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Complete List of Authors:	Awan, Usman; International Center for Agricultural Research in the Dry Areas (ICARDA), Tischbein, Bernhard; University of Bonn, Center for Development Research Martius, Christopher; Center for International Forestry Research (CIFOR),
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SIMULATING GROUNDWATER DYNAMICS USING FEFLOW-3D GROUNDWATER MODEL UNDER COMPLEX IRRIGATION AND DRAINAGE NETWORK OF DRYLAND ECOSYSTEMS OF CENTRAL ASIA[†]

USMAN KHALID AWAN[1,2*], BERNHARD TISCHBEIN[2], CHRISTOPHER MARTIUS[2,3]

[1]International Centre for Agricultural Research in the Dry Areas (ICARDA), Amman, Jordan

[2]University of Bonn, Centre for Development Research (ZEF), Bonn, Germany

[3]Centre for International Forestry Research (CIFOR), Bogor Barat, Indonesia

ABSTRACT

Surface and groundwater resources are often conjunctively used to cope with water scarcity in irrigated agriculture. Farmers in the dryland ecosystems of central Asia also utilize the shallow groundwater in addition to the surface water withdrawn from rivers. This study modelled the groundwater dynamics in an irrigation and drainage network in Khorezm Region, Uzbekistan. The system, characterized by a vast, unlined channel network used to convey water mainly for flood irrigation and an open drainage system, is typical for Central Asian irrigated areas. Groundwater levels in the region are shallow - this contributes to crop water requirements but threatens crop production through secondary salinization. High losses during irrigation in fields and through irrigation network are main causes of these shallow groundwater levels. The main objective of this study was thus to simulate groundwater levels under improved irrigation efficiency scenarios. The FEFLOW-3D model, applied in a case study to the Water Users Association (WUA) Shomakhulum in southwest Khorezm, was used to quantify the impact of improved irrigation efficiency scenarios on groundwater dynamics. The modelled scenarios were: current irrigation efficiency (S-A, our baseline), improved conveyance efficiency (S-B), increased field application efficiency (S-C), and improved conveyance and application efficiency (S-D). Recharge rates were separately determined for six hydrological response units (differing in groundwater level and soil type) and introduced into FEFLOW-3D model. After

[†] Simulation dynamique des eaux souterraines à l'aide de modèle d'eau souterraine FEFLOW-3D sous irrigation complexe et réseau de drainage des écosystèmes des zones arides de l'Asie centrale

[*] Corresponding author: U.K.Awan, International Centre for Agricultural Research in the Dry Areas (ICARDA), Amman, Jordan, e-mail: u.k.awan@cgiar.org, Telephone: +96265903120, Fax: +9626 5525930

successful model calibration (R^2 = 0.94) and validation (R^2 = 0.93), the simulations showed that improving irrigation efficiency under existing agro-hydro-climatic conditions would lower groundwater levels from the base line scenario (S-A) in August (the peak irrigation period) on average by 12 cm in S-B, 38 cm in S-C and 44 cm in S-D. Any interventions which would improve the irrigation efficiency will lower the groundwater levels and hence policy makers should consider it and formulate the policy accordingly.

KEY WORDS: shallow groundwater; irrigation efficiency; Amu Darya River.

RÉSUMÉ

Les ressources de surface et des eaux souterraines sont souvent conjonctive utilisés pour faire face à la pénurie d'eau dans l'agriculture irriguée. Les agriculteurs dans les écosystèmes des zones arides de l'Asie centrale utilisent également la nappe phréatique peu profonde, en plus de l'eau de surface prélevée dans les rivières. Cette étude a modélisé la dynamique des eaux souterraines dans un réseau d'irrigation et de drainage dans Khorezm région, l'Ouzbékistan. Le système, caractérisé par un vaste réseau, de canal sans doublure utilisé pour transporter de l'eau principalement pour l'irrigation par inondation et un système de drainage à ciel ouvert, est typique des zones irriguées d'Asie centrale. Niveau des eaux souterraines dans la région sont peu profondes - ce qui contribue à recadrer les besoins en eau mais menace la production agricole grâce à la salinisation secondaire. Des pertes élevées lors de l'irrigation dans les champs et à travers le réseau d'irrigation sont les principales causes de ces niveaux des eaux souterraines peu profondes. L'objectif principal de cette étude était donc de simuler les niveaux d'eau souterraine sous l'amélioration des scénarios d'efficacité de l'irrigation. Le modèle FEFLOW-3D, appliquée dans une étude de la Water Users Association (AUE) Shomakhulum au sud-ouest de Khorezm de cas, a été utilisé pour quantifier l'impact de l'amélioration de l'irrigation scénarios d'efficacité sur la dynamique des eaux souterraines. Les scénarios modélisés sont: courant efficience de l'irrigation (SA, notre scénario de référence), l'amélioration de l'efficience de transport (SB), l'augmentation de l'efficacité de l'application sur le terrain (SC), et l'amélioration de transport et l'efficacité de l'application (SD). Taux de recharge ont été déterminés séparément pour six unités de réponse hydrologique (différents du niveau des eaux souterraines et le type de sol) et introduites dans le modèle FEFLOW-3D. Après la réussite étalonnage du modèle (R2 = 0,94) et de validation (R2 = 0,93), les simulations ont montré que l'amélioration de l'efficacité de l'irrigation dans des conditions agro-hydro-climatiques existantes permettrait de réduire les niveaux du scénario de ligne de base (SA) des eaux souterraines en Août (à l'irrigation de pointe période) en moyenne de 12 cm de SB, 38 cm de SC et de 44 cm de SD. Toutes les interventions qui permettraient d'améliorer l'efficacité de l'irrigation vont baisser les niveaux des eaux souterraines et donc les décideurs doivent examiner et formuler la politique en conséquence.

MOTS CLÉS: eaux souterraines peu profondes; efficacité de l'irrigation; Amou-Daria.

INTRODUCTION

Khorezm Region of Uzbekistan is notorious for over-exploitation of surface water which is mainly withdrawn from Amu Darya River. Delivery performance ratio is higher than 1 which indicates that water is supplied more than the gross irrigation requirements (Awan *et al.*, 2011). Excessive water is stored in the groundwater reservoir and farmers use this shallow groundwater (reservoir) as a safety net (Awan *et al.*, 2012) for the times when surface water is short. The survey during field work, discussions with the irrigation officials, and results from the study conducted by Awan *et al.* (2011) and Forkutsa *et al.* (2009) revealed that farmers and irrigation planners in the region are much concerned with shallow groundwater levels and wish to prevent the decline in groundwater levels.

On the other hand, the luxury with which the water is currently being used to recharge the groundwater aquifer might not be possible in future. Strategically, around 80% of Uzbekistan's water supplies are from neighbouring countries (Mirzaev, 1996) which shows that irrigated agricultural policies in Uzbekistan have significant international dimensions. Along with this, competition for water between the local water users in the region has substantially increased (Abdullaev *et al.*, 2008a). Several studies have been conducted in the region to promote more efficient water use at the field level (Paluasheva, 2005; Forkutsa *et al.*, 2009) and on a regional scale (Conrad *et al.*, 2007).

A reduced surface water supply would reduce the recharge rates (Awan *et al.*, 2012) and thus can impact the shallow groundwater levels. The groundwater levels, as described above, are considered as a safety net against unreliable delivery of irrigation water to individual farms and fields and are a potential contributor to the crop water requirements (Forkutsa *et al.*, 2009; Awan, 2010) and achieving the yield targets in the region. Thus, any attempts at lowering the groundwater level in this region would need to address the possible risk of reducing yields.

