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Effects of the shallow water table on water use of winter wheat and ecosystem health: Implications for unlocking the potential of groundwater in the Fergana Valley (Central Asia)

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ABSTRACT

This paper analyzes the effect of the shallow water table on water use of the winter wheat (*Triticum aestivum L.*) that has replaced alfalfa (*Medicago sativa*) on the irrigated lands of the Fergana Valley, upstream of the Syrdarya River, in Central Asia. The effect of the shallow water table is investigated using HYDRUS-1D. Numerical simulations show that the contribution of the groundwater to evapotranspiration increases with a rising water table and decreases with increasing irrigation applications. Under irrigation conditions, an increase in the groundwater evapotranspiration is associated mainly with an increase in evaporation loss, causing a buildup of salinity in the crop root zone. Evaporation losses from fields planted with winter wheat after the harvest amount up to 45–47% of total evaporation thus affecting soil salinity and ecosystem health. Promoting the use of groundwater for irrigation in order to lower the groundwater table is suggested to achieve water savings from the change in the cropping pattern. Unlocking the potential of groundwater for irrigation in the Fergana Valley can also contribute toward managing soil salinity and improving the health and resilience of water, land and ecosystems of water, land and ecosystems (WLE).

1. Introduction

The basin water management, including the infrastructure and institutions, that was established in the Aral Sea Basin from 1960 to the mid-1980s, initially prioritized the water use for irrigation of cotton. From 1980 to 2010, the population of Central Asia doubled, increasing the demand for food production. Facing this food security challenge in new geo-political and socioeconomic environment after the forming of new independent states in the region after 1990, the states of Central Asia reoriented the focus of agricultural policy on food independency and prioritized food security. This was achieved in the region by the end of the 1990s by shifting from the cotton (6 years)/alfalfa (3 years) crop rotation to the cotton (2 years)/winter wheat (2 years) sequence. Since the irrigation season of alfalfa extends from March through September while winter wheat requires irrigation in October and then from March through May, the change of the cropping pattern from alfalfa to winter wheat results in the reduction of the summer irrigation. This released some of the water resources for the needs of the downstream water users. However, the water saving effect of this shift requires a certain clarification. As long as irrigation in Central Asia is entirely based on surface water, it is often associated with shallow groundwater tables. Water losses from irrigated fields and irrigation canals are the main source of groundwater recharge in the irrigated areas of Central Asia, amounting up to 70% of groundwater recharge in some regions, such as the Fergana valley (Borisov, 1990). Groundwater recharge from irrigation, coupled with poor natural and artificial drainage, leads to widespread shallow water table. On average, about 30% of the irrigated land has the water table less than 2 m below the soil surface. The water saving effect of the change in the cropping pattern becomes illusory for conditions with a shallow water table when intensive upward fluxes from the water table to the topsoil cause topsoil salinization, requiring more water for leaching.

The quantification of upward fluxes from a shallow groundwater table is a significant topic that has been extensively researched

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(Ganiev, 1979; Zhang et al., 1999; Soppe and Ayars, 2003; Kahlown et al., 2005; Babajimopoulos et al., 2007; Yang et al., 2007; Huo et al., 2011). In the Fergana Valley, Ganiev (1979) studied over a period of four years the capillary rise from a shallow water table in lysimeter experiments under fallow and natural conditions, and cropped with cotton or alfalfa. He found in loamy soils under cotton an increase in the capillary rise by 170, 280, and 330 mm for groundwater depths of 2.5, 2 and 1.5 m below the soil surface, respectively, compared to conditions with the water table below 3 m. In sandy loam soils, the capillary rise increased by 146 and 287 mm, and in sandy soils by 80 and 168 mm for groundwater depths of 2 and 1.5 m, respectively, as compared to conditions with the water table at a depth of 2.5 m or deeper. Zhang et al. (1999) reported that the ratio of the upward flux to alfalfa evapotranspiration (*ET*) varied between 25% and 65% for a non-saline soil with a groundwater table at a depth of 0.6–1 m. Soppe and Ayars (2003) maintained a groundwater table at a depth of 1.5 m in weighing lysimeters and found that groundwater contributed up to 40% of daily water used by the safflower crop. On a seasonal basis, 25% of the total crop water use originated from the groundwater. In the upper Indus basin near Lahore Pakistan, Kahlown et al. (2005) investigated the effect of shallow groundwater tables on the crop water use via 18 large-size drainage-type concrete lysimeters. They found that when a groundwater table was kept at a depth of 0.5 m, the entire water use of wheat was supplied by groundwater. Sunflower required only about 20% of its total water need from irrigation. However, in the same region, maize and sorghum were found to be sensitive to waterlogging, and crop yields were reduced with a rise of the groundwater table. Yang et al. (2007) quantified water fluxes in large weighing lysimeters, with a fluctuating groundwater table between 1.6 and 2.4 m during the wheat growth period and 0.7 and 2.3 m during the maize growth period, and found that, in a rotation system of wheat and maize, the cumulative capillary upward flux and the deep percolation were 89.6 and 55.9 mm, respectively. Liu and Luo (2011) conducted a lysimeter experiment to quantify the effects of shallow water tables on the water use and yield of winter wheat under rainfed conditions. The results showed that, under rainfed conditions, the seasonal contribution of groundwater met more than 65% of potential evapotranspiration of winter wheat when the water table depth was within 40–150 cm. Huo et al. (2011) studied the effect of the groundwater level and irrigation amounts on the water use of wheat in a lysimeter experiment at the Hongmen experimental station located in the Henan Province, China. Capillary rise supplied 29% of the water use of wheat during the time period from ripening to harvest when the groundwater table was 1.5 m deep, and was reduced when the depth of the groundwater table decreased. Water productivity of the wheat biomass increases and the yield decreases when groundwater levels decrease and the amount of irrigation water is reduced. Past studies indicated complex effects of the shallow water table on crop evapotranspiration.

The Fergana Valley, this study focuses on, has 900,000 ha of irrigated land and it thus represents an example of large-scale irrigated agriculture in Asia (Fig. 1a). The valley has significant potential for the production of food crops. For instance, the valley receives net radiation with the capacity to evaporate over 1120 mm/yr of water. Irrigated crops grown in the valley have the potential to utilize 70–80% of the available energy if the crop growth is not constrained by a water deficit or other factors. However, actual evapotranspiration is even lower and varies in the range of 611–722 mm/yr, of which only about 70% is transpired by crops (Karimov et al., 2012). The reduction of the area under fodder crops by replacing alfalfa with the winter wheat/fallow system reduced the crop water use in these areas on average by 30%. A risk of increasing soil salinity under shallow groundwater conditions in the Fergana Valley from a low saline to highly saline level may further reduce the crop water use and yields of cotton and wheat by about 25%. While productively utilizing only 38–45% of the available energy (due to many reasons such as a low fraction of the area covered by crops, short duration of the cropping season, or conventional furrow irrigation practices) farmers of the Fergana Valley produce over 850,000 Mg of cotton, 1300,000 Mg of wheat, and 1000,000 Mg of vegetables and other agricultural commodities. Current production volumes could be increased almost twofold if thermal, soil, and water resources are used in the most productive way. In order to achieve this, it is important to move into a cyclic process of reallocating water from a use that produces low or no benefits to one that generates higher benefits (Molden, 1997; Molden and Sakthivadivel, 1999) and thus achieves more welfare per drop of water (Molden et al., 2010). The change in the cropping pattern is one of the measures available to policymakers to meet the demand for scarce water, to increase food production through better exploitation of energy and land resources, and to tactically adapt to climate change (Hanjra and Qureshi, 2010).

