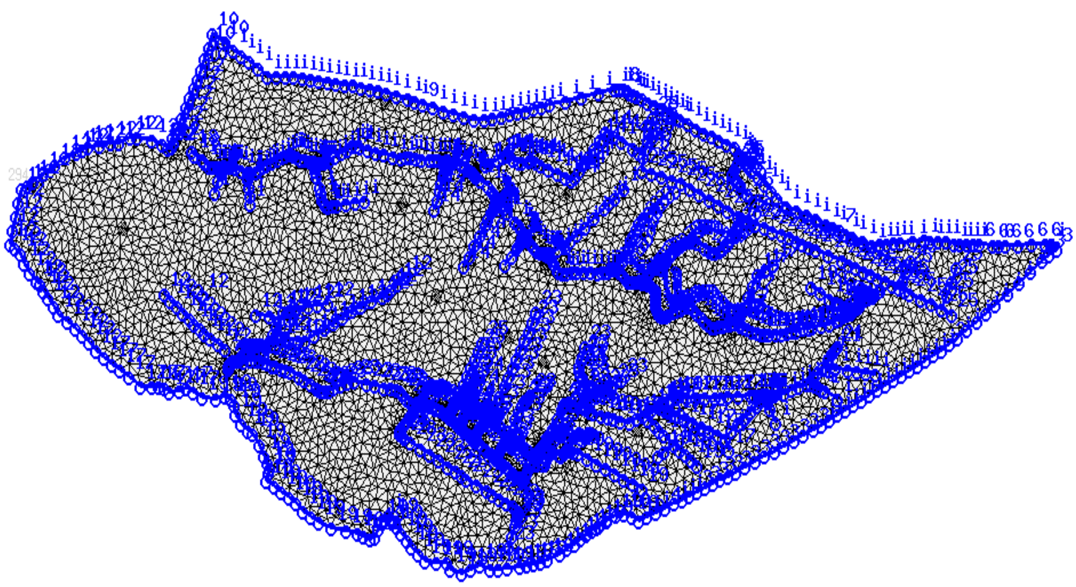


Figure 5.6 First kind or Dirichlet-type boundary condition for canals and collectors around and within the WUA Shomakhulum

To introduce the artificial bottom slope of the canals and collectors in the FEFLOW model, data on the bottom elevation from m.a.s.l. at different points in these canals and collectors were obtained from *TEZIM* (Irrigation System Authority). Historical surface water levels on a monthly basis were added to the bottom elevation of these points and treated as time-variant hydraulic data. The changes of the water level against time were prepared in ASCII format and designated as power function (time vs. water level) identification numbers (IDs) in FEFLOW. Akima linear interpolation was used to define the prescribed head boundary condition for the whole length of canals and collectors.

The existence of the dense drainage system has a significant influence on the GW flow, and therefore was also introduced in the domain of the model. The digitized map of the drains and collectors was prepared in ArcGIS and imported into the FEFLOW model. The 1st kind or Dirichlet-type boundary condition was used with the same procedure as described above for the surrounding canals and collectors.

Flow materials

The essential flow material properties for a GW model in a saturated zone include hydraulic conductivity, transmissivity, storativity, porosity and in-/outflow on top/bottom, etc. FEFLOW provides default values for most of these parameters. In this study the values for storativity and porosity were taken from the values provided by Freeze and Cherry (1979) for the aquifer characteristics similar to the study region.

Cross-section IV-IV in the geomorphological-lithological map was used to take the values of different hydraulic conductivity in different layers. According to the borehole results for this cross section, the hydraulic conductivity in the uppermost layer is 0.5 m/d, 24.5 m/d for the second layer, and 2.7 m/d for the third layer (Figure 5.7). As more detailed information was not available, the values are considered as uniform for the layers in the whole domain of the model.

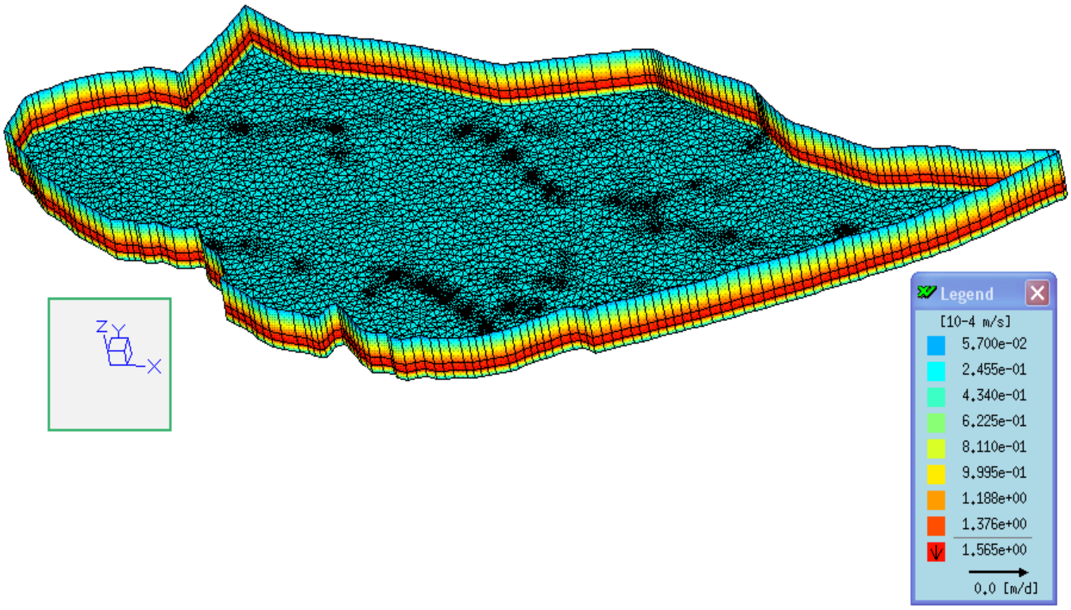


Figure 5.7 Hydraulic conductivity values in different layers of the FEFLOW model domain

Spatially variable recharge as the most important component in this surface-GW modeling was introduced as in-/outflow on top/bottom in the so-called 'flow material' menu of the model. The recharge values determined from the surface water balance model for the six HRUs and for the settlements were introduced on monthly time steps. The so-called 'T-list' in the menu controlling the creation of time-varying material distribution was used for time-varying recharge values.

The polygons for the HRUs and settlements were imported in ArcGIS format into the model. These polygons were assigned seven identification numbers (IDs). The monthly time-varying recharge data were prepared in ASCII format for each of the polygons. These curves were also assigned identification numbers (different IDs) and attached to the respective polygonal maps using the JOIN operation of the FEFLOW groundwater model. This operation assigned the values from power functions to the respective elements inside each polygon.

Table 5.1 Monthly recharge rates (mm) from water balance model as input to FEFLOW model for different hydrological response units (Source: Chapter 4)

(a) Scenario A

	April	May	June	July	August	September
Settlement			29	29	29	
HRU1	51	51	150	177	222	51
HRU2	33	39	138	234	288	6
HRU3	36	39	138	234	288	12
HRU4	51	114	162	222	246	24
HRU5	60	90	171	132	150	48
HRU6	33	45	171	231	261	39

(b) Scenario B

	April	May	June	July	August	September
Settlement			29	29	29	
HRU1	45	45	129	150	189	42
HRU2	27	33	120	198	246	6
HRU3	30	33	117	198	246	12
HRU4	42	96	138	189	207	21
HRU5	51	78	144	111	126	42
HRU6	30	39	144	195	222	33

(c) Scenario C

	April	May	June	July	August	September
Settlement			29	29	29	
HRU1	24	24	66	78	99	21
HRU2	15	18	60	102	126	3
HRU3	15	18	60	102	126	6
HRU4	21	48	72	96	108	9
HRU5	27	39	75	57	66	21
HRU6	15	21	75	102	114	18

(d) Scenario D

	April	May	June	July	August	September
Settlement			29	29	29	
HRU1	18	18	51	60	75	18
HRU2	12	12	48	81	99	3
HRU3	12	12	48	81	99	3
HRU4	18	39	54	75	84	9
HRU5	21	30	57	45	51	18
HRU6	12	15	57	78	90	15

Reliable data on irrigation practices and water level of canals and collector were only available on a monthly basis, so modeling was performed on a monthly basis. Yan and Smith (1992) emphasized the benefits of using the same time step to avoid inconsistency between surface and GW models.

5.2.10 Calibration

The GW model simulation was run for calibration and validation. In the calibration process (April to June), parameter values including drainage design (slope and depth) and recharge (driven by cropping pattern) were adjusted in order to optimize model performance (Wilby, 1997). During the validation process, simulation was performed for the period July to August. Nash–Sutcliffe coefficient, R^2 (Nash and Sutcliffe, 1970), and root mean squared error (RMSE) were used as error criteria to assess the goodness-of-fit for the observed and simulated GW values from the observed OW values. The Nash–Sutcliffe coefficient is defined as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(\lambda_{obs} - \lambda_{sim})^2}{\sum_{i=1}^{n}(\lambda_{obs} - \bar{\lambda}_{obs})^2} \tag{5.8}$$

where λ_{obs} is observed GW level, λ_{sim} is simulated GW level, and $\bar{\lambda}_{obs}$ is mean of observed GW level.

The RMSE is the square root of the average of squared differences between observed and simulated GW levels. The RMSE is usually considered to be the best measure of error if errors are normally distributed (Anderson and Woessner, 1992):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(\lambda_{obs} - \lambda_{sim})^2}{n}} \tag{5.9}$$

where n is the number of days of simulation.

Calibration and validation of the model after first run

In order to evaluate the performance of the integrated model, monthly GW levels simulated by the FEFLOW model were compared with the observed values. Out of the 15 observation wells, 10 were selected to evaluate the performance of the model. The remaining 5 wells are situated in the vicinity of the canals or drains and therefore did not represent the GW situation in the irrigated area. Figure 5.8 shows the averaged monthly simulated (standard deviation = 0.37) and observed (standard deviation = 0.12) GW levels of the selected 10 wells for the first run during the study period (April to September, 2007). The simulated and monthly GW levels are measured from the mean sea level (requirement of FEFLOW model).

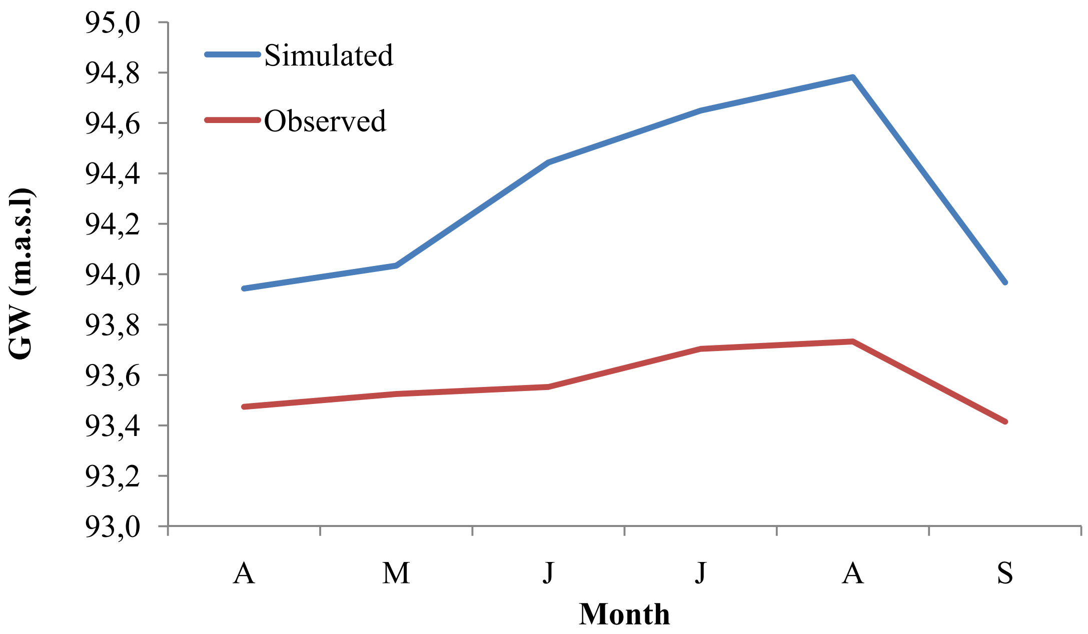


Figure 5.8 Monthly average of 10 selected wells of simulated (after first run) and observed GW levels

The observed GW levels are higher during July and August and reduce to a minimum in September. Higher GW levels in August are due to the highest recharge rates during this month (see Chapter 4). The difference in observed GW levels between April (start of the vegetation season) and August (peak irrigation season with highest GW levels) is 26 cm.

The trend of simulated GW levels is similar to that of the observed ones, i.e., higher GW levels in August and lower levels in September. However, the difference in simulated GW levels between April (start of the vegetation season) and August (peak irrigation season with highest GW levels) is 84 cm, which is 58 m higher than between the observed levels.

The difference between the simulated and observed GW levels in the beginning of the season was 0.47 m and increased to 1.1 m during the peak irrigation season. At the end of the season, both curves were closer to each other, and in September the difference reduces to 0.55 m. The data show that higher recharge rates during the vegetation season are not drained out from the domain of the model. The smaller difference (around 0.5 m) between observed and simulated GW level during the low irrigation period (April-May, June) is due to low recharge rates, which cannot fill the aquifer to the same level as in the irrigation period. A difference as high as 1 m between observed and simulated GW levels in the first run is not uncommon. Wang and Anderson (1989) reported that the heads computed from the first run of the model rarely match the field values. Arnold and Allen (1999) pointed out that although inputs to the model were based on observed or measured information, there is often considerable uncertainty in model inputs due to spatial variability and limited precision of the measurements, etc. Therefore, the model was calibrated before running the model for different irrigation efficiency scenarios.

Kim et al. (2004) reported that primary calibration parameters for the GW model are the aquifer hydraulic conductivity and storativity, whereas Sarwar (1999) reported that adjustment of the water levels (heads) surrounding the area, recharge rates and drainage depth can be the potential calibration parameters.

As discussed above, the model for the first run was not parameterized taking into consideration that it can drain out the high recharge rates. Low discharge from the drainage system due to underestimated drainage design (gentle slope and lesser depth), mixing of the lower hydraulic conductivity of the uppermost layer with much higher hydraulic conductivity of the second layer (smaller depth of the uppermost layer (1.5 m) and sparse information on topography) and higher recharge rates than the actual rates were recognized in this study as the potential reasons for higher simulated GW levels. As calibration involves determining the magnitude and spatial distribution of the model parameters, these model parameters were reproduced to come near to the observed system states with time. Depth and slope of the collectors and drains, hydraulic conductivity and recharge rates were then optimized by a trial and error procedure (Anderson and Woessner, 1992).

For the calibration and later validation of the model, the GW dataset for the whole vegetation season (April to September 2007) was divided into two parts. The GW data for the first half of the vegetation season (April to June) were used for calibrating the model, while the GW data for the second half (July to September) were used to validate/check the model.

The calibration of the simulated run was done at two spatial levels, i.e., WUA and HRU. At the WUA scale, the drainage system was calibrated, while hydraulic conductivity and recharge rates were calibrated for the corresponding HRUs. Drains and collectors being spread all over the WUA in the form of a contiguous network cannot be treated separately in HRUs, and therefore the slope and the depth of the drains were calibrated at the WUA level. According to the officials of the WUA, the drainage depth is 2.0 m from the surface in the whole area. However, this information is very coarse and does not include spatially explicit information about the slope of the drains and collectors, which can substantially affect the drainage outflows. Therefore, the model was calibrated assuming that the drainage system follows a uniform slope and is not affected by the constraint of 2.0 m depth.