Objective of the current study was thus to simulate groundwater levels for four improved irrigation efficiency scenarios for Shomakhulum Water Users Association (WUA). The modeled scenarios were: current irrigation efficiency (S-A, our baseline), improved conveyance efficiency (S-B), increased field application efficiency (S-C), and improved conveyance and application efficiency (S-D).

Different approaches exist to simulate groundwater levels under different recharge rates. Modelling developments in surface water interventions allowed obtaining recharge as an output from surface water models (these models are conceptual and developed differently for different regions based on local conditions) which in turn can be used as an input in groundwater models. This linkage of recharge rates and surface water is being used in two different ways; (1) integrated surface-groundwater model (Bouraoui *et al.*, 1997; Jayatilaka *et al.*, 1998; Yu and Schwartz, 1998), and (2) linking existing groundwater model with a surface water model (Havard, 1995; Sarwar, 1999; Ramireddygari *et al.*, 2000; Sophocleous and Perkins, 2000; Ross *et al.*, 2005; Rodriguez *et al.*, 2008). The latter approach, e.g., linking the groundwater and surface water model by the recharge from the surface water model, was applied in the current study. Main advantage of this approach is development of conceptual water balance model for recharge estimates based on local conditions. Conceptual water balance model takes into account all those components which impact recharge rates locally. Existing integrated surface-groundwater models are not flexible enough to consider these components which not only affect the accuracy but also limit scenarios developments (Sarwar, 1999).

For the above said approach used for this study, recharge was estimated by a surface water balance model adapted to the Khorezm Region. The WUA was subdivided into six hydrological response units (HRU) where the conditions influencing the recharge process are homogenous. Recharge at the system level is best to be determined in a stepwise approach (Awan *et al.*, 2012): first at field level by taking into account capillary rise, cropping pattern, soil characteristics and then up-scale the recharge to the HRU level while linking this recharge to the efficiencies of the network and the field application and finally linking these efficiencies to the overall system efficiency. Recharge determined by the water balance model at HRU level was then introduced into the groundwater model. For the present study, FEFLOW-3D (Version 5.1) was selected for simulations of groundwater levels. FEFLOW-3D is a Finite Element Subsurface Flow & Transport Simulation System with a graphics-based and interactive user interface (Diersch and Kolditz, 2002), a data interface with GIS (Geographic Information System), and a programming interface to allow the solution of the complex problems. After calibration and validation of the model, groundwater levels were simulated for described improved irrigation efficiency scenarios by FEFLOW-3D model.

MATERIALS AND METHODS

Study area

The study was conducted in the Shomakhulum Water Users Association (WUA), which is situated in the southwest of the Khorezm Region in Uzbekistan. An intensive network of irrigation and drainage systems with high densities of 68 and 31 m ha^{-1}, respectively, is spread over the WUA. Data for the last ten years (1997-2007) showed that during the leaching and vegetation season, the average groundwater levels ranged 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, where groundwater levels ranged 1.0-1.2 m below surface during leaching and irrigation events (Ibrakhimov *et al.*, 2007). Soils in the WUA are predominantly loamy to sandy loam (United States Department of Agriculture (USDA) classification). In Shomakhulum, there are a total of 15 observation wells for monitoring the groundwater levels (Figure 1). Groundwater levels are monitored after each 5 days during the irrigation season (April to October) whereas interval increases to 10 days during the leaching period. However linear interpolation is performed to analyze changes in groundwater levels on daily basis.

Figure1 about here

Water balance model for recharge estimates

Recharge results are taken from study conducted by Awan *et al.* (2012) using water balance model. This study is also conducted in Shomakhulum Water Users Association for the same time period. According to this study, recharge is first estimated at field scale and then is up-scaled to hydrological response units (HRU) by using water balance model. HRUs are taken as those small spatial units which have relatively homogeneous groundwater levels and soil properties. Recharge at field level is taken as a fraction of the difference between the gross and net irrigation requirements (Awan *et al.*, 2012). Net irrigation requirements are calculated by the following equation:

$$NIR = ETp - C - P \tag{1}$$

where NIR is net irrigation requirements (mm), ETp is potential evapotranspiration (mm), C is capillary rise (mm), and P is effective rainfall (mm).

Gross irrigation requirements are calculated by the following equation:

$$GIR \ = \frac{ETp-C-P}{FAR*CR} \tag{2}$$

where GIR is gross irrigation requirements (mm), FAR is field application ratio, and CR is conveyance ratio.

Hence recharge, fraction of the difference between the gross and net irrigation requirements at field level, is:

$$R \ = \left(\left(\frac{ETp-C-P}{FAR*CR}\right) - (ETp - C - R)\right) * K \tag{3}$$

where R is recharge in mm and K is a fraction (0.9) of the difference between the gross and net irrigation which recharge the aquifer. Parameters used in equation 1, 2 and 3 are described in detail by Awan *et al.* (2012).

Up-scaling recharge from field to hydrological response unit (HRU) level

Six HRUs, having homogeneous soil texture and groundwater levels, are formulated in the WUA (Awan *et al.*, 2012). Each HRU again has different combinations of its characteristics (soil properties and groundwater levels) with cropping types. Three main crops are identified in the area e.g., cotton, wheat and vegetables. These combinations are drawn in the form of matrices to represents number of fields as follows:

Crop HRU

$$\begin{Bmatrix} \boldsymbol{C} \ \boldsymbol{S-SL} \\ \boldsymbol{W} \ \boldsymbol{M-SL} \\ \boldsymbol{V} \ \mathbf{D-SCL} \end{Bmatrix}$$

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

From matrix, 9 combinations are formed. The recharge is determined for these 9 combinations and is presented in Table I.

Using the recharge value for these 9 combinations at the field level and knowing the total area of each combination, the recharge was scaled up to the six HRUs using the following equation:

$$NRHRUi \ = \sum_{j=1}^{9} (RF)j * (Area \ of \ field)j \tag{4}$$

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

Scenarios

Impact of four different improved irrigation efficiency scenarios (product of field application ratio (FAR) and Conveyance Ratio (CR)) on groundwater levels is simulated. The scenario A (S-A), business-as-usual scenario, is based on the results of Awan *et al.* (2011) which refers to current low irrigation efficiency in the region i.e., FAR is 0.43 and CR is 0.76. In scenario B (S-B), conveyance efficiency is increased to maximum or target value of 0.84 (Jurriens *et al.*, 2001) with the current value of the FAR (0.43). In scenario C (S-C), the FAR is increased to the target value of 0.67 (Bos and Nugteren, 1974) but the current value of the CR (0.76) was retained. Finally, scenario D (S-D) is the combination of the target values of both the FAR and the CR, representing the maximum irrigation efficiency.

Recharge values for above described four scenarios for all the six HRUs taken from Awan *et al.* (2012) is presented in Table I.

Table I about here

GROUNDWATER MODEL

Numerical groundwater flow modelling was performed using FEFLOW-3D (Diersch, 2002a) model, which has successfully been tested for a number of benchmark examples in different regions (Diersch, 2002b) of the world. FEFLOW-3D model introduces the Darcy equation in the mass conservation equation of any phase.

Parameterization of FEFLOW-3D model

The FEFLOW-3D parameters for calculating the groundwater 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 groundwater 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. The interpolated values of the parameters for the whole model domain are achieved by Akima interpolation. The details of these parameters are presented in a sequence representing the set-up of FEFLOW-3D, i.e., top- to down-menu-based parameterization of the model.