Since 1992 the cotton/alfalfa crop rotation, which dominated in the Fergana Valley, has been replaced by the cotton/wheat sequence. Additionally, the cotton growing area was reduced by 82,000 ha by allocating 34,000 ha to vegetables and 48,000 ha to winter wheat. This approach was attractive for policy makers as a

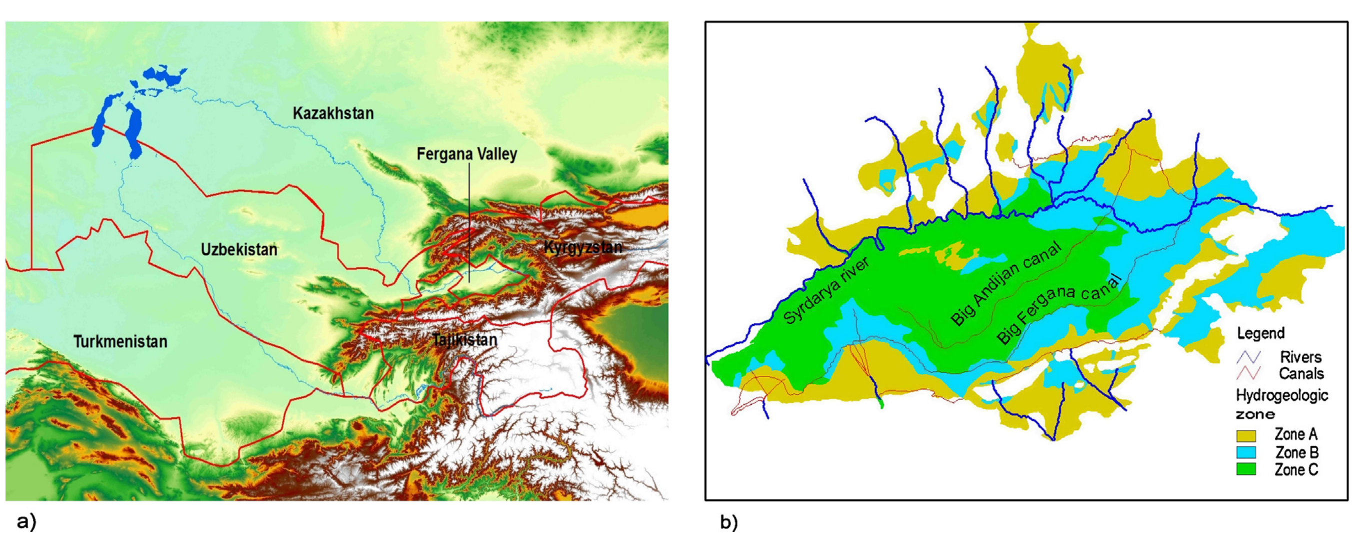

Fig. 1. (a) Central Asia and (b) hydrogeological zones of the Fergana Valley.

measure of achieving grain independence and as a low investment strategy that brought rapid results by decreasing the irrigation water demand. However, the real water savings via the decrease in the irrigation water demand are often assumed rather than empirically demonstrated in a post-policy implementation context. Additionally, associated socioeconomic benefits, including gains in farmers' income, employment, food security, and livelihood, are almost always ignored (Spoor, 1998; Cai et al., 2002; Nandalal and Hipel, 2007; Awan et al., 2011), and issues of salinity build up and its implications for water, land and ecosystem's (WLE) health and resilience are rarely examined. For instance, a shallow water table in a considerable part of the study area was not taken into account while the cropping pattern change was implemented. This is important because salinity, which is often associated with shallow groundwater tables, affects crop yield and reduces the productivity in large irrigation systems across Asia (Murgai, 2001; Smedema and Shiati, 2002; Khan and Hanjra, 2008). Additionally, salinization has ecosystem health linkages and implications for environmental water security (ADB, 2013).

This paper analyzes potential water savings due to the replacement of alfalfa by winter wheat under conditions with shallow groundwater in the context of the change of agricultural policy, implemented since 1992 in the Fergana Valley, the upstream of the Syrdarya River basin, in Central Asia. The study focuses on the contribution of shallow groundwater to evaporation and a salinity buildup in the root zone and its implications for ecosystem health. Therefore, the objectives of this paper are twofold: (1) to estimate the water-saving effect of growing winter wheat under shallow water table conditions, and (2) to suggest measures to reduce non-productive water losses from fallow lands and strategies for managing soil salinity to improve ecosystem health.

For this, the one-dimensional hydrological model HYDRUS-1D (Šimůnek et al., 2008a) was used to simulate crop transpiration and evaporation from winter wheat as affected by shallow groundwater under rainfed, deficit, and full irrigation conditions. Silt loam soils, dominating in the central part of the valley, were selected for this analysis. The results of this modeling exercise could be useful for planning land and water management in the river basins, facing similar water-scarcity challenges, and addressing salinity issues that challenge food production and WLE health in large irrigation systems.

2. Methods and data

2.1. Study area

The Fergana Valley is located upstream of the Syrdarya River and is a part of three countries in Central Asia–Kyrgyzstan, Tajikistan, and Uzbekistan. The climate is semi-arid with a low quantity of precipitation and high summer temperatures. Annual precipitation varies from 100 to 200 mm in the central part of the valley and increases to 300 mm in the piedmont areas. The mean average temperature is 14 °C. The altitude increases from west to east from 330 m above sea level (m asl) to 600 m asl. The valley is filled with alluvial deposits washed out by multiple rivers in the mountain zone. Three hydrogeological zones, representing hydrogeological conditions of the Fergana Valley, are a groundwater natural-recharge zone (Zone A), a groundwater springs zone (dominated by upward fluxes) (Zone B), and a groundwater discharge zone (Zone C) (Fig. 1b) (Mirzaev, 1974; Borisov, 1990).

These hydrogeological conditions are favorable for supporting fresh groundwater use. However, groundwater irrigation is practiced only in few areas as a supplement to canal irrigation. Over 55% of irrigated soils are prone to salinity, including 71,922 ha that are medium and highly saline in the hydrogeological Zone C (Supiev and Ganiev, 2005; Ergashev, 2011). Soil salinity poses a serious risk to sustainability of food production and resilience of ecosystems.

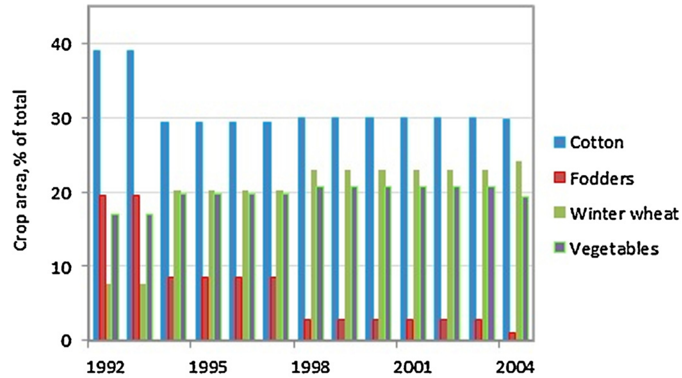

Fig. 2. Changes of the cropping pattern in the Fergana Valley.