After adjusting the drainage depth, the upper layer of the model was calibrated for the hydraulic conductivity. As this layer, due to its textural class (loam to sandy loam), may strongly influence the recharge rates, assigning correct hydraulic conductivity values to it is important. The difference in hydraulic conductivity between the first (0.5 m d^{-1}) and the second layer (24.5 m d^{-1}) is substantial, whereas the thickness of the first layer is only 1.5 m. Moreover, topographic maps are interpolated based on only 26 point values, and it is therefore difficult to exactly define the 1.5 m layer. Upper layer being sensitive to hydraulic conductivity which can affect the results a due consideration was given for assigning the upper layer depth in the FEFLOW model.

After calibrating the model for drainage design and hydraulic conductivity for the whole WUA, recharge rates were used for calibrating the wells in the individual HRUs. It was observed during the calibration that changes in hydraulic conductivity and most importantly the drainage design provided the desired results. Only small changes were necessary for the recharge rates.

When most of the simulated and observed GW levels were within 0.5 % of the absolute height (m.a.s.l.), calibration was terminated. It took around 80 simulation runs before this acceptable calibration was achieved. According to Sarwar (1999), it is not uncommon to make from 20 to 50 simulation runs before an acceptable calibration is reached.

The observed and simulated GW levels for the calibration period were drawn on a scatter plot (Figure 5.9). A 45°-line was drawn representing the relationship under ideal conditions, i.e, simulated GW levels are equal to the observed ones. The trend line of the observed versus simulated GW levels is quite close to the 1:1 line, which means that the model is calibrated successfully. The Nash–Sutcliffe coefficient (R^2), which determines the efficiency of the calibration, is 0.94. This shows that the deviation of the simulated GW levels from the observed ones is only 6 %. The root mean square error (RMSE) of the simulated GW levels from the observed ones is only 0.20 m.

After successful calibration of the model, it was verified for the GW dataset from July to September (Figure 5.10).. The Nash–Sutcliffe coefficient (R^2) for the validation period is 0.93, which shows that deviation of simulated GW levels from the observed ones is only 7 %. The root mean square error (RMSE) of the simulated GW levels from the observed ones is similar to that of the calibration period.

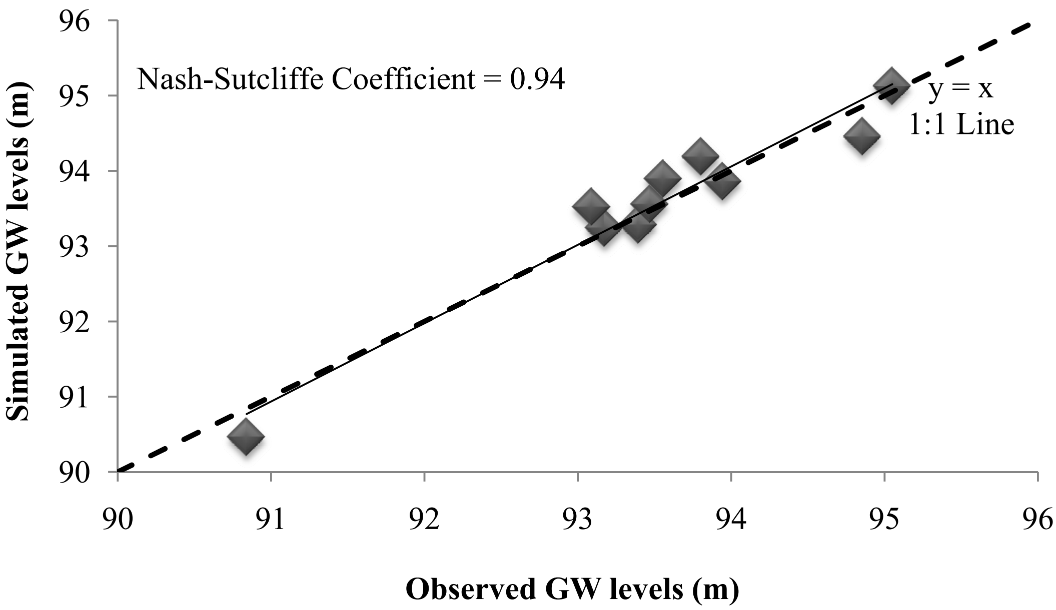


Figure 5.9 Nash–Sutcliffe coefficient for calibration. Dotted line = 45° line, continuous line = trend line

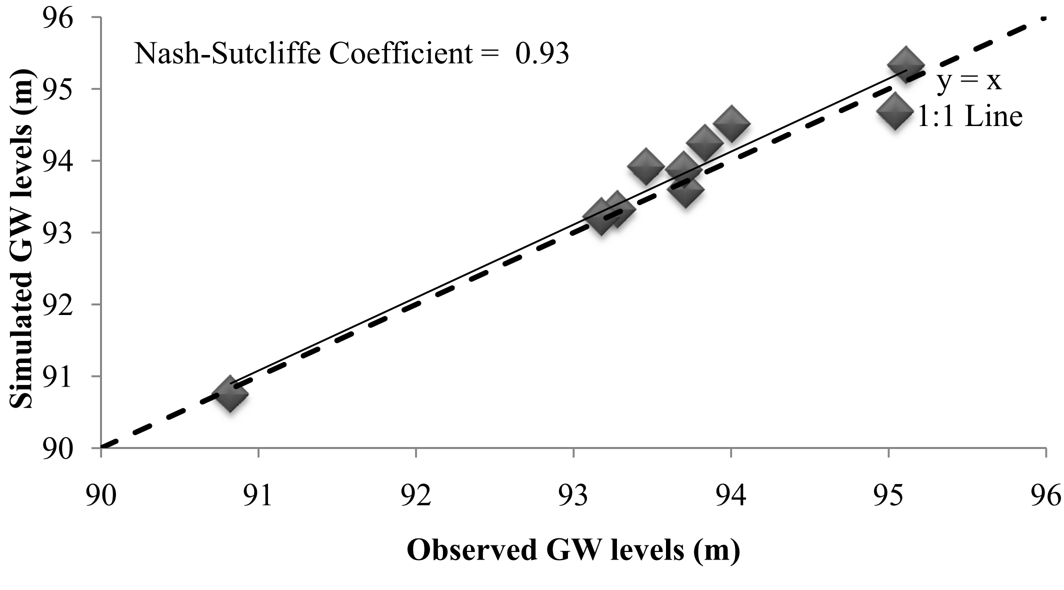


Figure 5.10 Nash–Sutcliffe coefficient for validation. Dotted line = 45° line, continuous line = trend line

5.2.11 Scenarios of ground water dynamics simulated by FEFLOW

From the water balance model, recharge based on four scenarios (S-A: baseline or business-as-usual (BAU), S-B: improving CR; S-C: raising FAR; S-D: improving FAR and CR together) was determined and introduced in the FEFLOW groundwater model. Recharge rates for all four scenarios were different on the basis of six hydrological response units (differing by soil type: shallow- silt loam (S-SL), medium-silt loam (M-SL) and D-SCL (deep-silt loam)) and therefore were introduced in FEFLOW model based upon these HRUs. The recharge values for these four scenarios are presented in Table 5.1, and the details of recharge estimation for these scenarios are given in Chapter 4.

5.3 Results and discussion

5.3.1 Groundwater dynamics simulated by FEFLOW model under business-as-usual scenario

Figure 5.11 and Figure 5.12 depict the groundwater surface before (May) and after (August) the peak irrigation period (June to August) for the WUA Shomakhulum under the business-as-usual scenario. To understand the behavior of GW levels within the WUA, the influencing factors, i.e., main canals, collectors and settlements were compared. The simulation map for May (Figure 5.11) shows that the dynamics of the GW surface are under the strong influence of these factors. This also applies to the situation in August.

The maps show the usual trend of GW dynamics, i.e., GW levels are shallow around the main canals and deep around the collectors. Shallow GW levels in the vicinity of the Povon and Zey-Yop canals are due to the higher seepage from these main canals. At the junction point of these canals, the effect of seepage is even higher and extends to larger areas resulting in shallow GW levels in these areas. GW levels are deep in the vicinity of the collectors. At the junction where the Sapcha collector falls into the south collector, the GW level is quiet deep. Deep GW levels around these collectors are due to ex-filtration from the GW to these collectors.

GW levels were expected to be deep in the settlement areas due to low recharge rates. However, this is not the case in the Shomakhlum WUA. GW levels in the settlement areas are almost the same as the GW levels in the fields. The reason can be the poor drainage due to lack of drainage infrastructure in the settlements.

The general slope of the GW level is from east to south, which is in line with the overall slope of the Khorezm region.

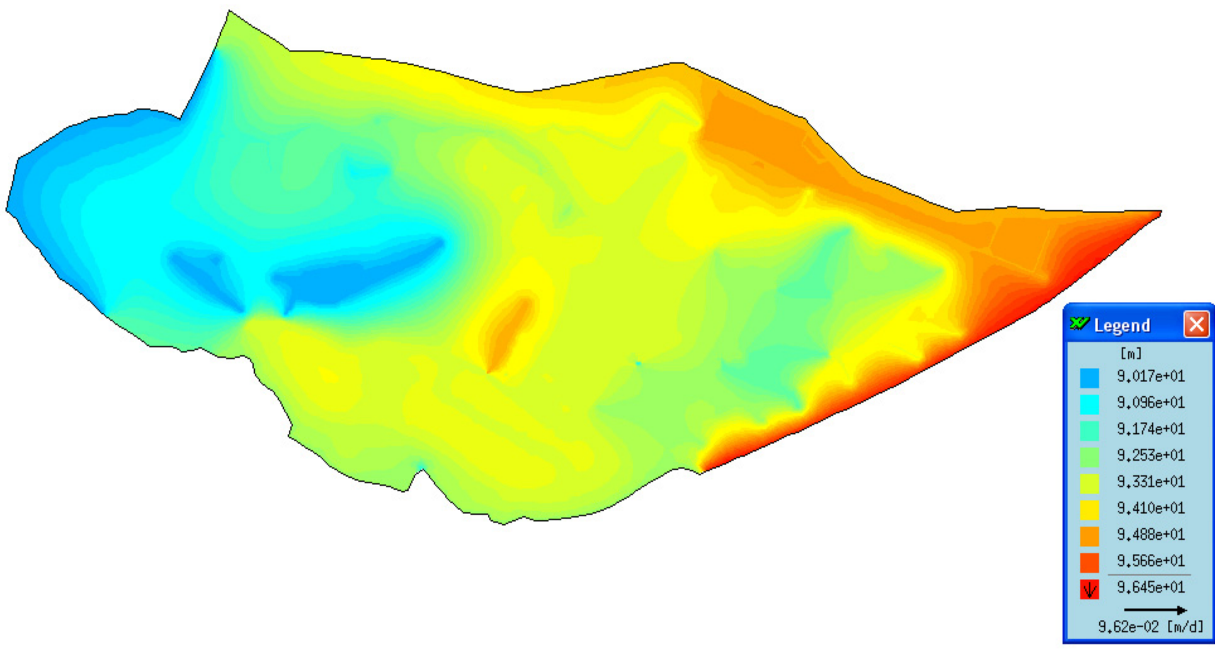


Figure 5.11 Groundwater surface simulated by FEFLOW model before peak irrigation season (May)

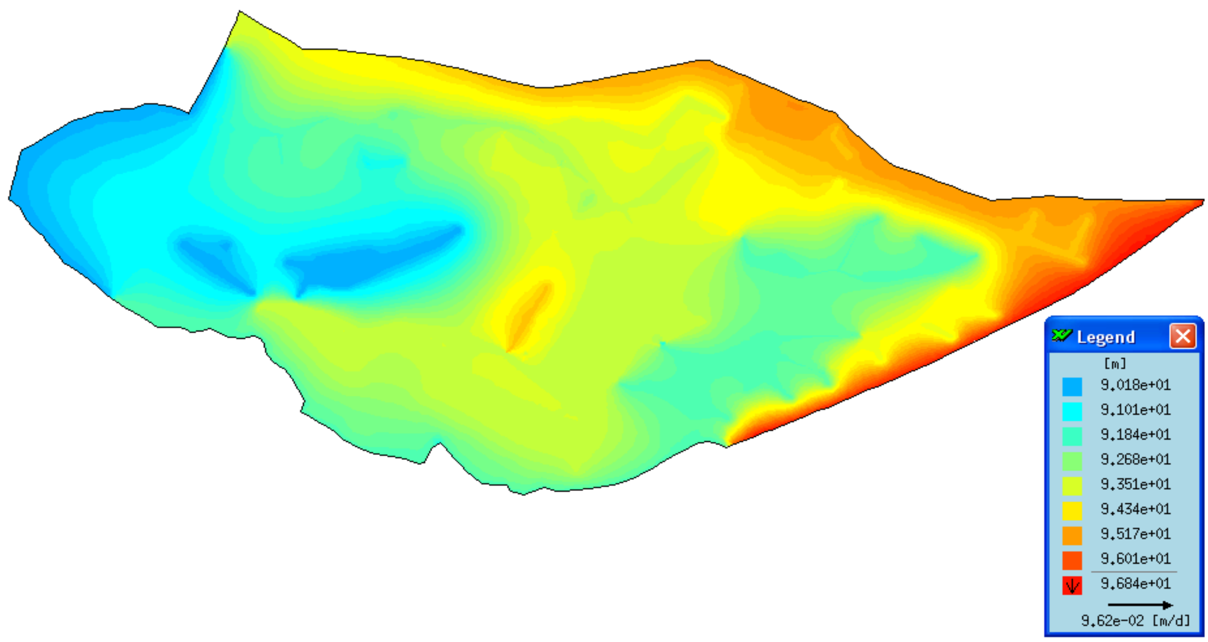


Figure 5.12 Groundwater surface simulated by FEFLOW model after peak irrigation season (August)

The model was further used to assess the behavior of GW levels under different irrigation efficiency scenarios.

5.3.2 Ground water dynamics simulated by FEFLOW model under different irrigation efficiency scenarios

The results of the scenarios are presented as the average of the GW levels from the 10 selected observations wells and thus represent the dynamics of the GW levels at WUA level (Figure 5.13). The monthly trend is similar for the first two scenarios, but quite different for the last two. In first two scenarios, i.e., S-A and S-B, irrigation efficiency is quite low, whereas irrigation efficiency is comparatively much higher in S-C and S-D. The trend differences can be explained by considering the GW levels for April and August. For S-A, the GW levels are 30 cm higher in April than in August, whereas this difference reduces to 19 cm for S-B. In contrast, in S-C and S-D the GW levels rise from April to August . The results of S-C show that GW levels are 5 cm higher in April than in August, while for S-D this difference increases to 10 cm.