To define the model area and to construct the super element mesh, the background map of the hydrological boundary of the WUA, collectors, and observation wells are imported as an ArcGIS shape files in the model (Figure 1). Groundwater levels and collectors/drains are introduced as add-ins, lines or points which FEFLOW-3D uses as focal points to create finite element nodes in the mesh generator in the FEFLOW-3D domain. A triangular mesh is used as a mesh generator around the groundwater levels and collectors (Figure 4).

Figures 3 and 4 about here

Due to the dynamic nature of groundwater 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 (zero atmospheric pressure) with the top slice as a free and movable surface (groundwater level) and bottom as a fixed surface (impermeable layer) is set as a problem class. 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 contain information on the geometry of strata, is obtained from the Hydro-Geological Station of Khorezm and introduced in a 3D-slice elevation menu of FEFLOW-3D. Among the available maps for four hydro-geological cross sections (I-I, II-II, III-III and IV-IV; Figures 5 and 6), the cross section IV-IV in northeast-southwest direction is the closest section near the WUA Shomakhulum. Based on this information, the vertical discretization corresponds to 3 layers and 4 slices.

Figures 5 and 6 about here

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 groundwater surface in the southern to western part of the WUA, respectively. Under these circumstances, the 1st- kind or Dirichlet- type boundary condition which describes a hydraulic potential at a node, is selected . The Dirichlet boundary condition is set by inputting head values of the canals and collectors around the simulated area (Figure 7).

Figure7 about here

The essential flow material properties for a groundwater model in a saturated zone include hydraulic conductivity, transmissivity, storativity, porosity, dispersivity and in-/outflow on top/bottom, etc. As the soil texture soil texture data for different depths profiles exists at the ZEF/UNESCO GIS center in Urgench, these data sets are used to determine flow material properties. For example, in this study the values for storativity and porosity is taken from the values provided by Freeze and Cherry (1979) and the values for dispersivity is taken from Gelhar (1984). Cross-section IV-IV in the geomorphological-lithological map is 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 md^{-1}, 24.5 md^{-1} for the second layer, and 2.7 md^{-1} for the third layer (Figure 8).

Figure8 about here

Spatially variable recharge as the most important component in this surface-groundwater modelling was introduced as in-/outflow on top/bottom in the flow material menu of the model. The recharge values (Table I) determine from the surface water balance model for the six HRUs and for the settlements is introduced on monthly time steps. The polygons for the HRUs and settlements are imported in ArcGIS format into the model. Reliable data on irrigation practices and water level of canals and collector were only available on a monthly basis, so modelling 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 groundwater models.

Calibration and validation

The groundwater model simulation is 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 groundwater values from the observed OW values. The Nash–Sutcliffe coefficient is defined as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (\lambda_{obs} - \lambda_{sim})^2}{\sum_{i=1}^{n} (\lambda_{obs} - \bar{\lambda}_{obs})^2} \quad (5)$$

where λ_{obs} is observed groundwater level, λ_{sim} is simulated groundwater level, and $\bar{\lambda}_{obs}$ is mean of observed groundwater level. The RMSE is the square root of the average of squared differences between observed and simulated groundwater levels. The RMSE is usually considered to be the best measure of error if errors are normally distributed (Anderson and Woessner, 1992):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (\lambda_{obs} - \lambda_{sim})^2}{n}} \quad (6)$$

where n is the number of days of simulation.

RESULTS

Calibration and validation of the model after first run

In order to evaluate the performance of the integrated model, monthly groundwater levels simulated by the FEFLOW-3D 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 were situated in the vicinity of canals or drains and therefore did not represent the groundwater situation in the irrigated area. Figure 9 shows the average monthly simulated (standard deviation = 0.37) and observed (standard deviation = 0.12) groundwater levels of the selected 10 wells for the first run during the study period. The simulated and monthly groundwater levels are measured from the mean sea level (requirement of FEFLOW-3D model).

Figure 9 about here

The observed groundwater levels were higher during July and August and reduce to a minimum in September. Higher groundwater levels in August are due to the highest recharge rates during this month (Awan *et al.*, 2012). The difference in observed groundwater levels between April (start of the vegetation season) and August (peak irrigation season with highest groundwater levels) is 26 cm.

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

The difference between the simulated and observed groundwater 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 cannot be drained out from the domain of the model. The smaller difference (around 0.5 m) between observed and simulated groundwater level during the low irrigation period (April-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 groundwater 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.

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

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 groundwater levels. These parameters hence were then optimized by a trial and error procedure (Anderson and Woessner, 1992).

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. Therefore, due consideration was given for assigning the upper layer depth in the FEFLOW-3D model.

When most of the simulated and observed groundwater 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 groundwater levels for the calibration period were drawn on a scatter plot (Figure 10). A 45°-line was drawn representing the relationship under ideal conditions, i.e, simulated groundwater levels are equal to the observed ones. The trend line of the observed versus simulated groundwater 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 groundwater levels from the observed ones is only 6%. The root mean square error (RMSE) of the simulated groundwater levels from the observed ones is only 0.20 m.

Figure10 about here

After successful calibration of the model, it was verified for the groundwater dataset from July to September (Figure 11). The Nash–Sutcliffe coefficient (R^2) for the validation period is 0.93, which shows that deviation of simulated groundwater levels from the observed ones is only 7%. The root mean square error (RMSE) of the simulated groundwater levels from the observed ones is similar to that of the calibration period.

Figure11 about here

Groundwater dynamics simulated by FEFLOW-3D model under business-as-usual scenario

Figures 12 and 13 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 groundwater levels within the WUA, the influencing factors, i.e., main canals, collectors and settlements were compared. The simulation map for May (Figure 14) shows that the dynamics of the groundwater surface are under the strong influence of these factors. This also applies to the situation in August.

Figures 12 and 13 about here

The maps show the usual trend of groundwater dynamics, i.e., groundwater levels are shallow around the main canals and deep around the collectors. Shallow groundwater levels in the vicinity of the Povon and Zey-Yop canals (Figure 2) 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 groundwater levels in these areas. Groundwater levels are deep in the vicinity of the collectors. At the junction where the Sapcha Collector falls into the south collector, the groundwater level is quite deep. Deep groundwater levels around these collectors are due to ex-filtration from the groundwater to these collectors.

Groundwater 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. Groundwater levels in the settlement areas are almost the same as the groundwater 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 groundwater level is from east to south, which is in line with the overall slope of the Khorezm Region. The model was further used to assess the behavior of groundwater levels under different irrigation efficiency scenarios.

Ground water dynamics simulated by FEFLOW-3D model under different irrigation efficiency scenarios

The results of the scenarios are presented as the average of the groundwater levels from the 10 selected observations wells and thus represent the dynamics of the groundwater levels at WUA level (Figure 14). 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 groundwater levels for April and August. For S-

A, the groundwater 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 groundwater levels rise from April to August. The results of S-C show that groundwater levels are 5 cm higher in April than in August, while for S-D this difference increases to 10 cm.

Figure 14 about here

The comparison of the simulated groundwater levels between April and August for all scenarios shows a continuous lowering of groundwater 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 groundwater 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 groundwater levels in these months.

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

The groundwater levels in S-B only slightly declined compared to the baseline scenario. The maximum decline in groundwater levels in S-B was 12 cm in August (Table II), whereas the minimum was 0cm in April. The overall decline in groundwater 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 groundwater levels.