Two main time periods can be identified in the recent history of the crop production in the Fergana Valley. Until the beginning of the 1990s, the cotton/alfalfa crop rotation dominated on the irrigated lands of the Fergana Valley (Fig. 2). The areas under cotton and alfalfa were 43% and 22%, respectively, of the total irrigated area, while winter wheat was grown on just 8% of the irrigated area. The irrigation demand of the Fergana Valley was in a range of 12,324–12,638 million (M) m^3/yr for the irrigated area of 900,000 ha. The crop production was well supplied with plentiful water in the study area at an early stage. After 1995, the dominant cotton/alfalfa crop rotation in the region was replaced by the cotton/wheat sequence, aimed at increasing the grain production and enhancing food security. The area under irrigated winter wheat was increased to 27%, while the area under alfalfa was reduced to 1% of the total irrigated area. In addition, the cotton growing area was reduced by 48,000 ha, mostly replaced by the cultivation of vegetables. Currently, two main crops, cotton and winter wheat occupy about 60% of the irrigated land. Farmers sow winter wheat in early October and harvest it in June, and sow cotton in April and harvest it in September-October. These changes in the cropping pattern had two main aims: (1) to increase the production of food crops, and (2) to reduce the consumption of water per unit of crop production, i.e., to increase water productivity. The first objective was easily achieved as the production of wheat grain in the Fergana Valley increased since 1990 as average wheat yield increased from 2 to 5.5 t/ha and area under wheat crop expanded to 27%.

The achievement of the second objective, i.e., increasing water productivity, was not obvious due to a wide spread of shallow groundwater, which results in upward fluxes to the crop root zone and mimic potential gains in water productivity. Reducing irrigation applications after shifting from alfalfa to winter wheat caused a lowering of the water table in the Fergana Valley (Fig. 3). Fig. 3 indicates a gradual reduction of the area with the shallow water table. However, this area, which is located mostly in the central part of the Fergana Valley, is still significant. It is estimated to be about 200,000 ha and it represents the hydrogeological Zone C with silt loam and loam soils. It is thus necessary to consider the effects of shallow water tables on the water use of winter wheat. A detailed description of the soils of the study area is given by Shreder et al. (1977) and Talipov (1992).

2.2. Research method

In this study, HYDRUS-1D, a variably-saturated water flow model (Šimůnek et al., 2008a), is used to estimate crop transpiration and evaporation. The HYDRUS-1D software package is a finite-element numerical model that simulates the one-dimensional

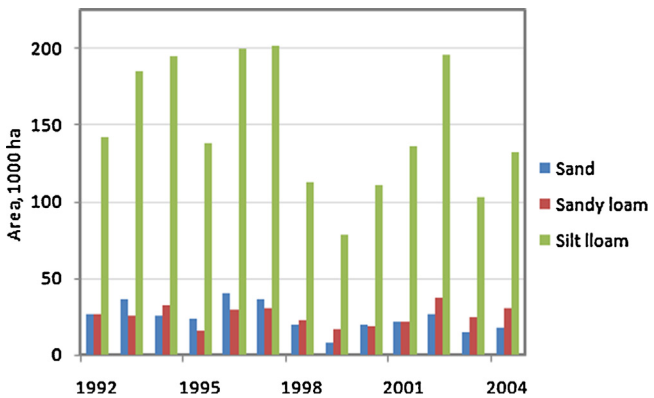

Fig. 3. Temporal changes in the areas with a shallow water table in the Fergana Valley.

movement of water, heat, and multiple solutes in variably-saturated media (Šimůnek et al., 2008b). The model has been previously used and verified in a large number of studies (e.g., Bah et al., 2009; Boudreau et al., 2009; Cao and Gong, 2003; De Vos et al., 2000; Endo et al., 2009; Gribb et al., 2009; Hao et al., 2008a,b; Heatwole and McCray, 2007; Hernandez, 2001; Liu and Xie, 1998; Meng et al., 2004; Sanchez et al., 2003; Šimůnek et al., 2008c; Wang et al., 2005; Xu et al., 2005). For example, Forkutsa et al. (2009) used the model to simulate water flow in fields with irrigated cotton and shallow groundwater on loam and sandy loam soils of the Khorezm region, located in the downstream part of the Amudarya River. Also, Shouse et al. (2011) used the HYDRUS-1D model for simulating root water uptake from a soil profile with shallow saline groundwater.

The HYDRUS-1D model simulates variably-saturated flow by solving the Richards' equation written as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} K \left(\frac{\partial h}{\partial z} + 1 \right) - S, \tag{1}$$

where θ is the volumetric water content (cm^3/cm^3), t represents time (day), z is the vertical coordinate (positive upward) (cm), h denotes the pressure head (cm), K is the unsaturated hydraulic conductivity (cm/day), and S is the soil water extraction rate by plant roots (cm^3/cm^3/day). The Richards' equation is solved numerically for given initial and boundary condition and for specified soil hydraulic properties, i.e., relations between soil hydraulic variables θ, h, and K. The soil water retention curve is described in the model using the formulation of Van Genuchten (1980):

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left(1 + \alpha_r \left| h \right|^n \right)^{-m}, \tag{2}$$

where S_e is effective saturation [–], θ_r and θ_s are residual and saturated water contents [cm^3/cm^3], respectively, and α_r [1/cm], m [–], and n [–] are shape parameters. The soil hydraulic conductivity function is described in HYDRUS-1D using the statistical pore-size distribution model of Mualem (Mualem, 1976; Van Genuchten, 1980):

$$K = K_s S^l \left[1 - \left(1 - S_e^{1/m} \right)^m \right]^2, \tag{3}$$

where K_s is the saturated hydraulic conductivity [cm/day], l [–] is a pore connectivity parameter, and $m = 1 - 1/n$, while $n > 1$.

Root water uptake by plant roots and its dependence on the soil water pressure head is described using the equation proposed by Feddes et al. (1978):

$$S = \alpha S_{\max}, \tag{4}$$

where $S_{\max}$ is the maximum potential water uptake rate [$cm^3/(cm^3$ day)] and α is a function of the pressure head [–].

HYDRUS-1D assumes that solutes in the soil profile can be transported by convection and dispersion in the liquid phase, as well as by diffusion in the gas phase (Šimůnek et al., 2008a). In irrigated fields, the total salt flux density can be described as a sum of convective and dispersive fluxes, while the gas-phase diffusion can be neglected (Singh et al., 2003):

$$J = J_{con} + J_{dis}, J_{con} = qC, J_{dis} = -qL_{dis} \frac{\partial C}{\partial z}, \tag{5}$$

where J is the total salt flux density [g/(cm^2 day)], J_{con} is the convection dispersion flux density [g/(cm^2 day)], and J_{dis} is the dispersion flux density [g/(cm^2 day)]. The convection–dispersion equation is in HYDRUS-1D solved numerically for specified initial and boundary (e.g., groundwater salinity concentrations) conditions (Šimůnek et al., 2008a).

The HYDRUS-1D model estimates crops evapotranspiration (ET) using the Penman–Montheith equation (Allen et al., 1998). Further details of the numerical approach used in the model are given by Šimůnek et al. (2008a). In this study, the HYDRUS-1D model was used to simulate water flow and solute transport in the unsaturated zone of the winter wheat fields with shallow and deep water table conditions.

In order to obtain a quantitative assessment of simulation results, root mean square error ($RMSE$), relative mean absolute error ($RMAE$) and correlation coefficient (r) were used to evaluate numerical simulation precision:

$$RMSE = \left[\frac{1}{n} \sum (E_i - M_i)^2 \right]^{1/2}, \tag{8}$$

$$RMAE = \frac{\frac{1}{n} \sum_{i=1}^{n} (M_i - E_i)}{\frac{1}{n} \sum_{i=1}^{n} M_i} \times 100\%, \tag{9}$$

$$r = \frac{\sum_{i=1}^{n} \left(M_i - \overline{M} \right) \left(E_i - \overline{E} \right)}{\sqrt{\sum_{i=1}^{n} \left(M_i - \overline{M} \right)^2 \left(E_i - \overline{E} \right)^2}} \times 100\%, \tag{10}$$

where M_i and E_i are the ith measured and simulated values, respectively, and n is the observation frequency.