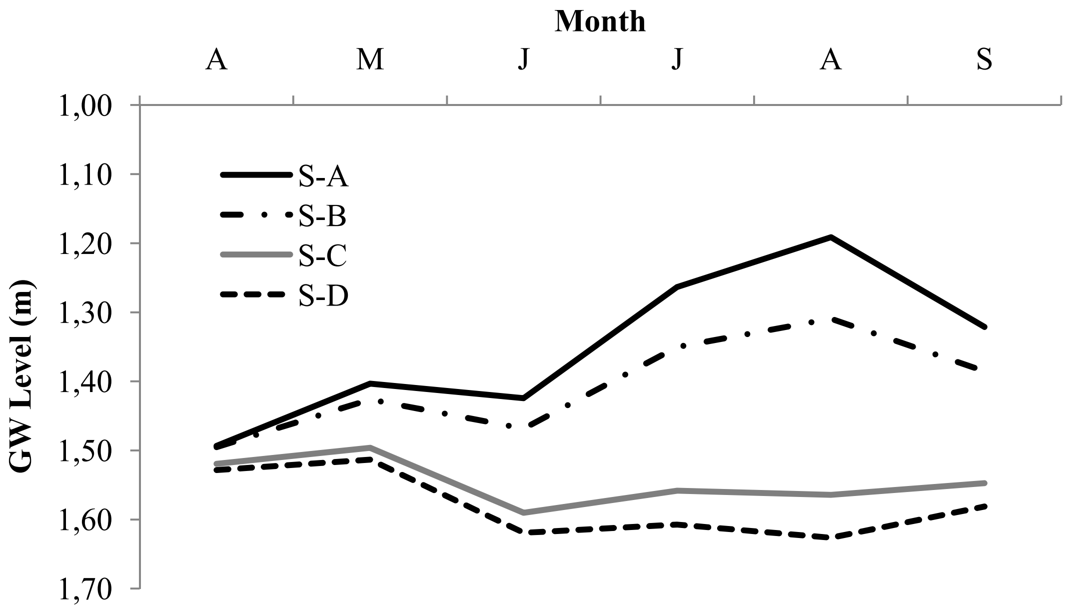


Figure 5.13 Simulated mean monthly GW levels for 10 observation wells for four improved irrigation efficiency scenarios (S-A = baseline or business-as-usual, S-B = improving conveyance ratio, S-C = raising field application ratio, S-D = improving field application ratio and conveyance ratio)

The comparison of the simulated GW levels between April and August for all scenarios shows a continuous lowering of GW levels in August, which even were lower than the levels of April in S-C and S-D.

The model was setup in a way that on the one hand, the recharge rates reduced with the improved irrigation efficiency, and on the other hand, the drainage design was kept constant for these scenarios. The drain capacity was designed for the higher recharge rates especially during the peak irrigation season (June to August), but when the recharge rates were reduced in S-B, S-C and S-D, the drainage design started to lead to over-draining and hence the GW levels dropped substantially, especially in the latter two scenarios. Although there was reduction in recharge values for the start and end of the irrigation season, the amount of recharge was already too low to substantially affect the GW levels in these months.

Comparing the monthly averaged simulated GW levels of the different irrigation efficiency scenarios helps with the interpretation of the data (Table 5.2). S-A being the baseline scenario was first compared with the other three scenarios, and then the other scenarios were compared with each other.

Table 5.2 Differences between monthly averaged simulated GW levels (cm) under different scenarios for the WUA Shomakhulum

Month	*SA-SB	SA-SC	SA-SD	SB-SC	SB-SD	SC-SD
A	0	2	3	2	3	1
M	2	9	11	7	9	2
J	4	16	19	12	15	3
J	8	29	34	21	26	5
A	12	38	44	26	32	6
S	7	23	26	16	19	3

The GW levels in S-B only slightly declined compared to the baseline scenario. The maximum decline in GW levels in S-B was 12 cm in August (Table 5.2), whereas the minimum was 0 cm in April. The overall decline in GW levels in S-B is due to the conveyance ratio (CR), which was increased to 0.84 in this scenario. As the CR in the WUA (0.76) is already close to the target value (0.84), the increased CR hardly affected the recharge rates and GW levels.

In S-C, the decline in GW levels compared to the baseline S-A is quite high (Figure 5.13). The GW levels dropped by a maximum of 38 cm (August) when compared to S-A. This significant lowering of the GW levels in S-C as compared to S-B is due to the higher gap between the current (0.43) and the target (0.67) application ratio.

In S-D, the decline in GW levels from the baseline S-A is highest when compared to all scenarios but is quite low when compared to S-C (Figure 5.13). The GW levels in this scenario dropped by a maximum of 44 cm (August) when compared to the baseline scenario. In this baseline scenario, the maximum achievable application and conveyance ratios are used, which resulted in maximum reduction in the net recharge and hence the maximum decline in the GW levels. When the results of this scenario are compared to those of S-C, the decline in GW levels is lowest. The low decline in GW levels in this scenario is again due to low increase in CR.

The decline in GW levels in S-C and S-D compared to S-B is similar (Table 5.2). In S-B, the current value of application efficiency (0.43) was used, whereas in S-C and S-D, the target (0.67) value was used. Although application efficiency in S-C and S-D is similar, the difference in decline in GW levels in both of these scenarios is due to the difference in the conveyance ratio.

Above results of the scenarios show that GW levels can decline by 5 to 44 cm during the vegetation season. There are only few studies on the influence of improved irrigation efficiency scenarios on GW levels. Sarwar and Eggers (2006) conducted a study in Rechna Doab, Pakistan, to determine the influence of changes in cropping patterns and intensities on GW levels. However, in one of their scenario analysis with FEFLOW, they showed that GW levels would decline by 44 cm if the irrigation efficiency were to increase by 25 %. However, in the WUA Shomakhulum, the same decline in GW levels (44 cm) would occur after improving the irrigation efficiency by 42 %. The difference in the findings can be well explained by comparing the GW conditions of the study areas. GW conditions in the WUA Shomakhulum are shallow, and therefore 90 % of the losses from the fields recharge the aquifer (as discussed in section 4.2.4). In contrast, mean GW levels in Rechna Doab are 4.01 m below the surface and therefore the author assumed that only 75 % of losses can recharge the aquifer. Based on these assumptions, it can be concluded that the results of the studies are comparable.

The results of the present study show that a GW decline of 3-44 cm during the vegetation season (June to August) can occur. As GW levels in the WUA Shomakhulum, like in the rest of the Khorezm region, ranged from 1 to 1.5 m during the vegetation season, a 3-44 cm decline can not only increase the surface water demand but also reduce the crop yield. Kahlown (2005) reported for Pakistan that most of the crops obtained a substantial part of their crop water requirements when the water table ranged from 0.5 to 2 m. However, GW contribution started declining after 1.5 m and reduced to minimum after 2.0 m. They also reported that shallow GW levels not only reduce the surface water demand but also increase the crop yield. Forkutsa (2006) reported that each centimeter of GW level decline can increase the surface water demand (see Chapter 6 and Chapter 7).

5.4 Conclusions

The focus of this study was to quantify the impact of improved irrigation efficiency scenarios on the dynamics of the GW levels. For this purpose, the FEFLOW model was parameterized for local conditions and successfully calibrated (R^2=0.94) and validated (R^2=0.93). A comparison of the simulated monthly GW levels shows that under existing conditions (S-A), the drainage design increased the GW levels by 30 cm from the start of the season (April) to the peak irrigation month (August). This difference reduces substantially in all the scenarios and eventually in S-D the GW levels declined by 10 cm from April to August. The results also illustrate that the existing drainage design in the S-A and S-B can lead to a draining out of the higher recharge, whereas in S-C and S-D the drainage can lead to over-drainage design by reducing the GW levels from the start of the season. The overall results show that under the existing drainage system, the improvements in irrigation efficiency will lower the GW levels by up to a maximum of 44 cm (S-A to S-D, for August). This decline in the GW level can lower the capillary rise contribution but at the same time can support leaching and reduce the salt accumulation. This study provides guidelines for the policy makers in the region and demonstrates the importance of improved irrigation efficiency with respect to the GW dynamics. Drainage outflow policies should be adapted to changing GW conditions.

***Abstract**: Simulating the groundwater situation under the complex irrigation and drainage network in the Shomakhulum water users association, Khorezm, Uzbekistan*

Surface and groundwater resources are conjunctively used in many parts of the world to cope with water scarcity in irrigated agriculture. Farmers in the Khorezm region of Uzbekistan also utilize the shallow groundwater (GW) in addition to the surface water withdrawn from the Amu Darya River The focus of this study is to model the GW situation in this extensive irrigation network, which is characterized by an insufficiently designed and poorly managed open drainage system. The FEFLOW-3D model was applied to a water users association (WUA Shomakhulum) situated in the southwest of Khorezm, and used to quantify the impact of improved irrigation efficiency scenarios on GW dynamics. The modeled scenarios are current irrigation efficiency (S-A baseline), improved conveyance efficiency (S-B), increased application efficiency (S-C), and improved conveyance and application efficiency(S-D). Recharge rates were separately determined for six hydrological response units (differing in soil type: shallow-silt loam (S-SL), medium-silt loam (M-SL) and D-SCL (deep-silt loam)) and introduced into FEFLOW. After successful model calibration (R^2 = 0.94) and validation (R^2 = 0.93), the scenario simulations show that improving the irrigation efficiency under the existing drainage system would lower the GW levels in August on average by 12 cm in scenario S-B, 38 cm in S-C and 44 cm in S-D. From the start of the season (April) to the peak irrigation month (August) GW levels would rise by 30 cm and 19 cm in S-A and S-B, respectively, and decrease by 5 cm and 10 cm, respectively, in S-C and S-D. These simulations show that when the recharge rates are high (S-A and S-B), the current drainage system cannot drain out the water properly from the WUA, which is due to inefficient drainage design at the outlet of the system and partially insufficient drainage depth, whereas with reduced recharge rates (S-C and S-D), the GW level could be lowered to a greater extent than at the start of the season. This shows that the current system could be re-designed for such recharge rates, which would improve irrigation sustainability in times of scarcity. Lowering the GW levels in July and August (especially in scenarios S-C and S-D) would significantly reduce the capillary rise but help to reduce soil salinity through reduced salt accumulation and increased leaching effect of percolation losses.

6 SIMULATING CAPILLARY RISE BY HYDRUS-1D

6.1 Introduction

Scenarios predict fresh irrigation water scarcity worldwide either due to the competition among the different users (agricultural, urban, industrial and environmental) or to the increasing food and fiber demands (Ayars et al., 2006) resulting from the growing world population (UN, 2004). The situation will likely be more serious in arid and semi-arid regions where water is already a scarce commodity. One of the options to mitigate water shortages is to investigate the utilization of groundwater (GW) resources. Babajimopoulos (1991) reported that the shallow GW in irrigation schemes in arid and semi-arid regions of the world can be used to irrigate crops either by using drainage water for irrigation (pumping) or through in-situ use (subsurface). Quantification of water uptake by crops from GW is a prerequisite to evaluate the option to use/include GW, and has been a challenge for different researchers in the past decades as it is dependent on several factors.

Wallender et al. (1979) found that cotton extracted up to 60 % of its evapotranspiration (ET) from a saline (6 dS m^{-1}) water table at a depth ranging from 1 to 2 m. Ayars and Schoneman (1986) reported that cotton extracted up to 49 % ET from a saline (10 dS m^{-1}) shallow water table (1.7 to 2.1 m) depending on the amount of fresh water applied. The maximum use of saline groundwater occurred when only one irrigation was applied after pre-plant irrigation for cotton. For a safflower crop, Soppe and Ayars (2003) found that for a saline (14 dSm^{-1}) water table at 1.5 m depth, the groundwater contributed up to 40 %. Kahlown et al. (2005) found that with a water table at 0.5 m depth, wheat met its entire water requirement from the groundwater and sunflower took more than 80% of its required water from there.

Most of the studies on in this issue were lysimeter studies, which provided accurate results. However, the results were based on the experimental conditions. The major problem of lysimeter experiments is upscaling the results to field or even larger scales. Recent developments in mathematical modeling enable determining the water flow and solute transport under given agro-climatic conditions.

HYDRUS-1D is a software package for simulating water, heat and solute movement in one-dimensional variably saturated media. The numerical codes in HYDRUS solve the Richard's equation (for details see below). HYDRUS-1D provides an interactive graphics-based user-friendly interface for the MS Windows environment, which simplifies the preparation and management of input data files, and a graphical display of the final simulation results.

HYDRUS (tested by Forkutsa, 2006 and Forkutsa et al., 2009 in Khorezm) was selected for the estimation of the capillary rise contribution in the Shomakhulum Water Users Association (WUA) situated in the southwest of the Khorezm region in Uzbekistan. This WUA, like the rest of Khorezm, suffers from untimely and unreliable water supplies. Due to the intensive density of the irrigation system with low application and conveyance ratios (low depleted fraction), recharge rates are quite high, which results in shallow GW levels (see Chapter 4) that often range 1.0-1.2 m below the surface during leaching and irrigation events (Ibrakhimov et al., 2007). The survey during the field work, discussions with the WUA officials, and results from the study conducted by Forkutsa et al. (2009) revealed that farmers and irrigation planners wish to prevent the decline in GW levels. The GW levels are considered as a safety net against unreliable delivery of irrigation water to individual farms and fields. These GW levels are a potential contributor to the crop water requirements. Due to the strategic importance of cotton, many studies in the past have been conducted in the region to determine the capillary rise contribution to the surface water requirements of cotton (Forkutsa, 2006; Abdullaev, 1995; Yusupov et al., 1979). The results of these studies were specific to the field conditions. However, the capillary rise contribution depends on several factors, e.g., soil texture, GW level and cropping pattern, which vary significantly in irrigation canal command areas or large irrigation schemes. To capture the spatial variation of these factors, six hydrological response units (HRUs) were established (see Chapter 4). Capillary rise was first calculated for different crops and for the characteristics of these HRUs at field level and then, using the aggregation method, was up-scaled to the respective HRUs and then to the whole WUA.

Furthermore, GW levels simulated by FEFLOW-3D model (Chapter 5) for S-SL, D-SCL and M-SL under four improved irrigation efficiency scenarios (S-A: current irrigation efficiency or business-as-usual (BAU), S-B: improved conveyance efficiency, S-C: increased application efficiency, S-D: improved conveyance and application efficiency) were then introduced into the HYDRUS-1D model to quantify the impact of improved efficiencies on capillary rise contribution (details on the scenarios are given in Chapter 2).

6.2 Materials and methods

6.2.1 Study area

Figure 6.1 shows the boundaries of the hydrological response units, the details of which are presented in Chapter 4. Details of the study area are presented in Chapter 2.

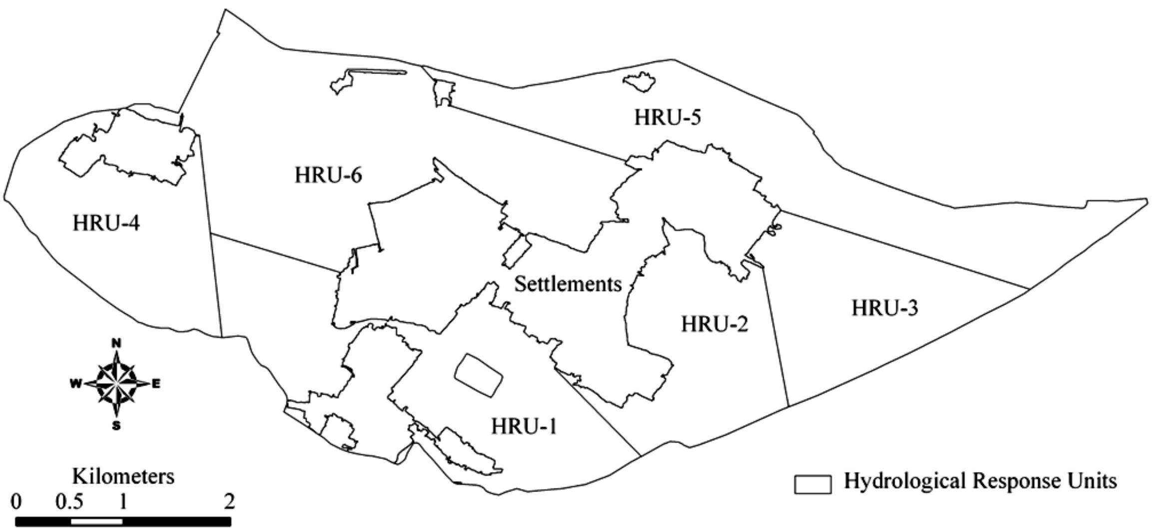


Figure 6.1 Location of hydrological response units in the WUA Shomakhulum, 2007

6.2.2 Hydrological response units

To represent the spatial dynamics of GW levels and the soil characteristics, the WUA was divided into spatial units in which characteristics influencing the magnitude of capillary rise were assumed uniform, i.e., hydrological response units (HRU; see Chapter 4). The matrices of soil properties, GW levels and cropping types in the HRUs are:

$$\begin{array}{c} \boxed{\text{Crop} \qquad\qquad\qquad \text{HRU}} \\ \begin{Bmatrix} \boldsymbol{C} & \boldsymbol{S-SL} \\ \boldsymbol{W} & \boldsymbol{M-SL} \\ \boldsymbol{V} & \end{Bmatrix} \\ \hline \text{(a)} \end{array} \qquad \begin{array}{c} \boxed{\text{Crop} \qquad\qquad\qquad \text{HRU}} \\ \begin{Bmatrix} \boldsymbol{C} & \boldsymbol{D-SCL} \\ \boldsymbol{W} & \\ \boldsymbol{V} & \end{Bmatrix} \\ \hline \text{(b)} \end{array} \tag{6.1}$$

where C is cotton, W is wheat, V is vegetables, S-SL is shallow-silt loam, M-SL is medium-silt loam, and D-SCL is deep silt clay loam.