In S-C, the decline in groundwater levels compared to the baseline S-A is quite high (Figure 14). The groundwater levels dropped by a maximum of 38 cm (August) when compared to S-A. This significant lowering of the groundwater 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 groundwater levels from the baseline S-A is highest when compared to all scenarios but is quite low when compared to S-C (Figure 14). The groundwater 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 groundwater levels. When the results of this scenario are compared to those of S-C, the decline in groundwater levels is lowest. The low decline in groundwater levels in this scenario is again due to low increase in CR.

DISCUSSION

The decline in groundwater levels in S-C and S-D compared to S-B is similar (Table II). 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 groundwater levels in both of these scenarios is due to the difference in the conveyance ratio.

Above results of the scenarios show that groundwater 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 groundwater levels. Sarwar and Eggers (2006) conducted a study in Rechna Doab, Pakistan, to determine the influence of changes in cropping patterns and intensities on groundwater levels. However, in one of their scenario analysis with FEFLOW-3D, they showed that groundwater levels would decline by 44 cm if the irrigation efficiency were to increase by 25%. However, in the WUA Shomakhulum, the same decline in groundwater levels (44 cm) would occur after improving the irrigation efficiency by 42%. The difference in the findings can be well explained by comparing the groundwater conditions of the study areas. Groundwater conditions in the WUA Shomakhulum are shallow, and therefore it was assumed that 90% of the losses from the fields recharge the aquifer. In contrast, mean groundwater 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 groundwater decline of 3-44 cm during the vegetation season (June to August) can occur. As groundwater 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, groundwater contribution started declining after 1.5 m and reduced to minimum after

2.0 m. They also reported that shallow groundwater levels not only reduce the surface water demand but also increase the crop yield. Forkutsa (2006) reported that each centimeter of groundwater level decline can increase the surface water demand (Awan *et al.*, 2012).

CONCLUSIONS

The focus of this study was to quantify the impact of improved irrigation efficiency scenarios on the dynamics of the groundwater levels. For this purpose, the FEFLOW-3D 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 groundwater levels shows that under existing conditions (S-A), the drainage design increased the groundwater 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 groundwater levels declined by 10 cm from April to August. The results also illustrate that in the S-A and S-B the existing drainage design 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 groundwater 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 groundwater levels by up to a maximum of 44 cm (S-A to S-D, for August). This decline in the groundwater 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 groundwater dynamics. Drainage outflow policies should be adapted to changing groundwater conditions.

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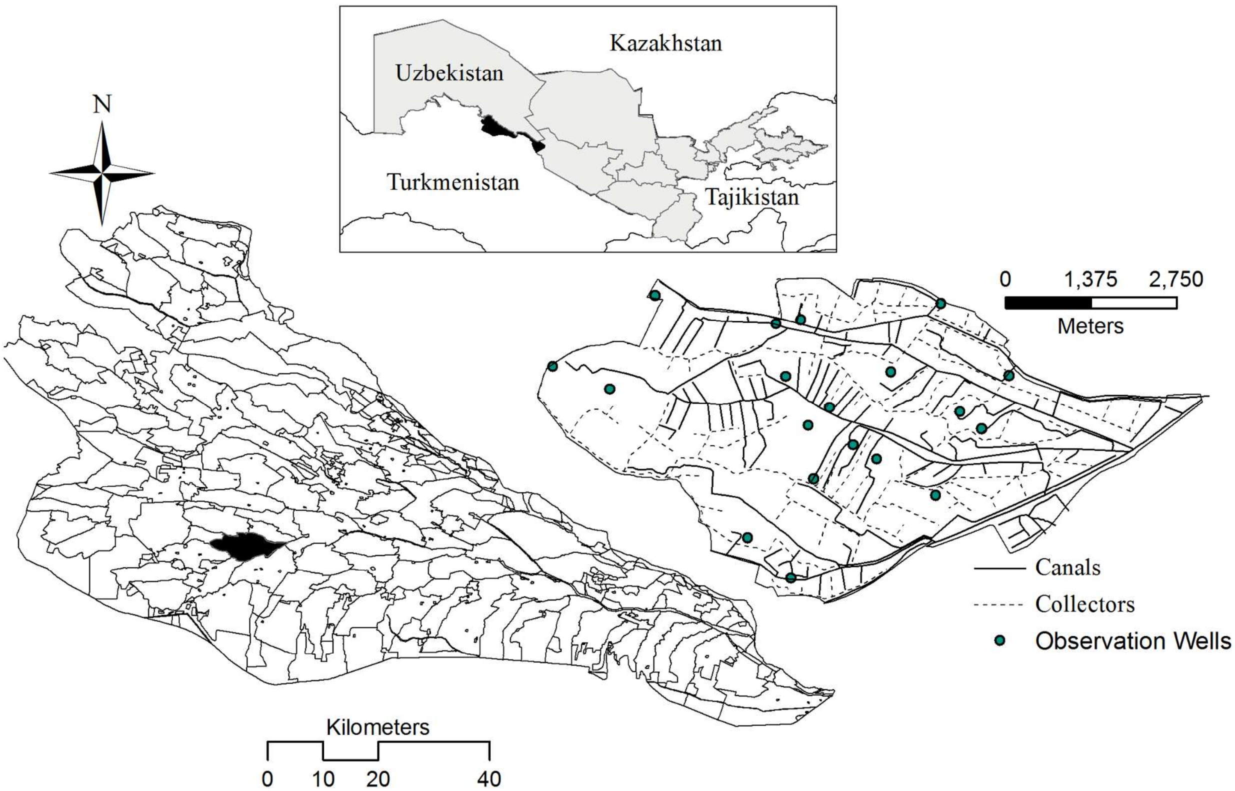