The yield and water productivity of winter wheat were estimated using the results of numerical simulations. The yield of winter wheat was calculated using the FAO expression relating the yield response to ET:

$$\left(1 - \frac{Y_a}{Y_x} \right) = k_y \left(1 - \frac{ET_a}{ET_x} \right), \tag{6}$$

where Y_x and Y_a are the maximum and actual yields, ET_x and ET_a are the maximum and actual cumulative evapotranspiration, and k_y is a yield responses factor, representing the effect of a reduction in evapotranspiration on yield losses. The relationship between the yield of winter wheat and transpiration is taken from a study of Sommer et al. (2013), who using the field data proposed the following relation for the study area:

$$Y_b = 0.18272 \times T + 0.40562, \tag{7}$$

where T is crop transpiration (in mm). This relation (7) was used to verify winter wheat yields estimated using the expression (6).

2.2.1. Input parameters in HYDRUS-1D

Calculations for water flow and solute transport, carried out to estimate evapotranspiration from shallow water table, covered a soil profile 300 cm deep. The soil moisture content was determined before sowing of winter wheat from the same soil horizons. Soil texture and soil bulk density were determined on soil samples collected in 2006 from the field in the Kuva district from soil depths of 0–0.3 m, 0.3–0.6 m, 0.6–0.9 m, 0.9–1.2 m, 1.2–1.8 m and 1.8–3 m. The Kuva district is located in the Fergana province, Uzbekistan, on the left bank of the Syrdarya River. The soil throughout the entire soil profile could be classified according to the USDA classification as a silt loam. For the purpose of numerical modeling, the soil profile was divided into six numerical layers and grouped into four soil horizons, determined by a soil description. The Van Genuchten–Mualem model (Van Genuchten, 1980) with an air-entry value of −2 cm was used to obtain a predictive equation for the unsaturated hydraulic conductivity function.

An atmospheric boundary condition is applied at the soil surface for the winter wheat growing period starting on October 4 and ending on June 11 of the next year and for the land fallowing period between winter wheat harvesting and its next sowing date. The lower boundary condition is the time-variable pressure head. It was assumed that farmers will continue their traditional practice of soil plowing after winter wheat harvesting to a depth of 20–22 cm. The climate conditions, including daily maximum and minimum air temperatures (°C), relative humidity (%), sunshine hours, rainfall (mm), and wind speed (km/day), were measured at the Fergana weather station located at longitude of 71.75°, latitude of 40.38°, and an elevation of 547 m asl. The canopy ground cover was used as the basis to separate calculated evapotranspiration (*ET*) into soil evaporation (*E*) and transpiration (*T*). The crop development is represented in the model by a daily crop height, a rooting depth, and a soil cover fraction (Allen et al., 1998). The maximum rooting depth was 100 cm. The maximum rooting depth was less than the potential rooting depth, because the shallow water table restricted the growth of the roots (Raes et al., 2012). Wheat parameters used in numerical simulations were assumed to be conservative and applicable for a wide range of conditions. Simulations were carried out for a period of 1717 days. Daily climate data for this time period were obtained from the Fergana weather station from October 1991 to September 1996.

The root water uptake method proposed by Feddes et al. (1978) was used to describe water and salinity stress conditions. An additive model was selected for the stress response function of the root water uptake model. The water stress reduction term was parameterized using parameter values found by Wesseling et al. (1991): $P_0 = 0$, $P_{Opt} = -1$ cm, $P_2H = -500$ cm, $P_2L = -900$ cm, $P_3 = -16{,}000$ cm, $r_2H = 0.5$ cm/day, $r_2L = 0.1$ cm/day. A critical stress index for root water uptake was taken as 1 and no root solute uptake was allowed.

Soil hydraulic parameters were determined by an inverse analysis of data from the lysimeter study carried out in the same area earlier by Ganiev (1979). This study was a part of a comprehensive assessment of the regional water budget conducted during that time in Uzbekistan. The lysimeters of 1.44 m^2 surface area were packed with a monolithic silt loam soil. Cotton was sown in the lysimeters. The groundwater table in the lysimeters was kept at a constant depth of 1.5, 2, 2.5, and 3 m below the soil surface. Soil water content before and after the crop vegetation season, along with the climate and cotton phenology parameters, were inputs to the model. Initial values of the Van Genuchten–Mualem parameters describing soil hydraulic properties of each soil layer were taken from the HYDRUS-1D database for silt loam soils. The inverse simulation period included 365 days from 10 April 1996 to 9 April 1997. Daily estimates of upward fluxes from the groundwater table were entered into the model as a data for the inverse solution.

Simulated and measured values of upward fluxes from the water table are shown in Fig. 4. The *RMSE* and *RMAE* between measured and simulated values were relatively low and equal to 0.0199% and 1.48%, respectively. The correlation coefficient between simulated and measured values (*r*) was 0.9274. The above analysis indicates that simulation results agreed well with the measured data and

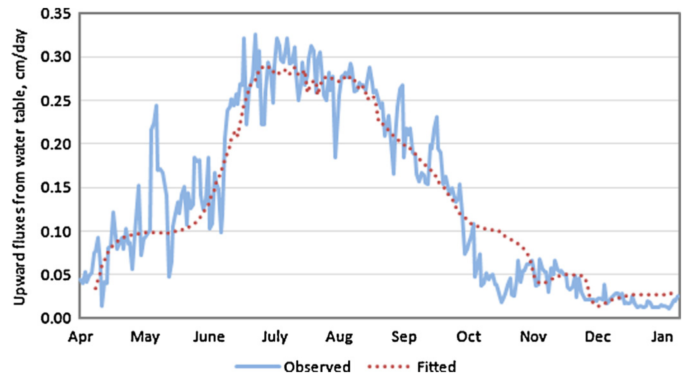

Fig. 4. Comparison between simulated and measured upward fluxes in the lysimeter study (Ganiev, 1979).

Table 1
Van Genuchten–Mualem parameters (Van Genuchten, 1980) to describe soil hydraulic properties.

Parameter	Soil layer [m]			
	0–0.6	0.6–1.2	1.2–1.8	1.8–3
Soil type	Silt loam	Silt loam	Silt loam	Silt loam
θ_r [cm^3/cm^3]	0.038	0.001	0.0012	0.001
θ_s [cm^3/cm^3]	0.407	0.250	0.301	0.336
α [1/cm]	0.0245	0.0001	0.0016	0.0157
n [−]	1.43	5.16	1.65	1.73
K_s [cm/d]	11.4	1.08	27.6	4.48
l [−]	0.00055	0.054	0.0098	0.0065

θ_r—Residual soil water content [cm^3/cm^3], θ_s—saturated soil water content [cm^3/cm^3],
K_s—Saturated soil hydraulic conductivity [cm/day], α [1/cm] and n [−] are shape parameters,
l—pore-connectivity parameter [−].

the results from the lysimeter studies. The final inversely estimated values of the Van Genuchten–Mualem parameters describing soil hydraulic properties of each soil layer are presented in Table 1.

Solute transport parameters were represented in the model by the dispersivity, which was taken to be a one-tenth of the profile depth (Beven, 1993; Cote et al., 2003), and the molecular diffusion coefficient in free water, which was taken equal to 2 cm^2/day. Salinity was simulated as a non-reactive solute assuming that there was neither precipitation nor dissolution of salts from soil primary material to the soil solution (Ramos et al., 2011). Absorption was neglected in the simulations. The initial concentration of soluble salts in the soil profile was taken as 1.5 g/l. Total dissolved solids (TDS) in the irrigation water were 0.5 g/l and in the groundwater were 1.5 g/l. The solute transport upper and lower boundary conditions were a concentration flux and the groundwater salinity, respectively. The concentration of soluble solids in the groundwater is relatively low because of the dominance of the lateral flow from the upper hydrogeologic zone B and filtration losses from dense canal systems. The presence of the lateral inflow permitted specifying the constant salinity boundary condition at the bottom of the model.