From matrix (a) for silt loam soils, 6 combinations were formed, and for matrix (b) for silt clay loam soils, 3 combinations were formed. The capillary rise was determined for these 9 combinations.

6.2.3 Determination of capillary rise using HYDRUS-1D model

Upward movement of water (capillary rise) was modeled using the version 4.0 of HYDRUS-1D, a software package for simulating water, heat and solute movement in one-dimensional variably saturated media. The model computer program numerically solves the Richard’s equation for saturated-unsaturated water flow, dual-porosity type flow and dual-permeability type flow, while advection- and dispersion-type equations are used for heat and solute transport.

6.2.4 Parameterization of HYDRUS-1D model

Richard’s equation is a fundamental equation used in the HYDRUS-1D model for calculating the water flow. HYDRUS-1D provides the codes for different sub-models and equations to calculate the unknown in the Richard’s equation.

The one-dimensional Richard’s equation simulates water movement in variably saturated media assuming that the air phase plays an insignificant role in the liquid flow process and that water flow due to thermal gradients can be neglected (Simunek et al., 2005). It is described as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K\left(\frac{\partial h}{\partial x} + \cos\alpha\right)\right] - S \qquad (6.2)$$

where h is water pressure head [L], Θ is volumetric water content [L^3L^{-3}], t is time [T], x is spatial coordinate [L] (positive upward), S is sink term [$L^3L^{-3}T^{-1}$], α is angle between flow direction and the vertical axis (α = 0° for vertical flow, 90° for horizontal flow), and K is unsaturated hydraulic conductivity function [LT^{-1}].

For vertical flow, the equation can be written as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K\left(\frac{\partial h}{\partial z} + 1\right)\right] - S \qquad (6.3)$$

where z is the vertical coordinate (positive upward).

The unsaturated hydraulic properties (soil water retention, θ (h), and hydraulic conductivity, K (h)) and sink term are determined using different models as described in the following sections.

6.2.5 Model for unsaturated soil hydraulic properties

Among the five different analytical models available in HYDRUS-1D to determine the unsaturated hydraulic properties of soils (Brooks and Corey, 1964; Van Genuchten, 1980; Vogel and Císlerová, 1988; Kosugi, 1996 and Durner, 1994), the soil-hydraulic functions of Van Genuchten (1980) with the statistical pore-size distribution model of Mualem (1976) were selected (Table 6.1).

According to this model, soil water retention, θ (h), is determined using the equation:

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{[1 + |\alpha h|^n]^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \qquad (6.4)$$

where θ_s is saturated water content [-],θ_r is residual water content [-],..m, n are empirical parameters [1/L], [-], [-], Se is effective water content [-].

Unsaturated hydraulic conductivity, K (h), is determined using the equation:

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \tag{6.5}$$

where Se is effective water content [-], l is the tortuosity parameter in the conductivity function [-], and K_s is saturated hydraulic conductivity [L/T].

$$m = 1 - \frac{1}{n}, \quad n > 1 \tag{6.6}$$

Table 6.1 Soil-hydraulic parameters for different soil types used in the HYDRUS-1D model

Soil type	θ_r (cm^3cm^{-3})	θ_s (cm^3cm^{-3})	α (cm^{-1})	N	Ks	l
Silt loam	0.067	0.45	0.02	1.41	10.8	0.5
Silt clay loam	0.089	0.43	0.01	1.23	1.68	0.5

6.2.6 Water flow boundary condition and sink term in Richard's equation

In the preprocessing menu, water flow boundary conditions and the user-specified type of upper and lower boundary conditions can be defined. To permit the increase in the water layer on the surface by precipitation and or irrigation and to allow the decrease in the surface water layer by infiltration and or evaporation, the 'atmospheric boundary' condition with surface layer was selected as the upper boundary condition. The lower boundary condition depends on the dynamics of the GW levels; therefore 'variable pressure head' was selected to describe the lower boundary of the soil profile.

Richard's equation for flow incorporates a sink term (S) to account for water uptake by plant roots. It is defined as the volume of water removed from a unit volume of soil per unit time due to plant water uptake. For the determination of this sink term, the method proposed by Feddes et al. (1978) and modified by Van Genuchten (1987) to include multiplicative water and osmotic stress was applied. According to Feddes et al. (1978):

$$S(h) = \propto (h) S_P \tag{6.7}$$

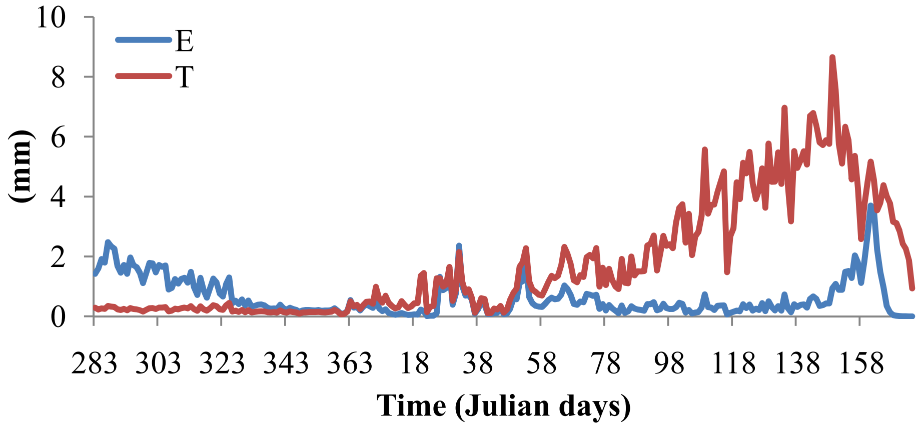
where the root-water uptake water stress response function α(h) is prescribed as a dimensionless function of the soil water pressure head ($0 \le \alpha \le 1$), and Sp is the potential water uptake rate [T-1].

The following values were used: h_1 = -10 hPa, h_2 = 25 hPa, $h_3$high = -200 hPa, $h_3$low = -6,000 hPa, and h_4 = 14,000 hPa, as suggested by Taylor and Ashcroft (1972).
The potential water uptake rate (Sp) is:

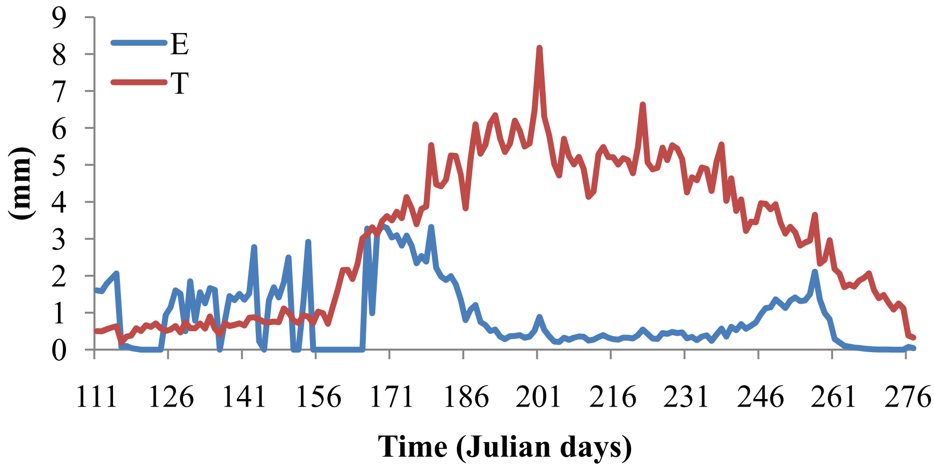
$$S_p = \frac{1}{L_R} T_p \tag{6.8}$$

where Tp is the potential transpiration rate [LT^{-1}] and L_R the depth [L] of the root zone.

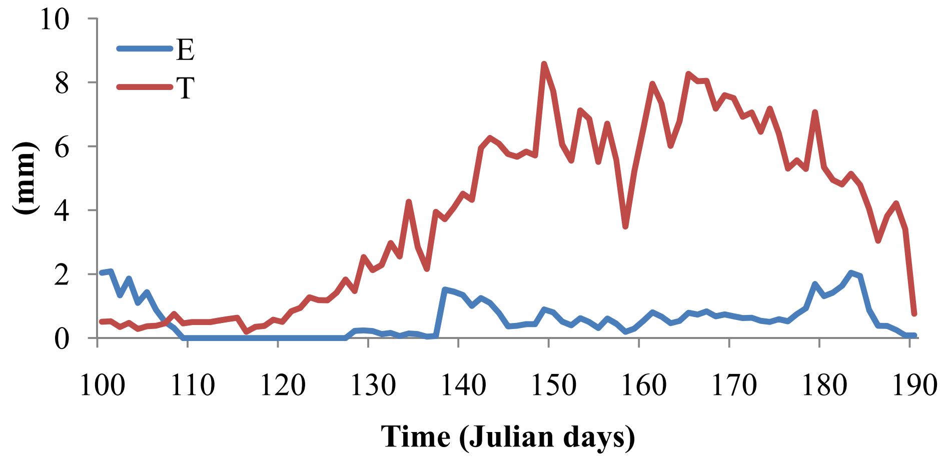
The upper boundary condition (evaporation) and the potential transpiration rate (sink term) was determined by the dual crop coefficient approach based on the FAO-56 Penman–Monteith equation and described in detail by Allen et al. (1998). In this approach, the effects of crop transpiration and soil evaporation are determined separately. Two coefficients, i.e., the basal crop coefficient (Kcb) to describe plant transpiration and the soil water evaporation coefficient (Ke) to describe evaporation from the soil surface were determined using the Excel spreadsheet of Allen et al. (1998). Evaporation and transpiration were determined for cotton, wheat and vegetables (Figure 6.2).



(a)



(b)



(c)

Figure 6.2 Evaporation (E) and transpiration (T) estimated using the dual crop coefficient for a) cotton b) wheat and c) vegetables for the 2007 vegetation season (April to September)

The potential evaporation and transpiration rates then were determined by multiplying the potential evapotranspiration with the corresponding coefficients:

$$ET_c = (K_{cb} + K_e) \times ET_o \tag{6.9}$$

where K_{cb} is basal crop coefficient, and K_e is soil water evaporation coefficient.

For the lower boundary condition, the averaged GW levels for each HRU collected on a 5 to 10-day basis were linearly interpolated to obtain daily model inputs.

6.2.7 Iteration criteria and time control

In this preprocessing menu for water flow, iteration criteria and time control, i.e., the parameters used to control the iteration process using a modified Picard method during the solution of the nonlinear nature of the Richards' equation, were defined. The maximum number of iterations was set to 23 during each time step, and absolute water content tolerance (maximum desired absolute change in the value of the water content between two successive iterations during a particular time step for nodes in the unsaturated part of the flow region) was set to 0.001 (unitless). Absolute pressure head tolerance, which represents the maximum desired absolute change in the value of the pressure head between two successive iterations during a particular time step for nodes in the saturated part of the flow region, was set to 1 (cm).

6.2.8 Root growth

To describe the root growth during the growing season, the Hoffman and Van Genuchten (1983) root distribution model was used. Initial root growth time, harvest time, initial rooting depth and the maximum rooting depth were described in the preprocessing menu of the model.

6.2.9 Up-scaling capillary rise from field level to hydrological response unit level

After quantifying the required parameters of the HYDRUS-1D model, capillary rise for 9 different combinations were calculated. Using the capillary rise values for these combinations at field level and the area of the particular crop, the capillary rise was up-scaled to the 6 HRUs using the following equation:

$$CHRUi = \sum_{j=1}^{9} (CF)j \times (Area\ of\ the\ field)j \qquad (6.10)$$

where $CHRU_i$ is capillary rise for hydrological response unit i (i = 1- 6) in m^3, and CFj is capillary rise from field j in $m^3\ ha^{-1}$.

6.2.10 Up-scaling capillary rise from hydrological response units to water users association level

To determine the capillary rise occurring across the WUA, the capillary rise calculated for 6 HRUs was up scaled to the WUA level using the following equation:

$$CWUA = \sum_{i=1}^{6} (CHRU)i \qquad (6.11)$$

where CWUA is capillary rise from WUA in m^3, and $CHRU_i$ is capillary rise from HRUi in $m^3\ ha^{-1}$.

6.2.11 Scenarios

Improved irrigation efficiency scenarios (S-A: current irrigation efficiency or business-as-usual (BAU), S-B: improved conveyance efficiency, S-C: increased application efficiency, S-D: improved conveyance and application efficiency) (Chapter 4) and the GW levels simulated based on these scenarios (Chapter 5) were used to determine the capillary rise.

6.3 Results

6.3.1 Capillary rise contribution to cotton water requirements computed by HYDRUS-1D model at field, HRU and WUA level

Field level

Capillary rise under cotton during the vegetation season (April-September) 2007 was approx. 3 to 5 times higher than under wheat and vegetables for S-SL and 7 times higher for M-SL, There was no capillary rise for D-SL under wheat and vegetables (Table 6.2).

To determine the capillary rise contribution of the crop-specific evapotranspiration (ET_c), the ET_c values 596 mm for cotton, 363 mm for wheat, 397 mm for vegetables were used (see Chapter 4). The capillary rise contribution of these crops in the WUA ranged from 16 to 28 %, 0 to 9 % and 0 to 12 %, respectively. The maximum value for cotton was 28 % for the S-SL HRU, and reduced to 23 and 16 % for M-SL and D-SCL, respectively. For wheat from April till harvest in June for S-SL, the value was only 9 %, which reduced to 6 and 0 % for M-SL and D-SCL, respectively. Similarly, 12 % of the ET_c of vegetables was met in S-SL, which reduced to 5 and 0 % for M-SL and D-SCL, respectively.