Fig. 1 Drainage network and observation wells in the WUA Shomakhulum

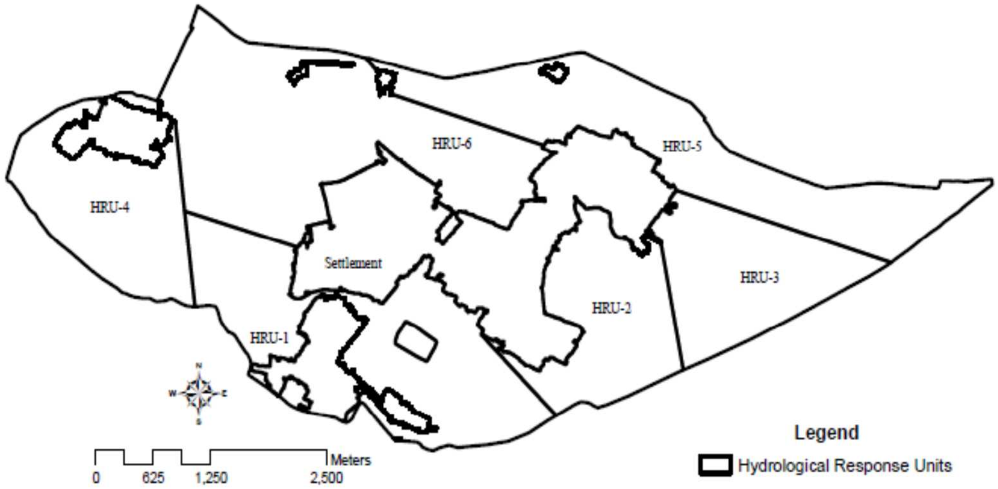

Fig. 2 Hydrological response units in the WUA Shomakhulum

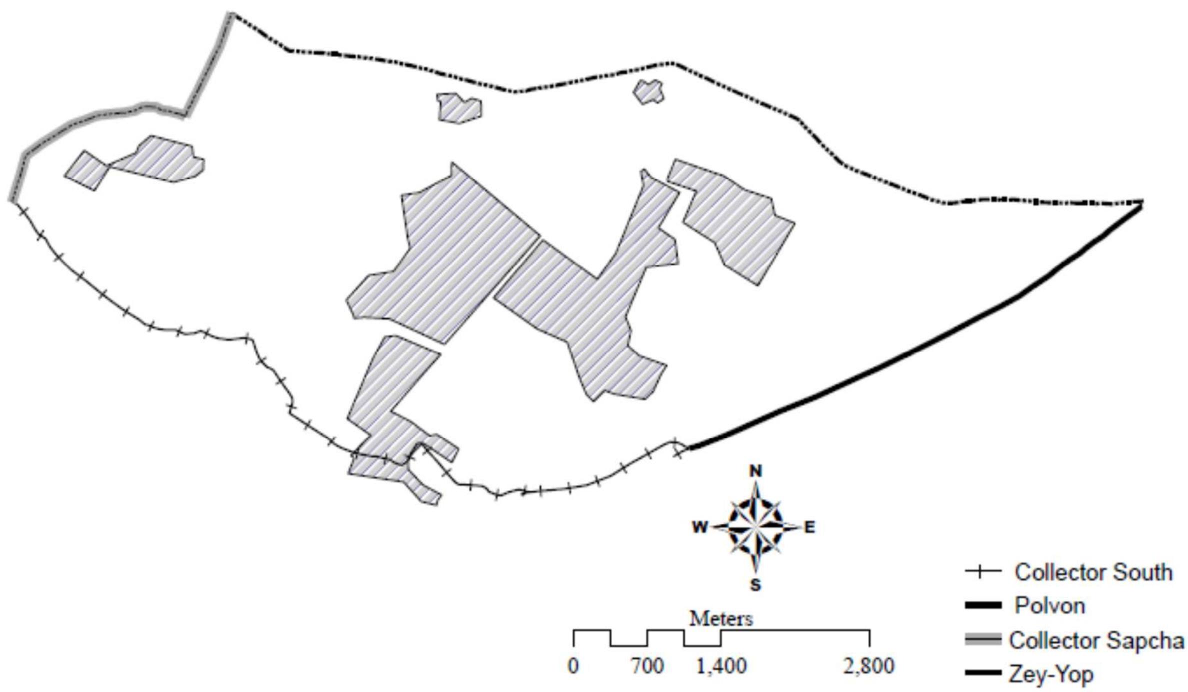

Fig. 3 Location of the settlements, canals and collectors forming the hydrological boundary of the WUA

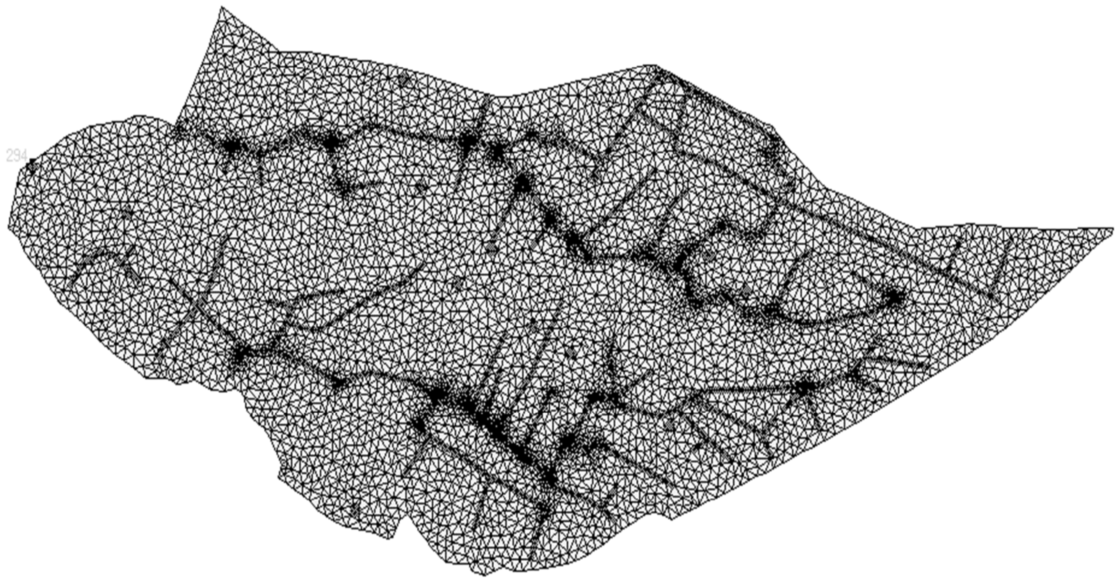

Fig. 4 Finite element mesh (triangle) with high refinement around the collectors and observation wells

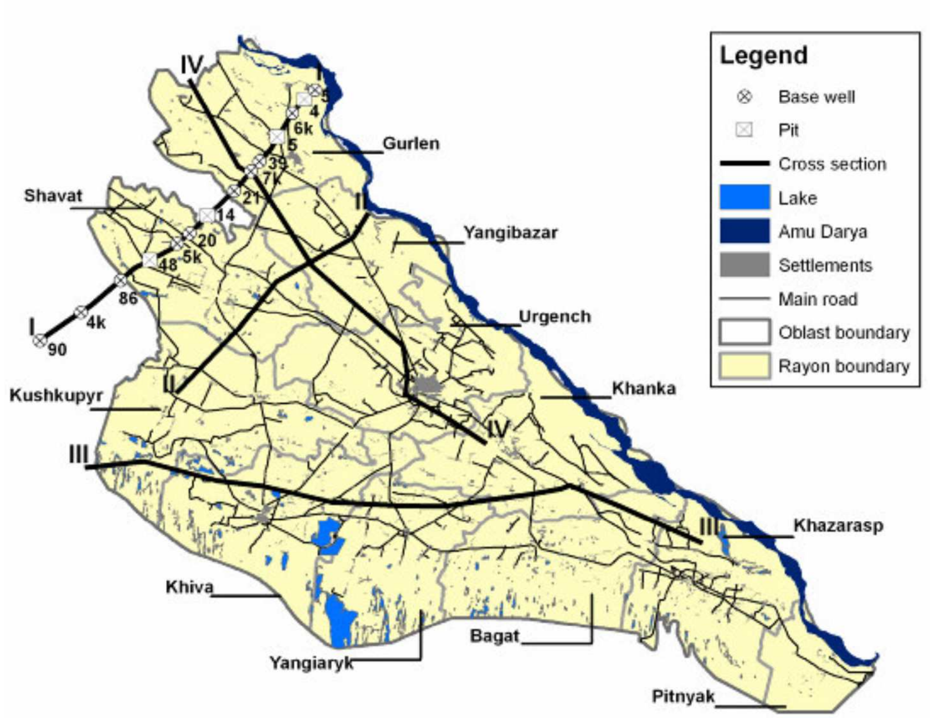

Fig. 5 Location of the four different hydrogeological cross sections in Khorezm. The cross section IV-IV passes near the WUA Shomakhulum (Pre-Aral Hydro-Geological Expedition, 1982)