2.2.2. Irrigation scenarios simulated

Five irrigation regimes (Table 2) were considered:

(1) *Full irrigation* (FI): in addition to precipitation (16.6 cm/yr), two irrigations with a total of 10.1 cm before the winter season and four irrigations with a total of 27.8 cm after the winter season were simulated, with a total water application $M = 54.5$ cm/yr. The full irrigation scenario represented the irrigation regime recommended for silt loam soils with the groundwater table

Table 2
The irrigation regimes of winter wheat simulated in HYDRUS-1D to estimate upward fluxes from shallow water table and the topsoil salinity.

Irrigation scenario	Precipitation (cm)	Irrigation applications (cm)				
		October	March	April	May	Total
Full irrigation (FI)	16.6	10.1	5	13.9	8.9	37.9
Low deficit irrigation (LDI)	16.6	10.1		5	7.9	23
Deficit irrigation (DI)	16.6	5		5	7.9	17.9
High deficit irrigation	16.6	5		5		10
Rainfed winter wheat	16.6					

at 3 m and deeper below the soil surface (Shreder et al., 1977). Irrigation dates were specified using the Excel sheet developed by Allen et al. (1998) and using the depletion fraction of total available soil water at 0.55;

(2) *Low deficit irrigation* (LDI): compared to scenario FI, only three irrigations were considered after the winter season that were additionally further reduced by 10%, resulting in a total water application $M = 39.6$ cm/yr;
(3) *Deficit irrigation* (DI): compared to scenario LDI, only one irrigation was considered before the winter season, $M = 34.5$ cm/yr;
(4) *High deficit irrigation* (HDI): only two short irrigation events, one in October and one in April, 5 cm each, were considered under this scenario, $M = 26.6$ cm/yr;
(5) *No irrigation*: only precipitation, rainfed cultivation of winter wheat (RF), mean annual rainfall $M = 16.6$ cm/yr.

Variable daily pressure heads, reflecting the position of the groundwater table, were specified at the bottom of the soil profile. Four groundwater table depths of 3, 2.5, 2, and 1.5 m were considered in the modeling study.

In the entire Fergana Valley, 70% of groundwater recharge is due to losses from the dense system of canals and irrigated fields, while about 12–14% is subsurface inflow from upper lands. In the hydrologic zone C, lateral inflow from the upper hydrological zone and leakage from canals are estimated to be between 60% of total groundwater recharge in dry years to 85% in wet years. The density of the open drainage system within the hydrological zone C averages 59 m/ha and the close pipe system an additional 2 m/ha. The drainage depth is from 2.5 to 3.5 m. In spite of the dense drainage system, the water table in this area is less than 2 m below the ground on 57% of the irrigated land. The groundwater table has a minimum level in April, rises during the crop irrigation season, and then gradually falls in winter.

3. Results and discussion

3.1. Effects on the water use

Raising the water table from 3 to 1.5 m depth below the soil surface increased crop evapotranspiration (*ET*) from 36 to 57.9 cm under rainfed conditions and from 58 to 66.5 cm under full irrigation conditions. These *ET* values are close to those obtained in lysimeter studies conducted earlier by Ganiev (1979) in the study area. Fractions of groundwater contributions (a net upward flux) to total *ET* (*GWe.ET*), as affected by a shallow water table and the irrigation schedule, are given in Fig. 5.

Fig. 5 shows that upward fluxes increase when the water table is raised and decrease when irrigation applications increase. Thus, for a shallow water table 1.5 m below the soil surface, the groundwater evapotranspiration decreases from 62% to 9% of total evapotranspiration when natural rainfall (RF) is supplanted with a full irrigation regime (FI). For a water table at a 3-m depth, the corresponding decrease is from 17% to 0%. Contribution of groundwater to crop evapotranspiration is negligible for a deep water table (e.g., 3 m)

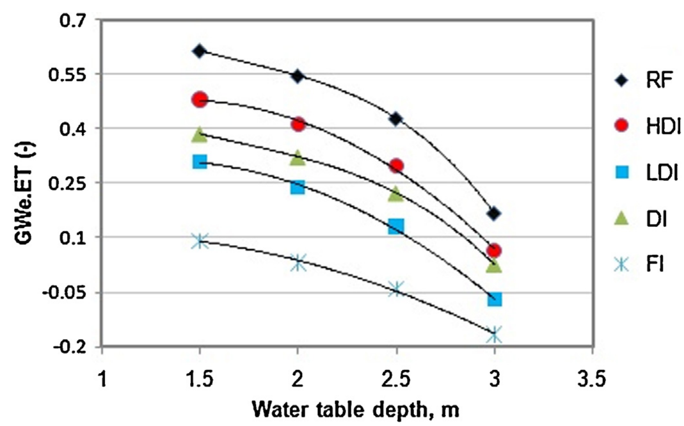

Fig. 5. Groundwater contribution to crop evapotranspiration as fraction of *ET* (*GWe.ET*), as affected by a shallow groundwater table and an irrigation regime for winter wheat on silt loam soils, Fergana Valley (average for 1992–1996).

and irrigated conditions. This finding concurs with the conclusions of Ayars et al. (2006). Using the Meyer equation (Wu et al., 1999), Ayars et al. (2006) found that the maximum upward fluxes occur when the root zone is dry and groundwater table is shallow and the minimum upward fluxes occur when the root zone is wet, with either deep or shallow groundwater. Huo et al. (2011) came to similar conclusions based on their lysimeter studies of the water use of wheat.

Under conditions with a shallow groundwater table, farmers of the Fergana Valley tend to apply less irrigation and thus to shift the crop water supply from surface irrigation to groundwater in order to meet the crop water demand. However, the results of the simulations given in Fig. 6 indicate that under such sub-irrigation conditions, an increasing fraction of total *ET* is non-productive evaporation. Evaporation as a fraction of actual ET_a ($E.ET_a$) increased from 0.43 to 0.46 under rainfed conditions and from 0.44 to 0.50

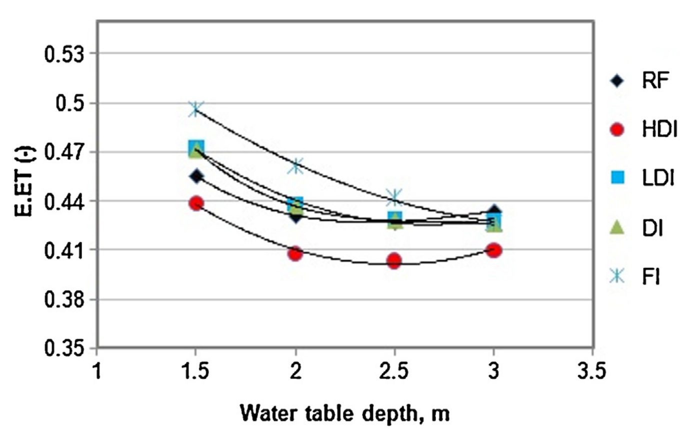

Fig. 6. Evaporation as a fraction of ET_a ($E.ET_a$) as affected by a water table depth and irrigation regime for silt loam soils of the central part of the Fergana Valley (1992–1996).