Table 6.2 Monthly capillary rise (mm) for cotton, wheat and vegetables in different HRUs in the Shomakhulum WUA determined by HYDRUS-1D for the year 2007

Month	Capillary rise (mm)								
	Cotton			Wheat			Vegetables		
	S-SL	M-SL	D-SCL	S-SL	M-SL	D-SCL	S-SL	M-SL	D-SCL
A	7	9	0	4	9	0	1	0	0
M	54	32	13	24	6	0	17	3	0
J	43	20	32	6	5	0	12	6	0
J	49	51	34	0	0	0	17	11	0
A	7	28	14	0	0	0	0	0	0
S	4	0	4	0	0	0	0	0	0
Total	164	140	97	34	20	0	47	20	0

For the baseline scenario, the maximum capillary rise contribution to the ET_c of wheat is in the S-SL HRU. However, this contribution is 79 % lower than for cotton. The reasons for the low contribution to wheat are GW levels, ET_c and climatic conditions. After the cold winter season, first irrigation to wheat is applied either at the end of

March or in early April. Due to low ET_c of wheat during these months, the capillary rise contribution to ET_c of wheat is very low. ET_c of wheat is high along with shallow GW levels in May, which resulted in the highest capillary rise during this month. Although the GW levels are shallow in June, ET_c of wheat is low during this month, which resulted in a low capillary rise. The capillary rise contribution for M-SL was 41 % lower than for S-SL. The GW levels in the D-SCL HRU were too deep to provide any contribution.

Although vegetables are grown from May to July when the GW levels are shallow and ET_c is high due to the short root length of vegetables the capillary rise contribution was not high. When the values for the S-SL HRU are compared with those for cotton, an 83 % reduction in capillary rise contribution for vegetables can be seen. The contribution of ET_c to vegetables in the M-SL HRUs is 53 % lower when compared with S-SL.

HRU and WUA level

The capillary rise contribution at field level was up-scaled to the HRUs (section 6.2.9). As cotton, wheat and vegetables are grown on more than 84 % of the cropping area of the WUA (Chapter 4), one average value of capillary rise contribution for all other crops (maize and perennial plants) was used. Results show that values ranged from 10 to 24 % of the average ET_c of the different crops in the respective HRUs. For HRU-1, 2 and 3 with S-SL characteristics, capillary rise contributed 21, 24 and 24 %, respectively (Table 6.2). In HRU-4 with D-SCL characteristics this was 10 %. For HRU-5 and 6 with M-SL characteristics, capillary rise contributed 15 and 20 %, respectively.

Table 6.3 Capillary rise contribution to crop-specific evapotranspiration for different HRUs and WUA

HRU/WUA	Capillary rise (mm)	Average ET_c (mm)
HRU1	104	505
HRU2	126	533
HRU3	129	541
HRU4	55	529
HRU5	64	424
HRU6	106	536
WUA	97	511

Values differ even for HRUs with the same characteristics. HRU-1, 2 and 3 have the same (S-SL) characteristics but different capillary rise contribution. Similar values in HRU-2 and 3 (Table 6.3) are due to the same share of cotton (66 %) in both HRUs, while a low value in HRU-1 is due to the lower share of cotton (31 %) in this HRU. Similarly, HRU-5 and 6 have the same characteristics (M-SL) but the capillary rise contribution for HRU-6 is 21 % higher than for HRU-5. The reason is that HRU-6 has a 58 % share of cotton, whereas this is only 21 % in HRU-5. In HRU-4, cotton is grown on 51 % of the cropped area but the capillary rise contribution is lowest (10 %) in this HRU. The low value is due to deep GW levels, which contributed the lowest capillary rise contribution for all crops. The HRUs with S-SL characteristics and the largest share of cotton show the highest values while the lowest values are for the HRUs with M-SL and D-SCL characteristics.

The capillary rise contribution in the HRUs was up-scaled to the WUA level (section 6.2.10). Results show that 10 to 19 % of the surface water supply at the WUA level can be met through capillary rise (Table 6.3).

6.3.2 Capillary rise contribution of cotton ET_c under different improved irrigation efficiency scenarios

The results of the three scenarios were compared to the baseline or business-as-usual scenario (S-A) (Figure 6.4). Results show that for S-A, the capillary rise contribution of ET_c of cotton is highest for HRUs with S-SL (shallow-silt loam) characteristics. This is due to the shallow groundwater levels in these HRUs. The monthly trend of capillary rise for S-SL can be explained by combining the evapotranspiration rates and the GW levels. During the early growth stage of cotton, although the GW levels were shallow, the low ET_c of cotton resulted in a lower capillary rise contribution of ET_c. The shallowest GW levels and high ET_c of cotton during the peak irrigation season (June to August) resulted in a maximum capillary rise contribution for this period. The GW levels decline during the month of September, and also ET_c of cotton was low during this month, which resulted in low values during this month. For HRUs with M-SL (medium-silt loam), capillary rise contribution was reduced by 15 % compared to S-SL. This value is similar to that of S-SL (low in April and September and high in the remaining (peak irrigation) months. The lower values for M-SL are due to the deeper GW levels.

For HRUs with D-SCL (deep-silt clay loam), capillary rise contribution to ET_c of cotton was reduced by 41 and 31 % compared to S-SL and M-SL, respectively. This high decrease is due to the deepest GW levels in these HRUs. Furthermore, the silt clay loam further reduced the capillary rise. However, the monthly trend of capillary rise contribution to the ET_c of cotton is the same as described above for the HRUs with S-SL characteristics.

Table 6.4 Scenarios of seasonal capillary rise contribution (mm) to cotton crop simulated using the HYDRUS-1D model

Scenario	Capillary rise contribution (mm)			Reduction in capillary rise contribution compared to baseline scenario (%)		
	S-SL	M-SL	D-SCL	S-SL	M-SL	D-SCL
S-A	164	140	97			
S-B	149	132	86	9	6	11
S-C	101	86	65	38	39	33
S-D	92	74	56	44	47	42

When the capillary rise contribution values for HRUs with S-SL are compared for different scenarios, the reduction corresponds to improve efficiency. If the irrigation efficiency can be improved from 33 % (S-A) to 36 % (S-B), the average decline in GW levels simulated by the FEFLOW model could be 12 cm (see Chapter 5). This small decline in GW levels therefore could cause only 9 % reduction in capillary rise contribution. However, if irrigation efficiency can be improved from 33 % (S-A) to 51 % (S-C), the average GW decline could be 38 cm. This could result in a 39 % reduction in capillary rise contribution. If the target value of 56 % can be achieved for irrigation efficiency (S-D), the decline in GW levels on average could be 44 cm, which is the highest decline for all the scenarios compared to the baseline scenario. For this highest decline, the capillary rise contribution would reduce by 47 %. This reduction would cause an increase in surface water demand of 11 %.

6.4 Discussion

Irrigated agriculture in the Khorezm region of Uzbekistan is operating at low irrigation efficiency (Conrad et al., 2007). High percolation as the major component of the huge irrigation losses recharges the aquifer which in turn results in shallow GW levels under the existing design and the current operation of the drainage system. These shallow GW levels contribute, on average over various soils and crops, 19 % to the crop water requirements. Hence, the improvements in irrigation efficiency called for in the context of water saving needed to adapt to global climate change that can lead to lower GW levels, which, as a consequence, can lower the capillary rise contribution. Therefore, it is not only necessary to quantify the capillary rise contribution under the existing irrigation and drainage system for the improvement of demand-supply procedures but also to quantify the capillary rise contribution under improved irrigation efficiency scenarios for the sustainability of the surface and groundwater resources.

Previous studies for quantifying the capillary rise were conducted either at field scale (Forkutsa et al., 2009; Wallender et al., 1979; Ayars and Schoneman, 1986) or in lysimeter experiments (Kahlown et al., 2005; Hoffman and Hall, 1996; Soppe and Ayars, 2003). However, none of these studies presented a procedure to quantify the capillary rise at the level of the irrigation system, which is of fundamental importance in demand-supply irrigation procedures. The hydrological response unit (HRU) approach used in this study facilitates quantification of the capillary rise contribution at a large scale. GIS software can easily create the Thiessen polygons for the soil texture and GW levels, parameters influencing the capillary rise. Based on this, 6 HRUs were created covering the WUA. Three of these HRUs have shallow-silt loam (S-SL), one has deep-silty clay loam (D-SCL) and two have medium-silt loam (M-SL) characteristics.

The capillary rise contribution to cotton determined for these HRUs ranged from 16 to 28 %. Forkutsa (2006) and Forkutsa et al. (2009) conducted a study in the Khorezm region to simulate the capillary rise contribution using the Hydrus-1D model and found that during the cotton growth in sandy loam soil, for a groundwater depth in the range of 1.4 m and water with an ECgw = 5 dS m^{-1}, the capillary rise contribution to evapotranspiration (ET) ranged from 12 % to a maximum of 47 %. The capillary rise contribution in these studies is comparatively higher than in the simulations with the HYDRUS-1D model for WUA Shomakhulum, but these differences are due to different soil types and GW levels. Forkutsa (2006) and Forkutsa et al. (2009) conducted their study in sandy loam soils with varying shallow GW levels in the range of 1.4 m, whereas the soil types in the Shomakhulum WUA are silt loam and silt clay loam and GW levels vary from 0.5 m to more than 2 m.

The capillary rise contribution ranging from 16 to 28 % under the current GW conditions plays a significant role in water management at farm level. Due to unreliable water supplies in Khorezm, farmers often block the drains to prevent a decline in GW levels (Jabbarov et al., 1977). These shallow GW levels hence provide the necessary soil moisture to the plants and are used as a safety net against the unreliable water supplies.

Improvement in irrigation efficiency for four different scenarios showed a 12 to 44 cm decline in GW levels from the business-as-usual scenario (Chapter 4). This high decline can reduce the capillary rise contribution by 11 to 47 %. Improvement in irrigation efficiency can save around 33 % of the surface water supplies, but net water requirements would increase by 11 % due to the decline in GW levels and consequently GW contribution. One of the options to improve the irrigation efficiency and maintain the GW level at desire levels is controlling the drainage outflows. This concept is being practiced successfully in many parts of the world (Evans et al., 1995), including in Uzbekistan. If the water resources planners in the region wish to use the GW as a safety net, they need to regulate the drainage outflows, otherwise improvement in irrigation efficiency can strongly affect the GW contribution.

6.5 Conclusions

Results show that capillary rise contribution can range from 10-24 % of the crop water requirements at the level of hydrological response units. It can be 19 % of the crop water requirements at the WUA level. The results of the scenarios show that maximum capillary rise contribution is under the existing system (19-28 %). If the surface water supplies and eventually the losses are reduced, GW levels will decline, and thus the capillary rise contribution would reduce by 47 %. Therefore, it is recommended that before implementing any surface water intervention (improving irrigation efficiency) or drainage re-design in the WUA, a parallel strategy (controlled drainage as discussed above) should be adopted to avoid the decline in GW levels, which consequently can lower the capillary rise contribution.

Abstract: *A GIS-based approach for up-scaling capillary rise from field to system level*
Capillary rise represents an often neglected fraction of the water budget that contributes to crop water demand in situations of high groundwater levels. Such a situation is typical in irrigated areas of Central Asia where water from capillary rise is exploited by farmers to meet production targets in Uzbekistan under uncertain water supply. This leads to higher water inputs than needed and creates a vicious cycle of salinization that ultimately degrades the agricultural land. In this study, capillary rise is quantified at different spatial scales in the Shomakhulum Water Users Association (WUA), i.e., 2000 ha of farmland situated in the southwest of Khorezm, Uzbekistan. The mathematical model HYDRUS-1D was used to compute the capillary rise at field level for three major crops (cotton, wheat and vegetables) on six different hydrological response units (HRU) (see Chapter 4 for details). This capillary rise was then up-scaled to HRU and WUA level. Groundwater (GW) levels simulated by FEFLOW-3D model for the HRUs under four irrigation efficiency scenarios (S-A: current irrigation efficiency or business-as-usual (BAU), S-B: improved conveyance efficiency, S-C: increased application efficiency, and S-D;:improved conveyance and application efficiency) were then introduced into HYDRUS-1D to quantify the impact of improved efficiencies on the capillary rise contribution. Results show that the HRUs with shallow - silt loam (S-SL), medium - silt loam (M-SL) and deep - silty clay loam (D-SCL) this was 28, 23 and 16 % of the cotton water requirements, 12, 5 and 0 % of the vegetable water requirements and 9, 6 and 0 % for the wheat water requirements, respectively. Results of the scenarios for the whole WUA show that the maximum capillary rise contribution (19 %) to the average of all crops in the WUA was for the S-A scenario, which reduced to 17, 11 and 9 % for S-B, S-C and S-D, respectively. Therefore, it is recommended that, before any surface water intervention or drainage re-design, water managers should be informed about the impacts on GW hydrology and hence should adopt appropriate strategies, e.g., drainage out flows should be controlled by the irrigation planners and not by the individual farmers to prevent GW levels from declining below the recommended GW level of 1.5 m or rising above this level which can cause water logging and salinity.

7 HYDROLOGICAL TOOL FOR SURFACE AND SUB-SURFACE IRRIGATION MANAGEMENT

7.1 Introduction

During the past few decades, competition for water among different users has increased manifold in many parts of the world. The development of new resources is not economically and environmentally viable. Therefore, the increasing demands for water can only be met by using the existing resources more efficiently (FAO, 2003). The majority of irrigation networks around the world are operating at a low overall efficiency of 30 % against the minimum achievable efficiency of 56 % (Sarma and Rao, 1997). Inappropriate system design causes in a low overall efficiency, but even with appropriate design, a proper management for the effective operation and maintenance of irrigation water delivery systems is essential, and worldwide evidence shows that significant improvements can be gained through irrigation scheduling (Malano et al., 1999). Although the crop yield and seasonal evapotranspiration (ET) relationship have been widely used for the management of water resources, the effects of timing of water application are also of key importance especially for irrigation scheduling with high temporal resolution (Hanks, 1983; Vaux et al., 1983; Howell, 1990). Irrigation scheduling should answer as to when and how much to irrigate a cropped field. Given the complexity, a number of computerized simulation models (Kincaid and Heermann, 1974; Smith, 1992 and Mateos et al., 2002) to support and improve irrigation scheduling are available.

Unfortunately, most of the IS models cannot compute/incorporate groundwater (GW) contribution, which is an important parameter for water budgeting under shallow GW conditions, particularly so in arid and semi-arid regions. The recent developments in modeling enable simulation of the capillary rise under different agro-climatic conditions. These models simulate the water flow in the unsaturated zone (Simunek et al., 1998a; Costantini et al., 2002; Hammel et al., 2000; Mandal et al., 2002; Srinivasulu et al., 2004; Vanderborght et al., 2005 and Vrugt and Bouten, 2002). However, the selection of the model depends on the objective and the purpose for which the model is elaborated (Bastiaanssen et al., 2004), whilst the accuracy of the results depends upon the assumptions and simplifications made in the model and their relation to site-specific conditions (Zavattaro and Grignani, 2001).

The FAO CROPWAT model, which can compute the water balance on a daily basis, was adapted to the local conditions by taking into account the GW contribution. The developed model was used to simulate various scenarios to compare between current and flexible irrigation scheduling, options for water saving, cropping plan and strategies for situations of low water availability.

7.2 Materials and methods

7.2.1 Study site

The Shomakhulum water users association (WUA), located in the southwest of Khorezm, was chosen to assess the water use practices, since its environmental conditions are representative for the irrigated areas in Khorezm with respect to GW levels and salinity, soil characteristics, cropping patterns and climate (see Chapter 2).

7.2.2 Irrigation scheduling model

The FAO procedure, as described by Doorenbos and Pruitt (1977) and Allen et al. (1998), and implemented in the CROPWAT software (Smith, 1992; Clarke et al., 1998) was selected for this study to develop the irrigation schedule (IS) for the cotton crop, which is grown on more than 50 % of the irrigated area of the WUA (see Chapter 4). As the CROPWAT software has no facility to compute the capillary rise, which is an important parameter in water balancing under shallow GW conditions, the model was adapted to the local conditions (shallow GW levels). The capillary rise computed outside the domain of the model with the HYDRUS-1D model was introduced in the CROPWAT model by using the so called 'users defined irrigation' option (see Chapter 6).