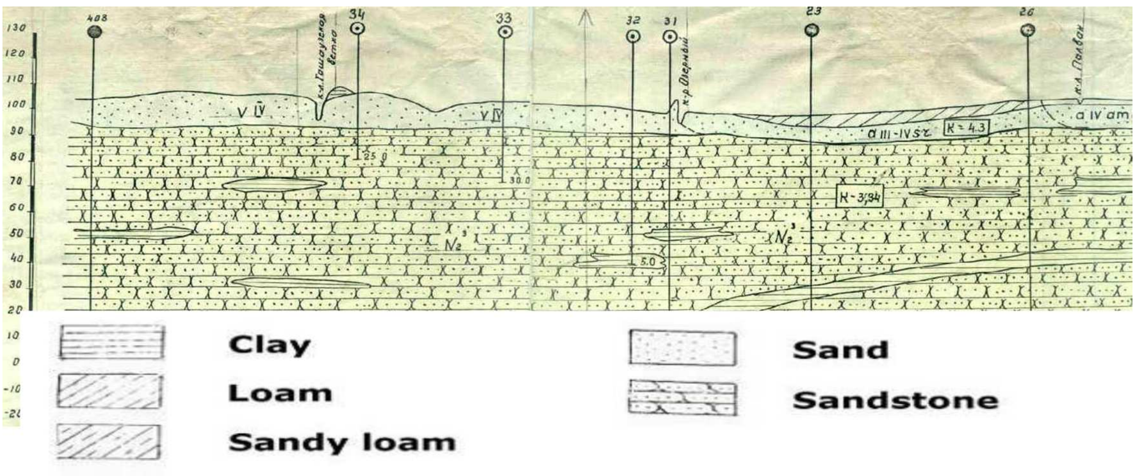

Fig. 6 Material properties of different strata for IV-IV hydrological cross section

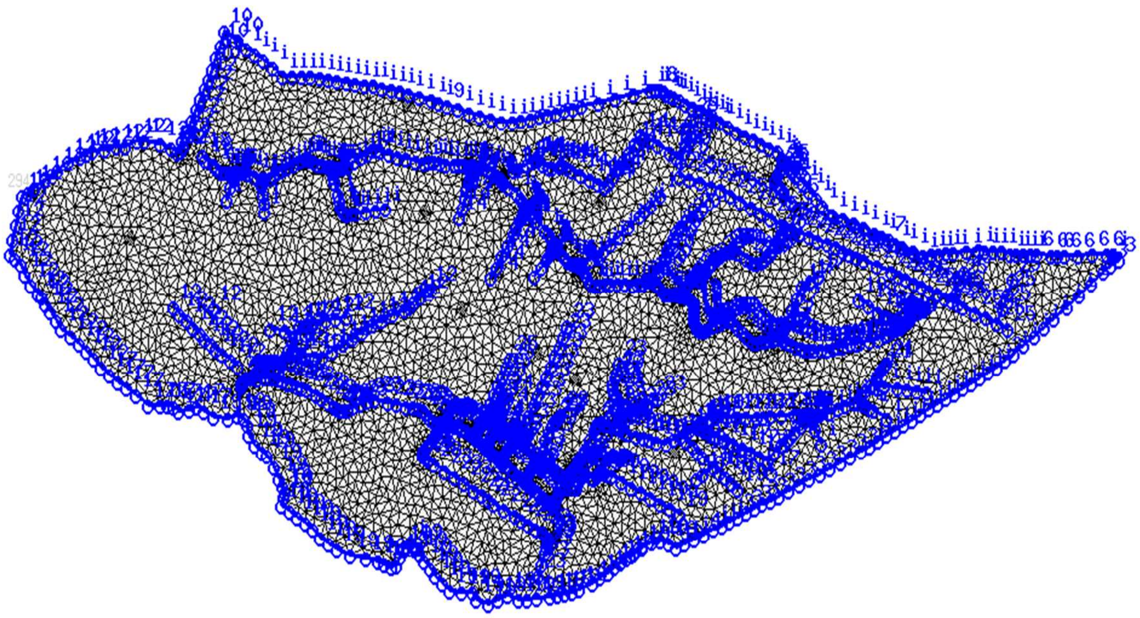

Fig. 7 First kind or Dirichlet-type boundary condition for canals and collectors around and within the WUA Shomakhulum

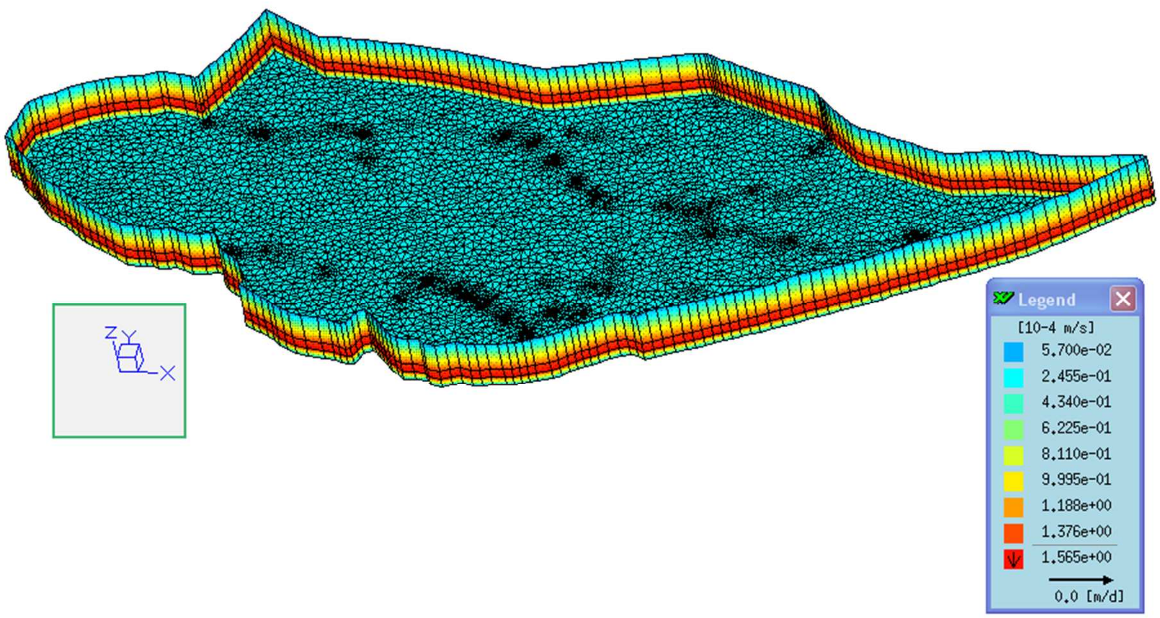

Fig. 8 Hydraulic conductivity values in different layers of the FEFLOW model domain