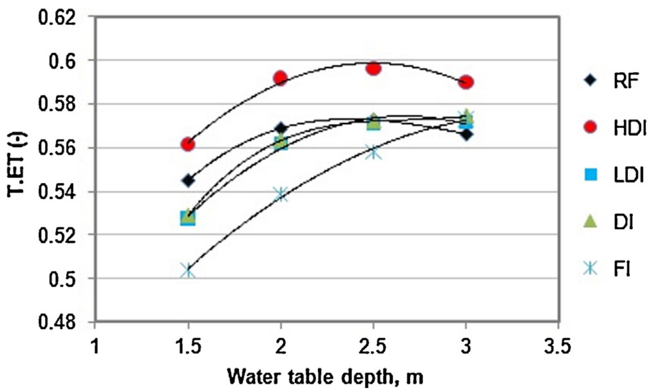

Fig. 7. Transpiration as a fraction of ET_a ($T.ET_a$) as affected by a shallow water table and irrigation regime (1992–1996).

under full irrigation when the water table was raised from 2 to 1.5 m below the soil surface. These numbers suggest that raising the water table from 2.5 to 1.5 m produces additional non-productive evaporation of 108 mm under rainfed conditions and 82 mm under full irrigation. It is important to note, that the minimum value of the evaporation fraction was received for the HDI scenario, when irrigation supplements precipitation (Fig. 6).

Under the same conditions, raising the water table from 3 to 1.5 m below the soil surface increased crop transpiration by 112 mm under rainfed conditions and by only 3 mm under full irrigation (Fig. 7). However, transpiration as a fraction of ET_a ($T.ET_a$) is reduced from 0.57 to 0.54 under rainfed conditions and from 0.57 to 0.50 under full irrigation. The simulation results suggest that raising the water table does not necessarily produce significant gains in productive crop transpiration under full irrigation. Again, the highest transpiration fraction of ET_a was estimated for the HDI scenario when irrigation supplements precipitation.

3.2. *Effects on soil salinity and ecosystem health*

An increased contribution of groundwater to soil surface evaporation produced an increase in the soil salinity (Fig. 8). Fig. 8 shows simulated TSS under the rainfed conditions in the topsoil (Fig. 8a) and in the root zone (a soil layer of 0–100 cm) (Fig. 8b). After five years of winter wheat cultivation under the rainfed conditions, the top soil (0–30 cm soil layer) salinity increased from an initial value of 1.5 g/l to 5.73, 8.51, 8.66, and 11.23 g/l when the water table was 3, 2.5, 2, and 1.5 m below the soil surface, respectively. Similarly, the average root zone salinity increased from an initial value of 1.5 g/l to 5.29, 8.01, 8.51 and 10.41 g/l when the water table was 3, 2.5, 2, and 1.5 m deep, respectively. The salinity at the bottom of the vadose zone is not changed under rainfed conditions.

Under the deficit irrigation (DI) scenario the increases in estimated salinities were smaller than under the scenario of a rainfed cultivation of winter wheat (Fig. 9). Higher concentrations of salts in the topsoil as compared to those averaged over the root zone still indicate the salinity buildup in the soil profile, i.e., salts moving with the upward fluxes are accumulating in the topsoil. More salts enter the vadose zone under shallow groundwater conditions, and consequently more salts accumulate in the topsoil—with implications for crop yield and ecosystem health (Kijne, 2006; Khan and Hanjra, 2008).

Although the full irrigation regimes reduced accumulation of salts in the soil profile due to salt flushing (Kijne, 2001), the contribution of shallow groundwater to soil salinization was still obvious (Fig. 10). Under a full irrigation scenario, salinity in the topsoil, in the root zone, and at the bottom of the vadose zone, is less dependent on the depth of the water table. However, there are

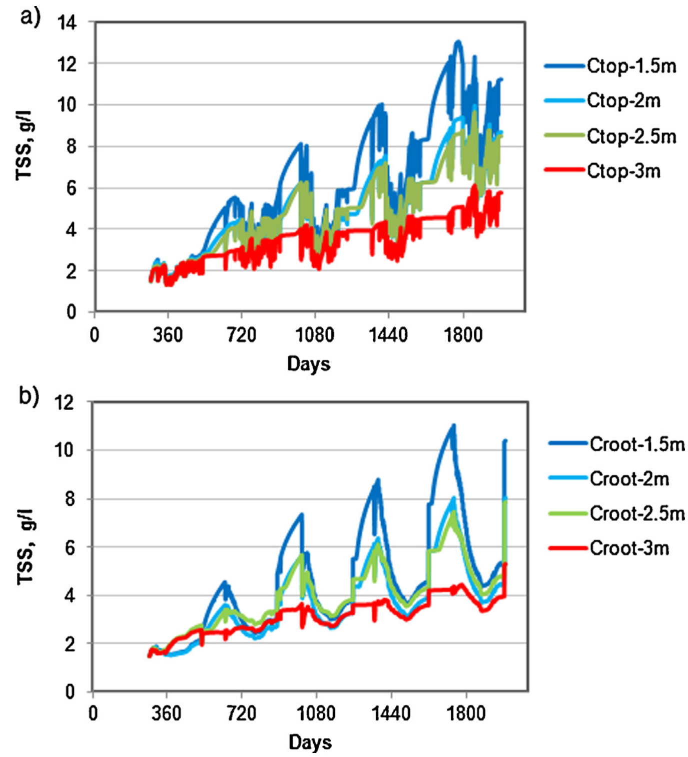

Fig. 8. Temporal changes in soil salinity (a) in the topsoil (Ctop) and (b) averaged over the root zone (Croot), as affected by a shallow water table (1.5, 2, 2.5, and 3 m) under rainfed conditions (1992–1996).

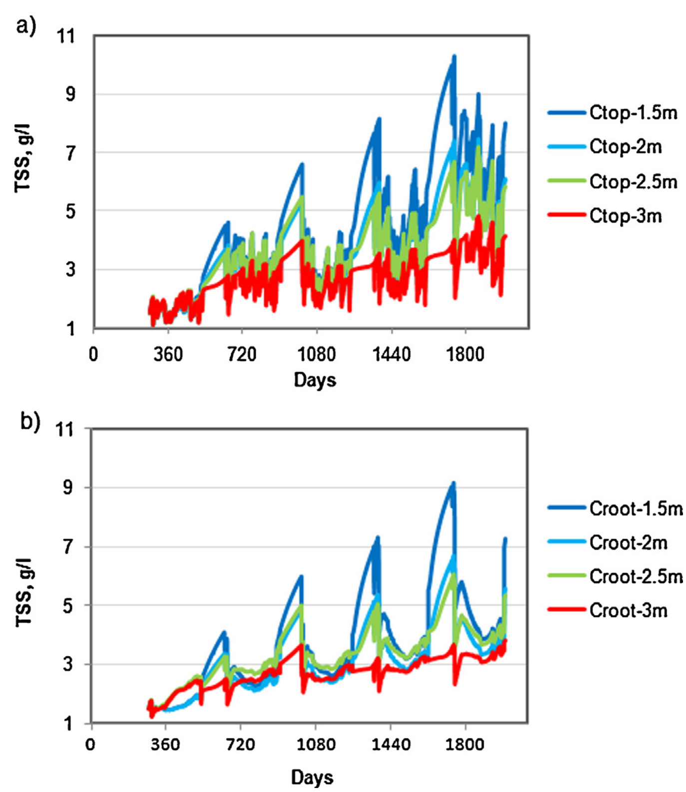

Fig. 9. Temporal changes in soil salinity (a) in the topsoil (Ctop) and (b) averaged over the root zone (Croot), as affected by a shallow water table (1.5, 2, 2.5, and 3 m) under deficit irrigation conditions (1992–1996).