7.2.3 Scenarios used in the model

A main reason for using models results from their ability to simulate alternative irrigation scenarios based on different levels of allowed crop water stress and on various constraints in water availability (Pereira et al., 2007). In this study, various scenarios were developed to compute optimal irrigation schedules for cotton improved irrigation efficiency scenarios, compare the current and flexible irrigation scheduling, derive options for water saving, and develop strategies for situations of low water availability.

7.2.4 Optimal irrigation scheduling

For four irrigation efficiency scenarios (see, Chapter 3), S-A; current irrigation efficiency or business-as-usual (BAU), S-B; improved conveyance efficiency, S-C; increased application efficiency and S-D; improved conveyance and application efficiency, under characteristics of six developed hydrological response units (see, chapter 4), S-SL (shallow-silt loam), D-SCL (deep-silt clay loam) and M-SL (medium-silt loam), GW levels were simulated using the FEFLOW-3D model (see Chapter 5).

The 12 simulated GW levels for the combination described above were then introduced in the HYDRUS-1D model to compute the capillary rise contribution for cotton against each GW level. For details on the methodology see Chapter 6. The computed capillary rise was then introduced in the CROPWAT model to develop 12 optimal irrigation schedules for cotton.

7.2.5 Irrigation scheduling in practice

Farmers' practices

To compare the current farmers' irrigation schedules (IS) and the optimal IS, two farms in the Shomakhulum WUA with different but representative GW levels, soil textures and cropping patterns were selected. Farm-1 had a total area of 13 ha, where cotton and different vegetables were grown on 9 and 4 ha, respectively. On Farm-2 (10.1 ha) cotton and wheat were cultivated on 6 and 4.1 ha, respectively. At the main inflow point of each farm, 2 m long concrete cross sections with a width of 1 m were constructed to facilitate the discharge measurements. The total amount of water applied during each irrigation event at both farms was determined using the stream gauge technique (Chapter 3).

Recommendations by WUA officials

The official irrigation scheduling plan for WUA was collected from the WUA officials. The official method for establishing irrigation scheduling is to divide the irrigated area into different hydromodules (Veldwisch, 2007, Bobojonov, 2008). The average crop water requirements (irrigation quota) values based on the hydromodules for each crop within the WUA is used. Application of this irrigation amount for each hydromodule by the farmers at 10-day intervals is recommended. For details on water demand and supply procedure in the WUA see Chapter 2.

Yield reduction on both farms with the actual irrigation schedule and the official irrigation schedule was estimated in CROPWAT using the yield reduction functions proposed by Doorenbos and Kassam (1979).

7.2.6 Optimizing irrigation scheduling with reduced water supply

For the years of low water availability, optimized irrigation schedules under deficit irrigation situations were developed. In this scenario, the water was reduced by 25 and 50 % of the current water supply. The situation can be managed in two ways, i.e., a proportional deduction of water from each irrigation event as suggested in the optimal irrigation schedule, and b) a reduction in the number of irrigation events. The impacts of reduced water supply for these two managerial options was compared for the proportional yield losses simulated in the CROPWAT model using the yield reduction functions proposed by Doorenbos and Kassam (1979).

7.2.7 Water saving scenarios

In the water saving scenarios (WSS), different water saving options were introduced. In WSS-1, high water demand crops, e.g., cotton and rice, were replaced by low water demand crops, e.g., vegetables. The share of cotton was reduced from 50 to 30 and 20 % and replaced by vegetables. Rice is only grown on 1 % of the irrigated area in the WUA, therefore it was eliminated from the crop portfolio. On the other hand, if 20 to 30 % area of the present cotton area were to be replaced by rice, there would be rise in water use, which was quantified in this scenario.

In WSS-2, marginal land (soils having low productivity either due to soil salinity or due to coarse soil texture (sand)) was eliminated from the irrigation plan. Martius et al. (2004) reported that 15-20 % of the Khorezm area (based on the soil bonitet (soil fertility indicators)) consists of marginal land areas, which vary in size and are scattered over the region.

In WSS-3, irrigation efficiency at system level was evaluated. During irrigation, 37 to 47 % of water is lost in the fields, while 24 % is lost during conveyance in the irrigation network, resulting in only 33 % irrigation efficiency. This current efficiency of the irrigation system in the WUA can be increased to 56 % (Bos et al., 2005). The amount of water saved by increasing the irrigation efficiency was quantified in this scenario. The amount of water saved by improving the irrigation efficiency and the reduction in capillary rise contribution due to improved efficiency (Chapter 6) was also determined.

7.3 Results

7.3.1 Irrigation scheduling

Optimal irrigation schedule and practiced irrigation schedule

The optimal irrigation schedules for the improved irrigation efficiency scenarios for cotton under scenarios S-A, S-B, S-C and S-D (Table 7.1 to Table 7.4), show that the capillary rise contribution has a significant impact on the irrigation schedule. In all scenarios, the irrigation quota for the HRUs increases in the order S-SL < M-SL < D-SCL. The quota is related to depth of GW levels; they are shallowest in the S-SL and deepest in the D-SCL HRUs. In the S-SL HRUs, the lower irrigation quota is due to a higher capillary rise contribution due to shallow GW. In contrast, the higher irrigation quota in D-SCL is due to a lower capillary rise contribution also due to shallow GW levels.

The comparison of the irrigation quota for different irrigation efficiency scenarios shows that the irrigation quota does not differ much in S-A and S-B for all HRUs. The small difference in irrigation quota for S-A and S-B is due to the small difference in the capillary rise contribution for these scenarios (Table 7.1 and Table 7.2). However, the irrigation quota for S-C and S-D differs substantially from that of S-A and S-B. The higher irrigation quota for S-C and S-D compared to S-A and S-B is again due to the difference in capillary rise contribution. The low values in S-C and S-D increased the irrigation quota in these scenarios. The trend of change in irrigation quota for these scenarios among HRUs is the same.

The irrigation scheduling recommended by the irrigation planners in the WUA (Table 7.5) not only shows higher irrigation quota, but also yield losses. The high yield losses are due to inflexible irrigation timing (norm-based), which cannot completely meet the time-dependent water requirements. When the irrigation schedule implemented by the farmers is compared to the optimal irrigation schedule of cotton simulated by CROPWAT, it shows not only yield losses (7 %) but also a wastage of water (9%) by deep percolation.

This indicates firstly that the farmers do not necessarily follow the recommended irrigation schedules but often applied untimely and large amounts of irrigation water, and secondly that the farmers seem to manage as well as if they had followed the official recommendations. Nevertheless, their irrigation practice can be improved. When the IS of cotton typically used by farmers (Table 7.5) was fed into the CROPWAT program, the results were not only yield reductions but also water losses. The farmer at Farm-2 applied three irrigations, which resulted in a reduction of 33 % yield and an 84 mm irrigation water loss by deep percolation during the cotton season. At Farm-1, the farmer applied two irrigations, which resulted in a loss of 354 mm of irrigation water by deep percolation and a 41.6 % reduction in cotton yield. He applied more water than necessary in the first irrigation, and only 6 days after the first irrigation, he applied the second. When questioned, he replied that he had the opportunity to irrigate which might not have been possible later, and did not want to waste it. This actually did happen, and the farmer could not keep to his schedule for the next irrigation in contrast to the other farmers, and therefore could not irrigate his fields.

It is important to mention that irrigation schedule data for the farmers are only based on two farm samples. The farmers' irrigation schedules depend on several factors, e.g., water availability, pump operating problems (electricity cut off, pump out of order) and the agreement between different farmers to apply the water on the same day (see Chapter 3).

Table 7.1 Simulation of irrigation scheduling (optimized) for cotton in HRUs with S-SL, M-SL and D-SCL characteristics (Scenario A)

S-SL		M-SL		D-SCL	
Irrigation interval (days)	Irrigation quota (mm)	Irrigation interval (days)	Irrigation quota (mm)	Irrigation interval (days)	Irrigation quota (mm)
51	55	63	61	28	42
16	64	16	69	33	58
14	71	11	71	13	65
11	72	11	68	11	71
13	72	11	74	11	68
13	70	13	72	11	69
17	79	20	86	12	70
				16	78
Total	483		501		521

Table 7.2 Simulation of irrigation scheduling (optimized) for cotton in HRUs with S-SL, M-SL and D-SCL characteristics (Scenario B)

S-SL		M-SL		D-SCL	
Irrigation interval (days)	Irrigation quota (mm)	Irrigation interval (days)	Irrigation quota (mm)	Irrigation interval (days)	Irrigation quota (mm)
60	58	63	61	44	50
13	64	13	69	20	60
11	73	11	72	12	67
10	67	11	71	10	69
11	71	12	70	10	68
12	72	12	72	11	70
15	77	17	82	12	71
				16	79
Total	482		497		534

Table 7.3 Simulation of irrigation scheduling (optimized) for cotton in HRUs with S-SL, M-SL and D-SCL characteristics (Scenario C)

S-SL		M-SL		D-SCL	
Irrigation interval (days)	Irrigation quota (mm)	Irrigation interval (days)	Irrigation quota (mm)	Irrigation interval (days)	Irrigation quota (mm)
26	41	34	46	27	54
33	58	25	59	16	62
13	64	14	64	11	66
11	73	11	71	10	69
10	68	11	71	11	73
11	72	12	73	11	68
12	72	13	71	12	68
14	74	18	79	19	83
Total	522		534		543

Table 7.4 Simulation of irrigation scheduling (optimized) for cotton in HRUs with S-SL, M-SL and D-SCL characteristics (Scenario D)

S-SL		M-SL		D-SCL	
Irrigation interval (days)	Irrigation quota (mm)	Irrigation interval (days)	Irrigation quota (mm)	Irrigation interval (days)	Irrigation quota (mm)
33	45	33	41	24	40
25	59	25	53	33	57
14	64	14	60	14	65
11	70	11	71	11	72
11	72	11	68	10	69
11	67	11	68	11	73
13	72	13	71	12	73
17	77	17	70	13	71
			80	28	95
	526		582		615

Table 7.5 Irrigation scheduling recommended by WUA officials and currently practiced by farmers

Official recommendation		Farm-1		Farm-2	
Irrigation interval (days)	Irrigation quota (mm)	Irrigation interval (days)	Irrigation quota (mm)	Irrigation interval (days)	Irrigation quota (mm)
40	11	70	355	40	117
10	17	6	183	51	130
10	58			14	32
10	64				
10	68				
10	68				
10	77				
10	68				
10	58				
10	47				
10	17				
Total	553		538		279

Optimizing irrigation scheduling with reduced water supply

For years of low water availability, deficit irrigation may be an option. This was calculated assuming a 25 and 50 % water reduction (Table 7.6). If a 25 % reduced surface water supply were proportionally deducted from each irrigation quota in the optimal irrigation schedule (Table 7.1), yield losses would vary from 10 - 18 % of the potential yield, while for 50 % water reduction, the yield losses would be 22 - 30 %.

Table 7.6 Effect of reduced water supply on crop yields (% loss of potential yield)

HRU	Proportionally reduced irrigation		Reduced number of irrigation events	
	*YR (%) with 25 % **RWS	YR (%) with 50 % RWS	YR (%) with 25 % RWS	YR (%) with 50 % RWS
S-SL	10	22	16	24
M-SL	11	25	13	26
D-SCL	18	30	20	29

* *YR = yield reduction*
** *RWS = reduced water supply*

The second option to manage the reduced surface water supply is to reduce the number of irrigation events. This would result in yield reductions of 24-29 % with 50 % deficit irrigation for all the studied crops, whereas with 25 % deficit irrigation, the yield losses would be 13 to 20 % (Table 7.6). Results further show that there is almost no difference in the yields between the proportionally reduced irrigation and reduced number of irrigation events for both 25 and 50 % reduced water supply. This is due to irrigation at a time when the impact of dry stress on yield is minimal.

7.3.2 Options for water saving

The scenarios were WSS-1: a change in cropping pattern by introducing low water demand crops (e.g., vegetables), WSS-2: leaving marginal areas out of the irrigation plan (areas with low water productivity, e.g., saline and sandy soils), and WSS-3: quantifying the water savings by improving the irrigation efficiency at system level.

WSS 1- Changing cropping pattern by introducing low water demand crops

Different types of vegetables are the most promising crops in the study area owing to their low net irrigation requirements of about 340 mm (against 601 mm in cotton; Chapter 4). Reducing the cotton area from currently 50 to 30 % and replacing it with vegetables would save about 6 % water. If 30 % of the cotton area were replaced with vegetables, 9 % of water could be saved while concurrently increasing farmers' incomes (Bobojonov et al., 2008). If rice is eliminated from the system, which is 1.54 % of the cropped area, up to 1 % of the required water can be reduced. On the other hand, if 20 to 30 % of the present cotton area were replaced with rice, there would be an increase in water use, which could amount to 7 to 10 %.

WSS 2 - Not irrigating the marginal areas

Eliminating marginal areas from the irrigation plan is another option to save 15 to 20 % surface water. This would be extremely beneficial in years of water shortage (Djanibekov, 2008), as such saved water can irrigate the routine crops, e.g., cotton. This water in normal years of water availability could also be used for cultivating crops with higher income potential such as rice. Under the existing official cropping pattern, only a smaller share of rice can be cultivated due to the higher crop water requirements of rice against the limited water supply. Alternatively, the saved water could be used in the improvement of the ecological situation of the landscape (water for newly planted trees) as recently advocated (Rudenko, 2008).

WSS 3 - Improving irrigation efficiency

By increasing the current average application efficiency from 43 to 67 %, a total of 35 % water can be saved. By improving the application and irrigation network efficiency to the target values, 41 % can be saved. By improving the irrigation network efficiency from 76 to 84 % without changing the current application efficiency, 8 % can be saved. A 56 % overall irrigation efficiency in the WUA is feasible and would result in water savings of about 36 %. The improved irrigation efficiency on other hand would result in 11 % net irrigation requirements.

7.4 Discussion

Norms and recommendations for water resources use were developed in Central Asian countries during the era of collective farming systems. Despite reforms initiated since independence, these former practices still dominate the mind-set of the present practitioners. At the same time, the share of areas with medium and heavy salinization and shallow GW levels is continuously growing, indicating the inefficiency of such practices (Ibrakhimov et al., 2007). Shallow GW levels are dynamic in nature and play an important role in root-zone water balancing. Therefore, to update the norms for the existing conditions is a prerequisite for sustainable water resources management in the area.

Water balance models are used to develop an optimum irrigation schedule (Brown et al., 1978; Odhiambo and Murty, 1996; Mishra, 1999). Pereira (1989) developed the IRRICEP and ISAREG water balance model and tested its performance against field data. Paulo et al. (1995) validated the IRRICEP model for selected sectors of the Sorraia irrigation system in Brazil. Khepar et al. (2000) developed a water balance model to predict deep percolation loss during wet and dry periods. However, these models are applied in the conditions where GW is deep, and this deep GW does not affect the root-zone water balance. George et al. (2004) reported that the problem of irrigation scheduling is complicated by a number of factors (weather, response of crop to irrigation, spatial and temporal variability of infiltration characteristics, soil water availability, etc.), and therefore a user-friendly irrigation-scheduling model is required.