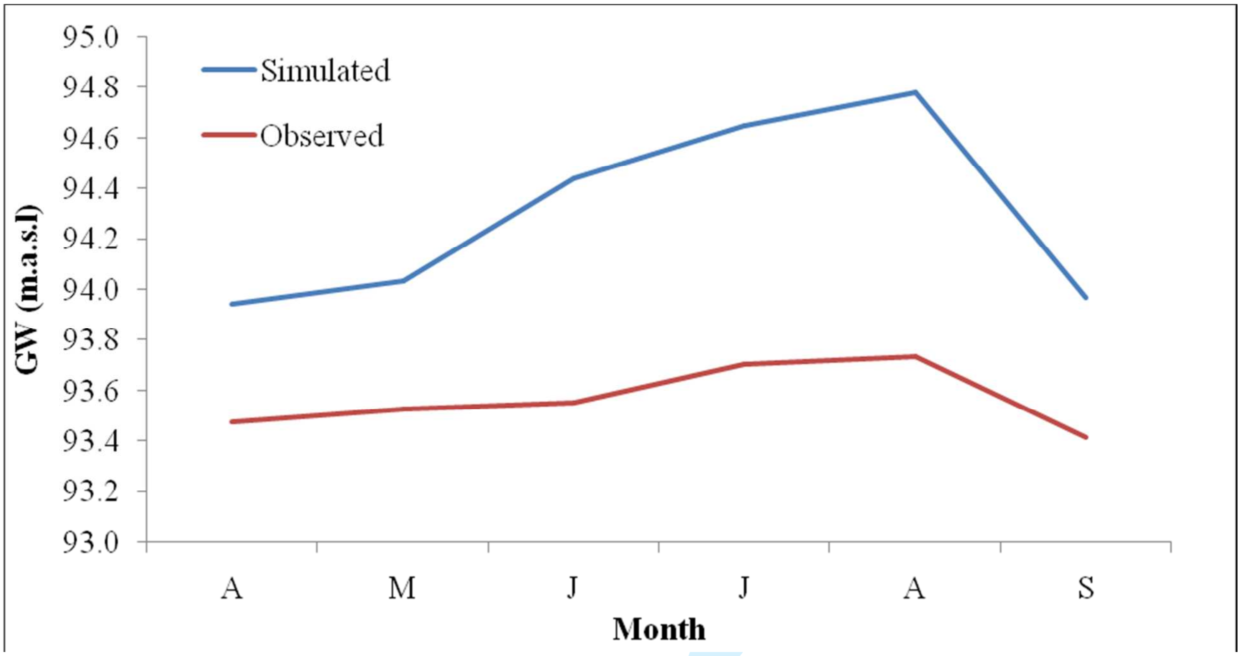

Fig. 9 Monthly average of 10 selected wells of simulated (after first run) and observed GW levels

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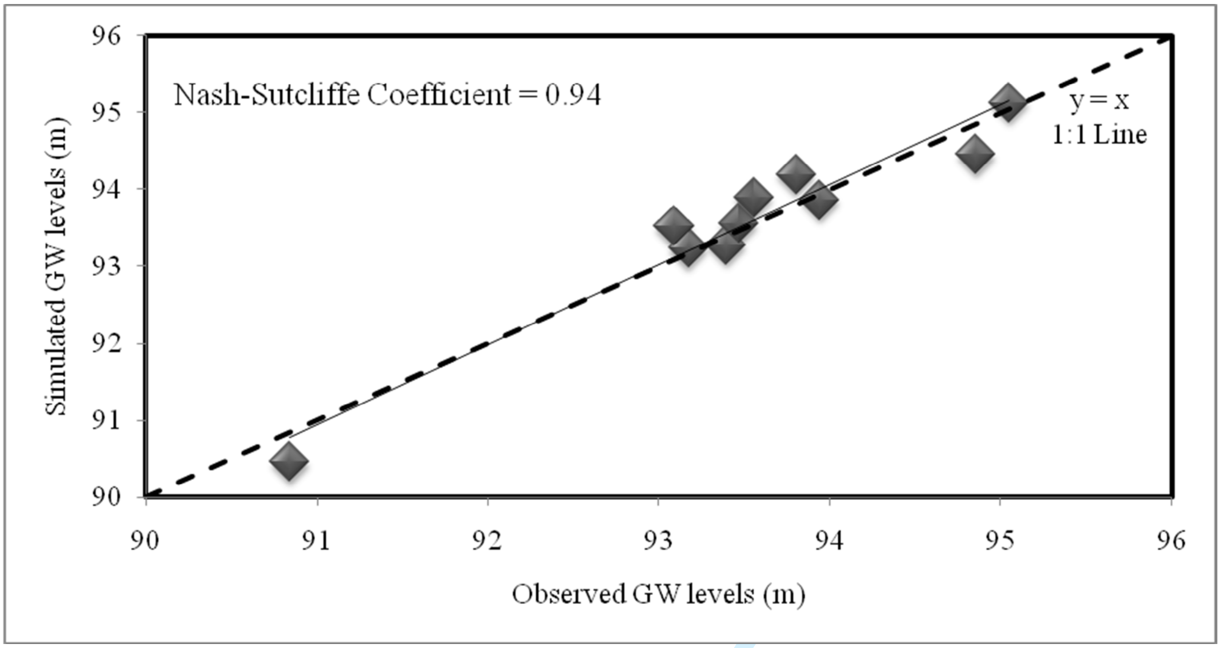

Fig. 10 Nash–Sutcliffe coefficient for calibration. Dotted line = 45° line, continuous line = trend line

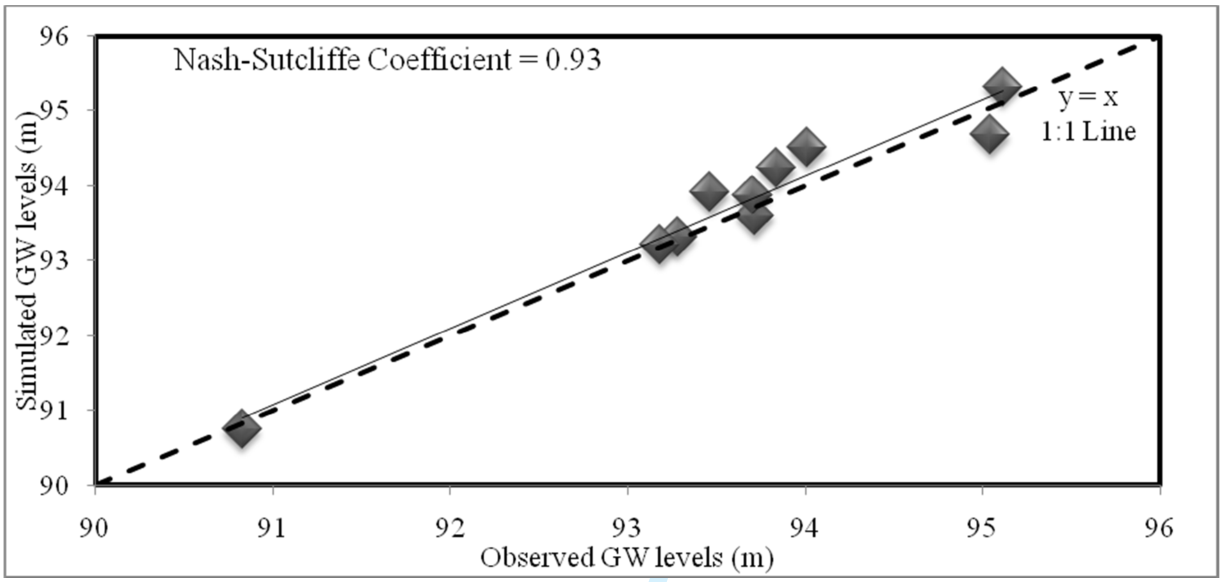

Fig. 11 Nash–Sutcliffe coefficient for validation. Dotted line = 45° line, continuous line = trend line