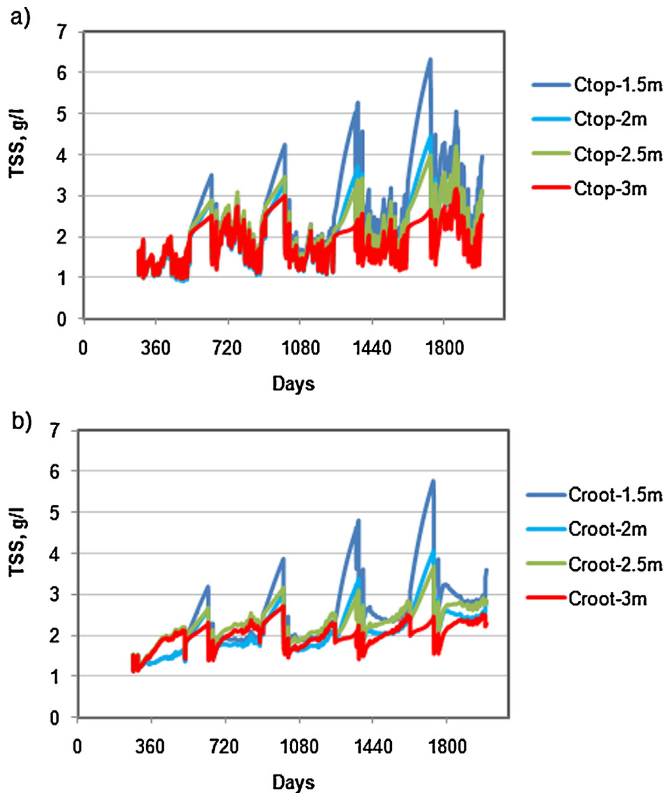

Fig. 10. Temporal changes in soil salinity (a) in the topsoil (Ctop) and (b) averaged over the root zone (Croot,), as affected by a shallow water table (1.5, 2, 2.5, and 3 m) under full irrigation (1992–1996).

still peaks in soil salinity under shallow water table conditions between individual irrigation events. The topsoil salinity increased from 1.5 to 3.96 g/l when a shallow water table was 1.5 m below the soil surface. The increase in salinity levels for other groundwater table depths was much smaller. The average root zone salinity increased from an initial value of 1.5 to 2.29 g/l and 3.59 g/l for water table depths of 3 and 1.5 m, respectively. These estimates indicate a potential stabilization of the topsoil salinity over time under deep groundwater conditions. The salinity at the bottom of the vadose zone is not changed significantly under full irrigation conditions.

3.3. Effects on wheat yield and water productivity

Table 3 summarizes simulated results for different groundwater table depths (*D*) and for different irrigation scenarios in terms of upward flux from the groundwater table (*GWe*), transpiration (*T*), evaporation (*E*), evapotranspiration (*ET*), and crop yield (*Y*). Evaporation and transpiration fluxes are also expressed as a fraction of the actual evapotranspiration ($E.ET_a$ and $T.ET_a$, respectively). Variations in crop transpiration and soil salinity are reflected in estimated yields of winter wheat (Table 3). The *RMSE* between values of winter wheat yields estimated using relations (6) and (7) was 0.2838.

These estimates of crop yield are based on the assumption that other inputs to crop production, such as soil tillage, fertilizers, and pest and weed control remain the same. The results presented in Table 3 show that raising the water table from 3 to 1.5 m below the soil surface produces a 31% increase in the yield of wheat under the rainfed conditions and no yield increase for a full irrigation scenario. This means that there are no significant gains from having a shallow water table under a full irrigation scenario, while a shallow water table under the rainfed conditions may cause soil salinization and may require extensive leaching and drainage to maintain low salinity levels. Various deficit irrigation scenarios produce intermediate salinity levels between the rainfed farming and full irrigation.

3.4. Toward improved water and land management practices

One of the reasons for high evaporation losses under shallow water conditions is fallowing of the land from June 11 till October 4 after harvesting of winter wheat and before sowing of the next year's crop (Table 4). It must be noted that since the fields are not mulched after the harvest, evaporation losses are significant and that has practical implications for residual moisture and water management.

The results of the modeling study show that under full irrigation conditions, even a shallow groundwater does not contribute to crop evapotranspiration. Under low deficit irrigation, net upward fluxes are smaller during a crop vegetation period as compared to a land fallowed period. As the magnitude of the deficit during the crop vegetation season increases, so does the contribution of the groundwater to crop evapotranspiration.

For groundwater 1.5 m deep below the soil surface, evaporation from June 10 to October 1 is estimated to be 47% and 45% of total evaporation under rainfed and full irrigation conditions, respectively. For conditions with a deep water table (3 m), evaporation after winter wheat harvesting is estimated to be 23% and 27%, respectively. Raising the water table from 3 to 1.5 m produces an increase in evaporation of 1.9 cm during the vegetation season and 8.8 cm after wheat harvesting—that is, greater losses due to land fallowing practice. For a full irrigation scenario, there is no increase in evaporation during the vegetation season and 8.1-cm increase after wheat harvesting. Therefore, lowering the water table could reduce evaporation losses by 10.7 cm under rainfed conditions and by 8.1 cm under full irrigation, which will significantly contribute to preventing salinity build-up in the topsoil. This implies that improved water and land management practices hold the key to water savings and environmental sustainability in the Fergana Valley.

3.5. Unlocking the potential of groundwater for irrigation in the Fergana Valley

Improved water and land management practices are the main pathway for unlocking the potential of groundwater for irrigation in the Fergana Valley. For instance, replacement of alfalfa by winter wheat reduces the irrigation demand at least by 200 mm/ha (Shreder et al., 1977), or 486 Mm^3/yr for the entire Fergana valley. However, due to the presence of a shallow water table on 200,000 ha of the irrigated land, a shift to cultivation of winter wheat will increase non-productive evaporation after wheat harvesting by 40–45 mm/ha. Temporarily, at early stages, the yield of winter wheat can reach a maximum level but the wheat yield will be sub-optimal and the yield ceiling will be reached sooner. However, a gradual increase of soil salinity will require an increase in the amount of water for salts leaching. In general, at the initial stage, rainfall and irrigation will control much of the salt accumulation. At later stages, under shallow water conditions, the sum of crop evapotranspiration and water required for leaching of soluble solids from the root zone of winter wheat may become comparable to the amount of water initially used for evapotranspiration of alfalfa, thus potentially offsetting a large part of the reduction in the irrigation deficit and water savings. For example, under full irrigation, evapotranspiration from an alfalfa field with a groundwater table 2 m deep was estimated to be 905 mm, while for a winter wheat/fallow system 665 mm. The amount of water required for leaching of soluble solids, according to Shreder et al. (1977), is in the range of 200–300 mm/yr.

Table 3
Water productivity and winter wheat yield as affected by a shallow water table for the silt loam soils of the Fergana Valley (averaged for 1992–1996).