Due to shallow GW conditions in the WUA Shomakhulum, the capillary rise contribution cannot be neglected (Forkutsa et al., 2009). None of the developed irrigation scheduling models can estimate this contribution, which is an important parameter in the context of the Khorezm conditions. Smith (1992) developed a simulation model CROPWAT, which has a user-friendly interface and therefore was selected for this study. Capillary rise contribution estimated against four different groundwater levels (see Chapter 5) by the HYDRUS-1D model (see Chapter 6) was successfully introduced in the CROPWAT model using the ‘User Defined Irrigation’ option in the model.

Results of the irrigation schedule for cotton under the business-as-usual scenario show that 9 to 13 % of the irrigation water can be saved as compared to following the norms in optimum irrigation schedule. The water saving in the optimum irrigation schedule is due to the introduction of the capillary rise contribution in the CROPWAT model. The capillary rise contribution (see Chapter 6) is within the range of the studies conducted in the region by Forkutsa et al. (2009) and the studies conducted in regions with the same climatic conditions, e.g., in Pakistan (Kahlown et al., 2005). Therefore, capillary rise has a significant impact on the surface water requirements and needs to be addressed when designing the irrigation norms.

The results of the scenarios show that by improving the irrigation efficiency to the target value (from scenario S-A to scenario S-D), the irrigation quota for cotton would increase by 8 to 15 % compared to the business-as-usual scenario. This increase in surface water demand is due to the decline of the GW levels. 19 % of the average surface water demand for all the crops can be met through the capillary rise contribution (Chapter 6).

Instead of improving the irrigation scheduling, overall irrigation efficiency in the WUA could be improved. As the major losses are during the field application, these could be reduced if the farmers were to implement water saving measures such as double-side irrigation, surge irrigation, siphon irrigation, or drip irrigation. The improvement in application efficiency would also become feasible through the use of laser leveling especially on the large fields. These approaches are successfully practiced in many part of the world, and water saving linked to these approaches has been successfully tested in Khorezm. For example, benefits of double-sided irrigation are mentioned for Khorezm conditions by Paluasheva (2005), while Masharipova (2009) suggested the use of laser leveling among the solutions to increase the field application ratio in Khorezm. However, these modern techniques are expensive, e.g., farmers cannot implement drip irrigation on their own and therefore need help from the land and water resources management institutions. Intensified maintenance of canals would lead to higher conveyance efficiency. However, lining is not recommended due to the shallow GW, as lining requires plentiful resources and to maintain the lining with fluctuating GW levels needs additional resources. An increase in irrigation network efficiency can also be realized by reducing operational losses. Better coordination of operational activities would avoid or at least reduce the overflow of water from the canals into the drains.

By improving the irrigation efficiency to the target value, 36 % surface water can be saved. However, this would lower the GW levels, and consequently cause an 11 % reduction in the capillary rise contribution. The decline in GW level is not a feasible option for the farmers or for the water management institutes, because it not only provides the necessary soil moisture to the roots at the existing level, but is also needed as a safety net against the unreliable water supplies. When farmers are not supplied with the surface water, they block the drains and thus raise the GW levels. Forkutsa (2006) reported that farmers grow cotton under shallow GW levels even when they have no surface water supplies. For the sustainability of agriculture in the Khorezm region under the current situation, a decline in GW levels is not a feasible option (Chapter 6).

Therefore, the impact of efficiency improvement on the current irrigation and drainage system assessed in this study clearly shows that compensation for the safety net function of the groundwater needs to be considered by institutional strengthening to make water supply at the farm level more reliable.

7.5 Conclusions

The following conclusions can be drawn:

- The developed framework for hydrological tool highlights the importance of groundwater in the WUA Shomakhulum.
- 33 % of the surface water can be saved by improving the irrigation efficiency near to the target values but this would result in a decline in the GW level, which is not a feasible option for the farmers in the region.
- Shallow GW levels provide 19 % of the crop water requirement for the whole WUA, and farmers want to use GW levels as a safety net to cope with the unreliable water supplies.
- An option to improve the irrigation efficiency along with maintaining the current GW levels is to institutionalize the control of drainage outflows, which at the moment is practiced by the farmers on an individual basis.

Abstract: Modeling irrigation scheduling as a tool for management of surface and sub-surface irrigation at the level of water users association

The framework for a hydrological tool was developed (Chapter 1) for the Shomakhulum water users association (WUA) in the southwest of the Khorezm region, Uzbekistan, a region characterized by highly inefficient irrigation practices. Besides the poor state of the irrigation infrastructure, major reasons for the low efficiency are on the one hand a lack of detailed and up-to-date information on the system, and on the other hand a lack of options for considering detailed information in water distribution plans. To tackle these problems, an irrigation scheduling (IS) model, FAO CROPWAT, was adopted for

the study area as an alternative to the current, rather rigid, water distribution planning. Groundwater (GW) levels were simulated using the FEFLOW-3D model, to compute the capillary rise, an important water balance parameter in the area, HYDRUS-1D model was used for six hydrological response units (HRUs) and four irrigation efficiency scenarios. The HRUs 1, 2 and 3 were on shallow-silt loam (S-SL), HRU-4 was on deep-silt clay loam (D-SCL) and HRUs 5, 6 on medium-silt loam (M-SL). The scenarios were current irrigation efficiency or business-as-usual (S-A), improved conveyance efficiency (S-B), increased application efficiency (S-C), and improved conveyance and application efficiency (S-D). The CROPWAT model uses capillary rise values to calculate the water balance and optimal IS for the cotton crop and to develop water management scenarios under a deficitary water supply. In the deficitary water supply scenario, optimal IS of cotton with minimum yield loss was developed for a 25 to 50 % reduced surface water supply, either by proportional deduction of the irrigation quota or by reducing the number of irrigation events. Furthermore, three water-saving scenarios (WSS) were developed. The scenarios were 1) changing the cropping pattern by introducing low water demand crops e.g., vegetables (WSS-1), 2) leaving the marginal areas out of the irrigation plan (areas with low water productivity, e.g., saline and sandy soils) (WSS-2), and 3) quantifying the water saving by improving the irrigation efficiency at system level (WSS-3). The irrigation schedule recommended by the officials and irrigation schedules practiced by the farmers were compared with the optimal irrigation schedule to determine the irrigation loss and crop yield reduction.

The results show that by improving the irrigation efficiency to the target value (from S-A to S-D), surface water demand would increase by 8 to 15 %. In the deficitary water supply scenario (25 % reduced water supply), the yield losses varied from 10 to 18 %, while a water reduction of 50 % would cause 22 to 30 % yield losses. In WSS-1, approximately 9 % of water can be saved by growing vegetables instead of cotton. In WSS-2, a saving of 15 to 20 % can be achieved. In WSS-3, where the overall irrigation efficiency could be improved up to 56 %, 41 %of the water could be saved. In-practice IS when simulated with the FAO CROPWAT model to determine the yield losses showed a 7 to 42 % reduction in cotton yield. Therefore, the water managers in the area would be well advised to change current irrigation practices along these results for better yields and greater sustainability of agriculture.

8 GENERAL DISCUSSION

The Khorezm region of Uzbekistan not only relies on the surface water for crop water requirements but also has shallow GW levels. To develop a hydrological tool for the Khorezm region, a novel approach was used. George et al. (2000) reported that it is very hard to capture all the physical agro-climatic process in a single model. Rodriguez et al. (2008) suggested linking of the existing surface and groundwater models as a useful approach for achieving the specific objectives related to water resources management. Key characteristics of the region that can help to optimize the use of surface and groundwater resources have been identified in previous studies. For example, Conrad et al. (2007) reported inefficiency of the irrigation system in the Khorezm region, Ibrakhimov et al. (2007) reported the shallow nature of the GW levels, and Forkutsa et al. (2009) was the first to simulate the beneficial use of these shallow GW levels, but she only did this in a case study, and on field level. Simulating the shallow GW levels on a larger scale, as a basis for different surface water management interventions and then simulating the capillary rise contribution from these GW levels is not possible using just one GW model. FEFLOW (Diersch, 2002a) can simulate the GW levels, and HYDRUS-1D (Simunek et al., 2005) has been successfully tested in the region by Forkutsa et al. (2009) for quantifying the capillary rise contribution. Not only the quantification of these parameters is important for water balancing but also a suitable model is required for an optimum irrigation schedule for different crops.

The existing irrigation schedule models (Brown et al., 1978; Odhiambo and Murty, 1996; Mishra, 1999; Paulo et al., 1995; Pereira, 1989; Khepar et al., 2000) have no facility for detailed computing of the capillary rise, which is an important parameter in water balancing under shallow GW conditions. These models are applied under deep GW conditions, and this deep GW does not affect the root-zone water balance. In this study the CROPWAT model was used as a framework for irrigation scheduling. The CROPWAT model has a user-defined irrigation option which was used to introduce the capillary rise while establishing the optimum irrigation schedule. To consider capillary rise and the feedback of irrigation efficiency on recharge, the groundwater models FEFLOW and HYDRUS 1-D were used and results of the modeling were fed in the CROPWAT model.

The results of this study show that the irrigation system in the WUA Shomakhulum is inefficient, which is indicated by the depleted fraction of 40 % (see Chapter 3). This value is in the range of the value (33 %) estimated by Conrad et al. (2007) for the whole region of Khorezm. However, recent studies, e.g. by Karatas et al. (2009) in Turkey and Bandara (2006) in Sri Lanka show that irrigation efficiencies of 69-71 % are achievable by using modern irrigation techniques and lining of the canals. In fact, Bos et al. (2005) reported that an irrigation efficiency of 56 % is quite feasible for most of the irrigation systems in the world. The reasons identified for the low irrigation efficiency in the WUA Shomakhulum are (a) low field application efficiency and (b) flaws in the distributional mechanism (see Chapter 3). Abdullaev (2009) reported that Uzbekistan is passing through a transient stage, and a future partial or full market liberalization could lead to a high pressure on the water resources. Therefore, the authors suggested that non-water policies can have a major impact on water resources and therefore should be considered in any discussions of water sector reform. Abdullaev (2009) further reported that water allocation approaches should also be revised to include a greater participation of water users to increase the water use more beneficially.

Ill-managed irrigation in the study region resulted in a raise in GW levels to critical levels which enhance secondary soil salinization and degradation of land and water resources (UNDP, 2007). The annual loss of agricultural production in Uzbekistan due to land degradation is estimated at $ 31 million, and losses caused by land abandonment are approximately $ 12 million (IBRD Tashkent, 2002). Therefore, a recharge policy, which can guarantee sustainable GW levels without affecting the crop production, is a dire need in the study region. The farmer's involvement in designing policies for sustainable recharge is of paramount importance since their farm practices impact the regional salt and water balance. In previous studies such units are not fully taken into consideration while estimating the recharge rates (Yeh et al., 2007). Although the water table fluctuation (WTF) method has been extensively used for recharge estimates, it has shown various drawbacks.

First of all, recharge rates vary substantially within an irrigation scheme due to differences in vegetation, soil texture, GW levels and other factors (Fazal et al., 2005). Consequently, the common procedure to measure GW levels by observation wells that mirror the GW conditions mainly in the close vicinity of the wells is inadequate. Since also the cause of water-level fluctuations is not identified, recharge management based on sporadic and point measurements of GW levels with observation wells over larger areas, as recurrently done in the study region Khorezm, will be based on insufficient information and is likely to increase water irrigation use efficiencies only modestly.

Secondly, the WTF method is designed for estimating, overall seasonal recharges but not for managing situations with high recharge dynamics within the season as occur in the study region. Thirdly, in case of the rate of recharge being equal to the rate of drainage from the GW, according to the WTF method no recharge would be predicted and this also is not conform to the reality of the situation in the study region (high GW level fluctuation throughout the growing season; Ibrakhimov et al 2007).

Last, but not least, further difficulties with the WTF methods lie in determining the specific yield and hydraulic conductivity at a high spatial resolution. Given the first three inherent conditions of the WTF method, and given that the recharge rates in the study region were strongly affected by the cropping pattern and the varying GW levels in dependence of differences in soil texture, the WTF can only insufficiently support in the elaboration of an appropriate GW recharge management in the study region. For the latter a higher spatial and temporal resolution is required. Therefore, the water balance method, with a simple mass conversation equation, estimates recharge as the difference between the amount of water entering into a specific hydrological zone and the amount of water leaving that zone (e.g., Avon and Durban, 1994; Arnold and Allen, 1999; Arnold et al., 2000; Ketchum et al., 2000; Louie et al., 2000; Otto, 2001; Yeh et al., 2004). Although considered an accurate method, its implementation needs the quantification of all the components in the equation which influence recharge rates. Hence, even though water balance approaches are presently used in most of the irrigated areas, they are based on regional or subsystem water balances, thus excluding the activities at farm level which restrict the recharge management, as experienced in India and Pakistan (e.g., Sarwar, 1999; Hassan and Bhutta, 1996; Anuraga, 2006). Given their supra-field level approach, these studies did not take into account the contribution of capillary rise because their case study regions experienced deep GW levels and hence had no capillary rise. But in situations of shallow GW tables and in conditions where the capillary rise is of importance such as in

Australia (Khan, 2008) or Khorezm (Forkutsa 2009a and 2009b), this component must be considered as to determine the most fitting recharge management strategy.

On the other hand, in those cases (e.g., Khan, 2008; Khan et al., 2008; Bekele et al., 2003) where the recharge rates under shallow groundwater levels were determined, the recharge management has been defined only on seasonal basis and only at field level. This is an acceptable assumption in case of a regular and standard cropping portfolio such as in Australia, this approach excludes the integration of field level results plus the entire irrigation scheme. The latter is, however, of paramount importance in the irrigation schemes of Central Asia, where irrigation water distribution is centrally managed and the amount of water is allotted to producers based on cropping patterns only (Abdulaev et al., 2009). For example, when neglecting the contribution of the shallow GW level in the case study irrigation scheme, the net recharge would have been overestimated by as much as 18 %. This additional evidence underscores the necessity of including the contribution of shallow GW levels in the WB method.

Moreover, the recurrently reported surplus application of irrigation water in Khorezm (Veldwisch 2008) offers unprecedented options for increasing water use efficiencies when being aware of the in-season recharge potential. The combination of methods and approaches used in this study allows the net recharge management at the farm scale by changing the cropping pattern from, for instance, cotton to crops which provide a lower recharge, e.g., vegetables or rice and alfalfa - crops with a high potential recharge -, or by using perennial crops.

Results of the current study confirmed qualitative studies postulating that surplus irrigation water applications indeed occurs in the study region (Veldwish, 2007; Conrad et al., 2007), that these are higher than the crop water requirements (Ibrakhimov et al., 2007) and that they are causing the shallow GW levels. In Chapter 3 a set of indicators was used to assess the operational performance of the WUA, indicating that surplus water is delivered to the WUA. Moreover, during water distribution, the surplus water applications are dependent on land use; e.g., the important crop cotton received higher ‘water attention’ and thus had lower yield losses than the other crops. The water balance components used in this study are comparable to those used in previous studies in the region. For example, capillary rise contribution to cotton water requirement in this study is 28 %, which in agreement to the findings of 33 % by Forkutsa et al. (2009a, 2009b). Overall irrigation efficiency (38 %) used for developing the scenarios was in the range of the results provided by Conrad et al. (2007) and reported by UNDP (2007). The evapotranspiration for cotton was estimated in this study as 596 mm, which is in agreement with the SEBAL evapotranspiration results determined by Conrad et al. (2007). Rainfall, which is in the amplitude of not more than 5 % of the gross irrigation amount in the region, does not have any influence on the recharge rates as it usually falls outside the growing season (Conrad, 2006). Capillary rise, which is affected by GW levels, soil texture and cropping pattern, also demonstrated that an accurate knowledge on the recharge rate is not possible without taking into account the spatial variability of these factors. As recharge rates are affected by irrigation, the monthly time steps, which cover the five irrigation events of cotton, provided a high temporal resolution.