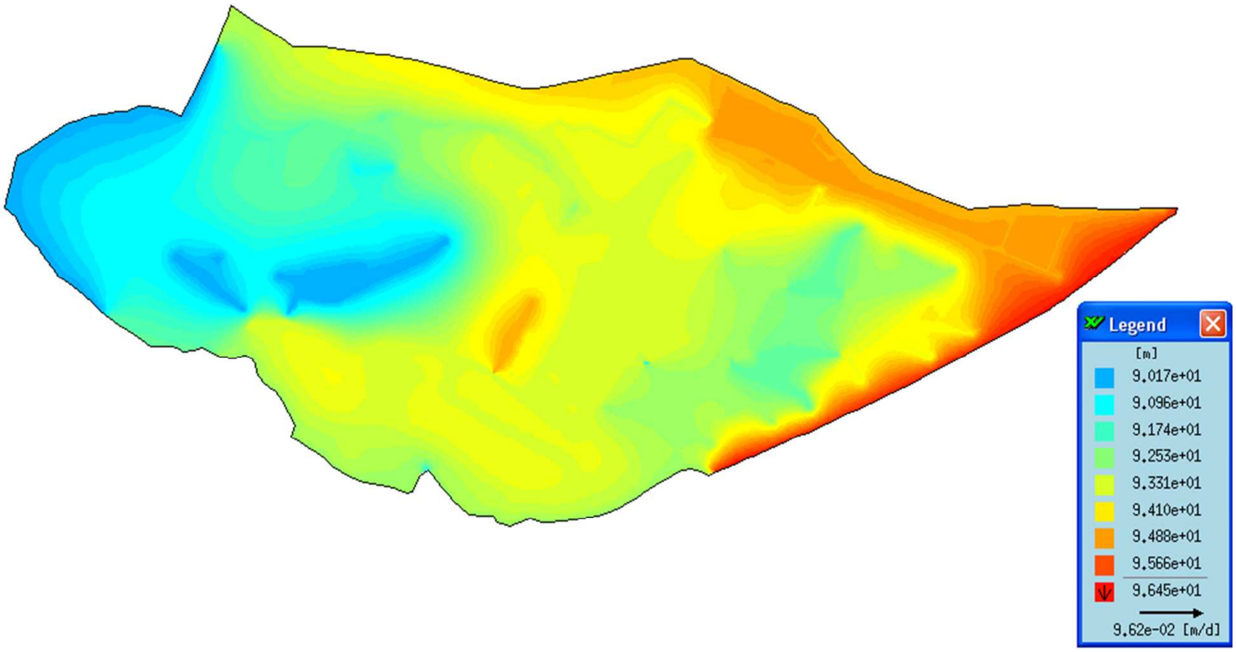

Fig. 12 Groundwater surface simulated by FEFLOW model before peak irrigation season (May)

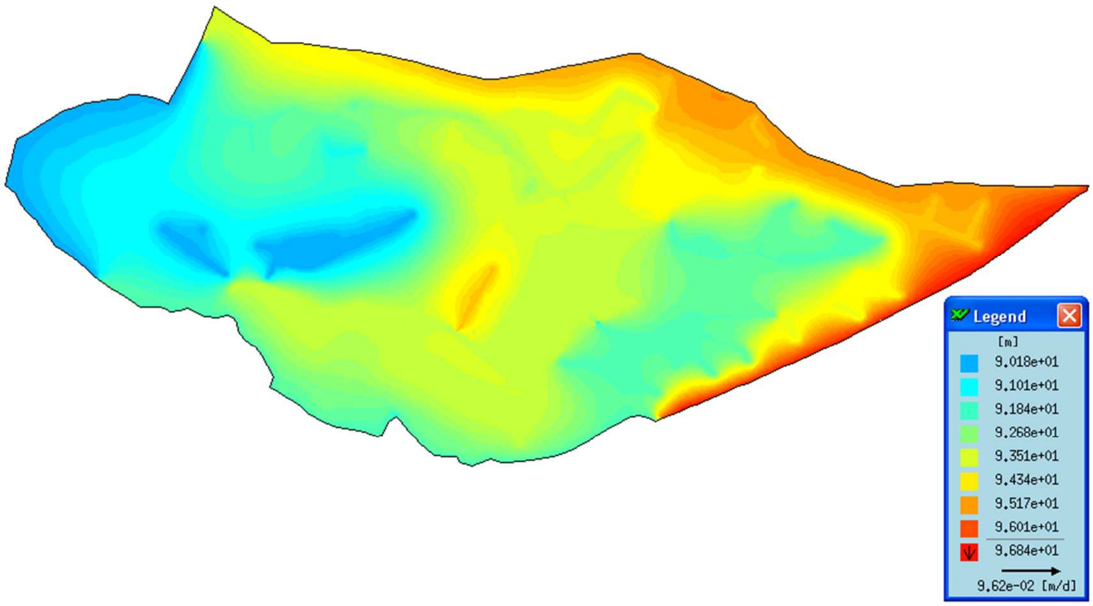

Fig. 13 Groundwater surface simulated by FEFLOW model after peak irrigation season (August)

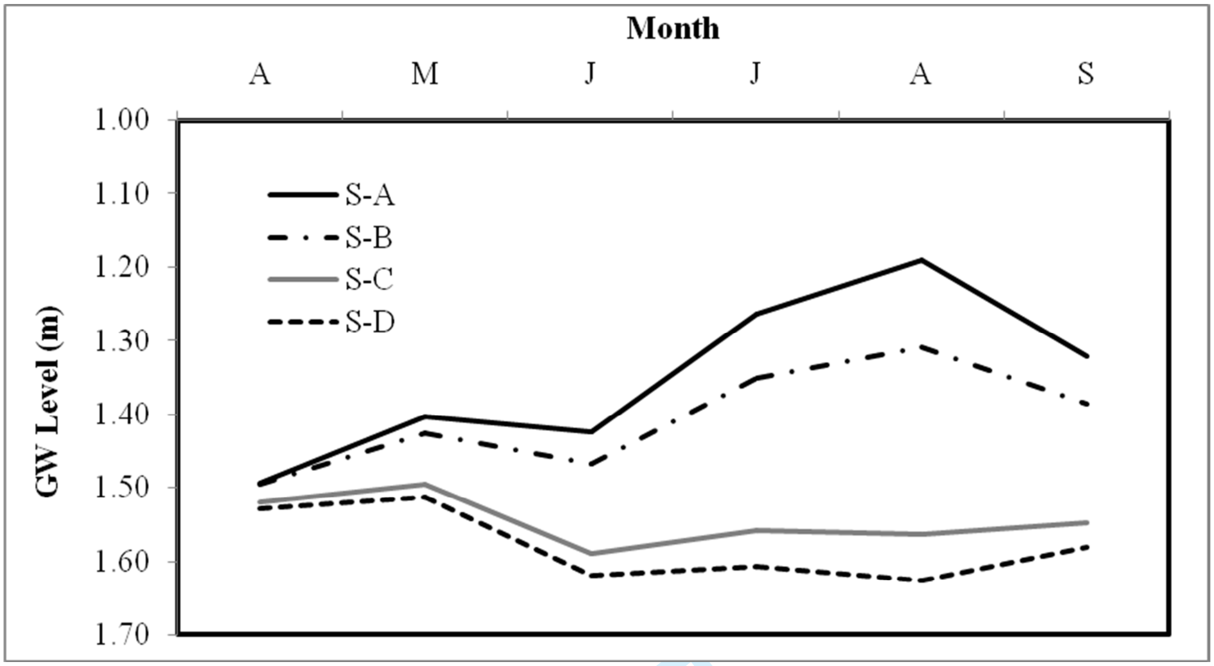

Fig.14 Simulated mean monthly GW levels for 10 observation wells for four improved irrigation efficiency scenarios (S-A = baseline or business-as-usual, S-B = improving conveyance ratio, S-C = raising field application ratio, S-D = improving field application ratio and conveyance ratio)

Table 1 Monthly recharge rates (mm) from water balance model as input to FEFLOW model for different hydrological response units (Source: Awan, 2010)

(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

Table 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