Therefore, the developed model is spatially and temporally highly detailed. To take advantage of the features of GIS in irrigation management (Hajilal et al., 1997, 1998), an up-scaling process by simple aggregation process was successfully carried out with GIS. The hydrological response units (HRU) concept used made it possible to recognize the sub-units, which had homogeneous characteristics of the variables that influence the groundwater recharge. The introduced HRU concept not only facilitated the identification of the farm and subunit characteristics, but also aided to extrapolate the recharge to the entire WUA level. The advantage of up-scaling the recharge at three different levels was two-fold: a) it takes into account the field level necessities and b) it allows selecting approaches to identify combinations of on-farm and regional options to achieve desired environmental objectives. This methodology hence also provides a tradeoff between the environmental and economical objectives.

The methodology described in this study to estimate net recharge can be used to determine a point source recharge at farm scale which involves the solution of GW management right at the basic units – the farm level. To control the GW levels at a specific level, detailed knowledge on recharge rates is of fundamental importance however, there are different factors (e.g., hydraulic conductivity, transmissivity, slope of the irrigated area) which influence the quantification of GW levels - hence, recharge rate is just a single but the most important parameter. GW levels for agriculture production should be at a level where they do not hamper the crop production and avoid ecological problems (e.g., waterlogging and salinity). In irrigated agriculture, therefore, the quantification of GW levels is of paramount importance. A good recharge policy therefore needs knowledge of how the recharge rates influence the GW levels. Different analytical models (e.g., MODFLOW by McDonald and Harbaugh (1988), and FEFLOW by (Diersch and Kolditz, 2002)) use the recharge rates for quantifying the GW levels. For this study FEFLOW-3D model was selected because a) it is a finite element model which refers to the spatial discretization of the groundwater model (when solving the basic equations). Finite elements are triangle and rectangles which can be applied in a flexible geometry, this facility is not available in finite difference models e.g., MODFLOW b) its interaction with GIS environment which provides the friendly environment to work and c) it has been successfully tested by Lockman (2006) in the study region. This model had previously been also successfully tested in other arid and semi arid climatic conditions for example by Sarwar (1999) in Pakistan but the delineation of the study area based on hydrological response units approach and then simulating the GW levels for four irrigation efficiency scenario (thus for four recharge rates) was novelty of the current GW modeling. Results of the GW modeling shows that recharge policy can lower the GW levels by 5 – 44 cm. The discussion about the results is presented in chapter 5.

In Khorezm where the GW levels are shallow, the decline or rise in GW levels can significantly influence the agriculture production. Farmers in the region rely on the shallow GW levels during the water scarce situation. The shallow GW levels on one hand can provide the necessary capillary rise but on the other hand can increase the soil salinization. The sustainable solution is reliable supply of fresh water resources with the deep GW levels by flushing the salts out of the root zone. The approaches exist to save the water by improving the irrigation efficiency and then using the saved water for water scarce times. However, the reliable fresh water supply is a question mark in the region as no storage infrastructure exists. Therefore, in this study by keeping in mind the perception of the farmers, the GW modeling in unsaturated zone was performed to see how the four simulated GW levels can influence the GW contribution – an irrigation source which farmers don't want to lose. HYDRUS-1D was selected for this study to simulate the capillary rise. The detail discussion about the capillary rise contribution is presented in chapter 6.

As capillary rise contributes to meet the crop water requirements, an irrigation schedule with capillary rise contribution was established for the WUA. The structure of the study involves the integration of the surface and subsurface irrigation which result in an optimal irrigation schedule which is a novelty of the study. This structure is named as a hydrological tool. In the last step, this tool was applied to establish the optimum irrigation schedule for cotton. The optimum irrigation schedule for cotton developed by the tool showed a water saving of 13-19 %. These results are in the range of the findings by Forkutsa et al. (2009) for the same region. Results further show that if the irrigation efficiency were to be increased to a target value of 56 %, the GW contribution could reduce to 9 %. The shallow GW levels not only reduce the surface water demand but also provide a security for the farmers against the unreliable surface water supplies (Forkutsa et al., 2009). For example, farmers block the drains to raise the GW levels (see Chapter 6 and Chapter 7).

By adopting the optimal irrigation schedule, 10% of the irrigation water can be saved at the farm level compared to the irrigation schedule recommended by the officials in the Khorezm region (referring to net irrigation depth). This irrigation schedule is based on norms that were developed in the 1960's. These norms were developed in a situation that was characterized by large production units in the former Soviet Union, relatively uniform water requirements due to cropping plans dominated by cotton, and a willingness to accept large water withdrawals from the resources. The hydromodule approach was used for spatial allocation of these norms. These hydromodules reflect the climatic situation, soil characteristics and groundwater level in a generalized way. Since the collapse of the Soviet Union, changes have been made and are underway in Uzbekistan, including the transformation of the former kolkhozes (collective farm enterprise) to new water users associations (WUA) (Veldwisch, 2007), and diversification of the cropping pattern to stabilize farmers' incomes (Bobojonov et al., 2009). Awareness of the need to limit water withdrawals is growing. Along with this, different modeling tools to calculate evapotranspiration (Conrad et al., 2007), determine capillary rise (Forkutsa, 2009), and estimate irrigation efficiencies (Conrad et al., 2007) have been developed. The hydrological tool in this study has integrated these aspects, and a framework was developed where these aspects are interlinked in a novel approach.

Moreover, this tool answers the questions that are not addressed in official norms, e.g., how does water management need to react to changing agro-climatic situations. Due to the dependency of Khorezm on water management in the upstream part of the Amu Darya basin and because of adverse impacts feared as a consequence of climate change on water availability, minimizing impacts of increasingly limited supply by controlled deficit irrigation considering high spatial and temporal resolution will become a topic of high relevance. To answer this question, two deficit irrigation scenarios, i.e., proportional deduction of the irrigation quota and reduction of the number of irrigation events, were developed. The results of the scenarios show that during the water scarce years, proportional deduction of the irrigation amount from each irrigation defined in the optimum irrigation schedule is the best management practice.

Model development in the past did not sufficiently reflect the situation of shallow groundwater. However, shallow groundwater levels can be observed in many irrigation schemes worldwide due to irrigation efficiency. Therefore, the hydrological tool developed in this study can be used as a framework to simulate the solution of different problems, e.g., increasing irrigation efficiency and as a consequence managing groundwater in these regions.

9 SUMMARY AND CONCLUSIONS

Present water distribution guidelines in the Khorezm region of Uzbekistan originate from the 1960's following the widespread development of areas for irrigated agriculture in the Aral Sea basin (Rakhimbaev et al., 1992; Sadikov, 1979). In these guidelines, water requirements of major crops such as cotton have been elaborated for different agro-hydrological, climatic and ecological areas whilst considering among others the contribution of shallow groundwater (GW) to soil moisture enhancement and soil texture. These guidelines allow a quick, but only rough estimation of large-scale water needs at district and regional level and are still being applied. In the Soviet past, with its emphasis on agricultural production at all costs, water availability, shallow GW tables and drainage problems were less pressing issues, even in remote regions. Despite the lack of precision in the calculation of water needs, water resources used to be sufficient to satisfy requirements under less stringent resource management. However, the frequent water insufficiencies felt from the 1990's onwards, particularly in the downstream and middle-stream reaches of the river (Olimjanov and Mamarasulov, 2006), have resulted in an urgent need to reconsider the guidelines to react to the challenges of reduced water availability.

A study conducted in the region by Forkutsa (2006) and Forkutsa et al. (2009) showed that the capillary rise contribution from shallow GW levels is an important component for determining the crop water requirements. The HYDRUS-1D model was parameterized in these studies to compute the capillary rise contribution under the existing GW levels. However, GW levels are dynamic and are under the strong influence of recharge rates, which are driven by irrigation efficiencies. The FEFLOW-3D model uses the recharge rates, determined by a water balance model, to simulate the GW dynamics. The capillary rise contribution computed for different GW levels can then be introduced into the CROPWAT model to develop the optimal irrigation schedule and water management scenarios and provide recommendations for water scarcity conditions. These applications have never been linked before for developing a spatially and temporally detailed water management tool.

This study was conducted in the Shomakhulum water users association (WUA) to assess the current irrigation performance in the WUA. Six indicators (delivery performance ratio (DPR), relative evapotranspiration (RET), depleted fraction (DF), drainage ratio (DR), overall consumed ratio (OCR), field application ratio (FAR) and conveyance ratio (CR) were selected to assess the operational performance of the WUA. The parameters required for these indicators were assessed using remote sensing (RS) and real-time hydrological measurements. Information such as actual evapotranspiration that cannot be determined in spatial detail by routine traditional methods was extracted through RS. Losses in different hierarchy canals were determined by ponding experiments. Losses in the field were determined in field experiments at two different farms. Results of this study show a 33 % irrigation efficiency of the system, which is below the minimum achievable efficiency of 56 %. Irrigation efficiency in the WUA can be improved either by reducing the losses in the canal (conveyance ratio (CR)) or by reducing the losses in the field (field application ratio (FAR)). CR and FAR can be improved from the current values of 74 and 43 to a target value of 86 and 67, respectively. By considering the improvements in the current values of FAR and CR till the target values, four improved irrigation efficiency scenarios were developed (baseline (S-A), i.e., business-as-usual), improving CR (S-B), raising FAR (S-C) and improving FAR and CR (S-D)).

Recharge to the aquifer for these scenarios was determined by the water balance approach under the assumption that a fraction of the difference between gross and net irrigation requirements feeds the aquifer. Recharge at field level depends mainly on soil texture, GW levels and the cropping pattern. ArcGIS software proved to be a useful tool to capture the spatial variability of these factors. Thiessen polygons were drawn in ArcGIS to capture the spatial variability of GW levels and soil texture, which determine the capillary rise and in turn the water balance and hence the recharge. Satellite remote sensing was used for the land-use classification in the area to verify the land-use information provided by the WUA officials. Based on the GW levels and soil texture maps, the identified six subunits of the WUA with homogenous conditions (GW and soil texture) were considered as hydrological response units (HRUs). HRU-1, 2 and 3 have S-SL (shallow-silt loam) characteristics, HRU-4 has D-SCL (deep-silt clay loam), and HRU-5 and 6 have M-SL (medium-silt loam) characteristics.

The recharge rates were then introduced into the FEFLOW-3D model to simulate the GW dynamics under the developed scenarios. Recharge rates are a major input to this model and summarize the impact of the scenarios on the GW system. The model was calibrated for the data set of half of the irrigation season (April- June). Calibration parameters were hydraulic conductivity, drainage design and recharge rates. After successful calibration (R^2 = 0.94), the other half-season data set was used for validation. After successful validation, the GW levels in four irrigation efficiency scenarios were simulated. The simulated GW levels served in turn as an input into the HYDRUS-1D model, which estimated the capillary rise contribution of the GW body. The main input to the HYDRUS model are GW levels, evaporation, transpiration, root length and hydraulic properties. Evaporation and transpiration were calculated using the FAO dual crop coefficient approach, while root length and hydraulic properties were estimated by the Hoffman and Van Genuchten (1983) equations. Capillary rise contribution was computed by HYDRUS not only for the crop water demands from the watershed but also for the daily demand of the key crops cotton, wheat and vegetables. The daily capillary rise contribution was in turn fed into the CROPWAT model to simulate optimal irrigation scheduling (IS) and different water management scenarios. CROPWAT needs climatic parameters and crop coefficients to calculate the daily crop water requirements. The daily crop water requirements were then adjusted by the daily capillary rise contribution computed by the HYDRUS.

This is the first time that groundwater recharge and capillary rise have been quantified in a model for irrigation water scheduling in Central Asia. The model can be applied to other situations and is therefore a useful tool for irrigation managers under conditions similar to Khorezm (very flat terrain, soil salinization). The main conclusions emerging from this study are:

- Irrigated agriculture in Khorezm region of Uzbekistan relies on inefficient surface water supplies. Due to lack of storage infrastructure, farmers have to rely on “storing the irrigation water as groundwater”, which provides them with a reduction in water delivery risks, but almost certainly increases the soil salinity to unsustainable levels. This is the major difference between the view from external water managers who focus on water saving and salinity control, and the farmers who focus on safety and reliability of crop production, which emphasizes the need for water at any costs (even that of salinization) (Oberkircher & Ismailova in prep.). This study provides the optimal solution of the management of surface and GW resources under the existing situation.

- The integrated approach for modeling surface and groundwater resources using GIS, RS and hydrological models provided a hydrological tool, which make it possible to develop an optimal irrigation schedule for cotton, wheat and vegetables, compare the current and flexible irrigation scheduling, derive the options for water saving (change in cropping plan, leaving marginal locations out or for alternative crops) and develop the strategies for situations of low water availability taking into account surface and groundwater resources and the interventions.

- Introduction of hydrological response units (HRUs) helped to capture the spatial dynamics of the soil and water parameters. GIS provided a useful environment for establishing the spatial maps of soil and GW characteristics.

- After adopting the water balance model to the local conditions, recharge rates at field, WUA and HRUs level were determined. Results show that HRUs with a large share of cotton provide more recharge (9.6 mm d^{-1} during August) than the HRUs with a small share of cotton (4.4 mm d^{-1}), which shows that recharge is under the strong influence of how the irrigation of the cotton crop is managed. For the different irrigation efficiency scenarios, it was found that by improving the irrigation efficiency, seasonal recharge reduced from a maximum of 4 mm d^{-1} (baseline scenario) to a minimum of 1.4 mm d^{-1} in S-D (improving field application ratio and conveyance ratio). Capillary rise was computed at field, HRU and WUA level using the HYDRUS-1D model. Results show that capillary rise contribution varied from 16 to 28 % of the cotton water requirements, 0 to 12 % for vegetables and 0 to 9 % for wheat under different HRU characteristics. For the whole WUA, the average capillary rise contribution over all crops was 19 % for the baseline scenario, and reduced to 17, 11 and 9 % for S-B (improving conveyance ratio), S-C (raising field application ratio) and S-D (improving field application ratio and conveyance ratio), respectively.

- After the successful calibration (R^2 = 0.94) and validation (R^2 = 0.93) of the FEFLOW model, the model was used to simulate GW levels under different scenarios. The results of the simulations show that an increase in irrigation efficiency under the existing drainage system could lower the GW levels by 12 cm by improving the conveyance ratio (S-B), 38 cm by raising the field application ratio (S-C) and 44 cm by improving the field application ratio and conveyance ratio (S-D) and hence can increase the surface water demand by 11 %.

After introducing the daily capillary rise contribution for the entire improved irrigation efficiency scenario, the CROPWAT model provided the optimal irrigation schedule for key crops. In-practice irrigation scheduling when simulated with the CROPWAT model showed a 7 % (official irrigation scheduling) to 41.6 % (irrigation currently practiced by farmers) reduction in cotton yield compared to the optimum irrigation scheduling. For the 25 % reduced water supply scenario, the yield losses varied from 10 to 18 %, while a water reduction of 50 % would cause much higher yield losses (22 to 30 %). The change in cropping pattern by introducing vegetables in place of cotton can result in a 9 % water saving. About 15 to 20 % of water can be saved by leaving marginal lands out of production. On the WUA level, the overall irrigation efficiency could be improved up to 56 % with a corresponding water saving of 41 %. Therefore, the results of the studies show a significant potential for water saving by using the hydrological tool.

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