$P+I$ (cm/yr)	D (m)	GWe (cm/yr)	T (cm/yr)	E (cm/yr)	ET_a(cm/yr)	$E.ET_a$ (−)	$T.ET_a$ (−)	Y_a (t/ha)	Y_b (t/ha)
16.57	1.5	35.7	31.6	26.4	57.9	0.46	0.54	4.9	5.4
(RF)	2	26.5	27.6	20.9	48.5	0.43	0.57	4.3	4.6
	2.5	18.1	24.2	18.0	42.2	0.43	0.57	3.9	4.0
	3	6.0	20.4	15.6	36.0	0.43	0.57	3.4	3.3
26.02	1.5	29.1	34.0	26.5	60.5	0.44	0.56	5.2	5.8
(HDI)	2	21.7	31.3	21.6	52.8	0.41	0.59	4.8	5.3
	2.5	14.0	28.1	19.0	47.2	0.40	0.60	4.5	4.7
	3	2.8	24.6	17.1	41.7	0.41	0.59	4.0	4.1
34.65	1.5	25.1	34.3	30.6	64.9	0.47	0.53	5.5	5.9
(DI)	2	18.9	32.9	25.5	58.4	0.44	0.56	5.3	5.6
	2.5	12.0	30.6	22.9	53.6	0.43	0.57	5.0	5.2
	3	1.3	27.7	20.6	48.3	0.43	0.57	4.6	4.7
39.62	1.5	20.1	34.2	30.6	64.8	0.47	0.53	5.5	5.8
(LDI)	2	13.8	32.7	25.5	58.3	0.44	0.56	5.3	5.6
	2.5	7.0	30.5	22.9	53.4	0.43	0.57	5.0	5.2
	3	−3.4	27.7	20.8	48.4	0.43	0.57	4.6	4.7
54.51	1.5	6.1	33.5	33.0	66.5	0.50	0.50	5.6	5.7
(FI)	2	2.0	33.4	28.6	62.1	0.46	0.54	5.6	5.7
	2.5	−2.5	33.4	26.4	59.8	0.44	0.56	5.6	5.7
	3	−9.6	33.2	24.8	58.0	0.43	0.57	5.6	5.7

D = Water table depth (m), $P+I$ = precipitation and irrigation amounts(cm), GWe—upward water flow from the groundwater (cm), T = estimated actual transpiration (cm), E = estimated actual evaporation (cm), ET_a = estimated actual evapotranspiration (cm), $E.ET_a$—evaporation as a fraction of ET_a (−), $T.ET_a$—transpiration as a fraction of ET_a, Y—yield of wheat (t/ha).

Table 4
Evaporation from the soil surface during the vegetative season of winter wheat and after its harvesting, during the land fallowing season, as affected by a shallow water table for the silt loam soils of the Fergana Valley (averaged for 1992–1996).

$P+I$ (cm/year)	D (m)	Net upward flux			Evaporation		
		Vegetation (cm)	Fallow (cm)	Total (cm)	Vegetation (cm)	Fallow (cm)	Total (cm)
16.57	1.5	25.0	10.7	35.7	13.9	12.5	26.4
(RF)	2	19.8	6.7	26.5	13.1	7.8	20.9
	2.5	12.8	5.3	18.1	12.6	5.5	18.0
	3	−1.2	7.3	6.0	12.0	3.7	15.6
26.02	1.5	18.5	10.6	29.1	14.0	12.6	26.5
(HDI)	2	15.0	6.7	21.7	13.8	7.8	21.6
	2.5	8.7	5.3	14.0	13.6	5.5	19.0
	3	−4.4	7.2	2.8	13.4	3.7	17.1
34.65	1.5	15.0	10.1	25.1	16.8	13.8	30.6
(DI)	2	12.9	5.9	18.9	16.1	9.4	25.5
	2.5	7.8	4.1	12.0	15.8	7.1	22.9
	3	−5.0	6.3	1.3	15.4	5.1	20.6
39.62	1.5	9.9	10.1	20.1	16.8	13.8	30.6
(LDI)	2	7.9	5.9	13.8	16.1	9.4	25.5
	2.5	2.8	4.1	7.0	15.8	7.1	22.9
	3	−9.7	6.3	−3.4	15.6	5.1	20.8
54.54	1.5	−3.4	9.5	6.1	18.2	14.8	33.0
(FI)	2	−3.3	5.3	2.0	18.2	10.4	28.6
	2.5	−5.7	3.1	−2.5	18.2	8.2	26.4
	3	−13.4	3.7	−9.6	18.1	6.7	24.8

D = Water table depth (m), $P+I$ = precipitation and irrigation amounts (cm),

Non-productive evaporation losses from the wheat grown area could be reduced by lowering the water table, and unlocking the productive potential of groundwater. Two alternative approaches could be suggested to achieve this. First, one can increase the intensity of drainage in the hydrogeological Zone C but this entails significant investment costs for the drainage infrastructure. Although this approach may lead to managing salinity levels in the crop root zone and improving the health and resilience of the agro-ecosystem, it may also generate return flow to the river during the winter season, when the downstream reservoirs are almost full. This measure would require additional storage capacities downstream on the Syrdarya River, and would further contribute to increasing the area with shallow water tables. These tradeoffs and associated cost-return matrix requires further analysis. The second approach is to shift from canal irrigation to conjunctive use of groundwater and canal water. Extracting groundwater for crop irrigation would lower its levels and reduce evaporative losses, salinity buildups in the topsoil, and saline return flows from the study area to the Syrdarya River. Extracted groundwater could be used in conjunction with canal water for irrigation of food crops, including double cropping. The water supply would become more uniform and reliable along the long canals, which cross the valley from east to west. Winter flows of rivers of the Fergana Valley could be used for groundwater recharge. There would be no need for additional storage capacities downstream, but this requires economic and policy incentives for promoting the conjunctive use of groundwater and canal water for irrigation in the Fergana Valley.

3.6. *Managing salinity for protecting ecosystem health*

Our modeling results and field observations show that salinity buildup in the root zone and salinization of agricultural land

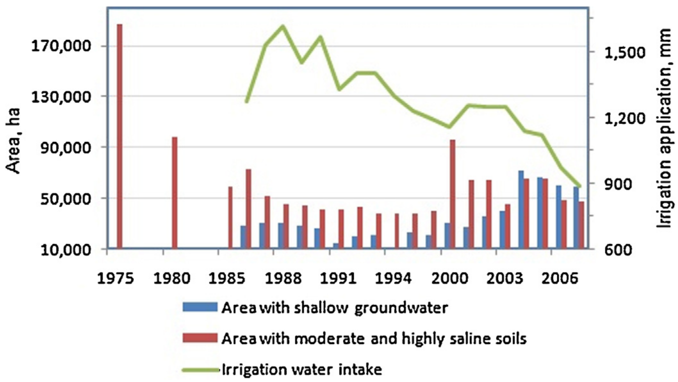

Fig. 11. Changes in areas with shallow groundwater, moderately and highly saline soils, and the water use over time (1975–2007) in the Fergana province.

with time may become a significant issue in the Fergana Valley, if no urgent action is taken to lower the shallow water table. Since a combination of over-irrigation in the zone C and lateral subsurface flow are the major source of shallow groundwater recharge, the shallow water table could be lowered by using groundwater for irrigation and other purposes and by improving irrigation technologies to arrest the salinity issue in the Fergana Valley. At present, about 55% of the irrigated land in the Valley is prone to salinity, including about 72,000 ha of land that are moderately and highly saline in the hydrological zone C. While irrigation application rates per ha have been reduced with the policy change that replaced alfalfa with winter wheat, areas with shallow groundwater and with moderately and highly saline soils have not, which remains a significant issue (Fig. 11). Furthermore, the spatial data show large salinity problems in many countries in Central Asia, including in the Fergana valley (Table 5). Salinity poses huge challenges to environmental sustainability and ecosystem health, as well as sustainability of food production, in large irrigation systems across Asia (Khan and Hanjra, 2008). For instance, China, India, Iran, Pakistan and Central Asian states are among the countries where a huge share of the productive irrigated cropland is affected by salinity. Soil salinity reduces water availability and crop yields, and threatens rural industries and livelihoods of millions (Postel, 1999; Khan and Hanjra, 2008). Irrigation induced soil salinity reduces agricultural production, threatens food security and imposes other economic, social and environmental costs. The socioeconomic impacts of water logging and salinity include the losses in income, lost returns on public investments, risks to public health due to saline water supplies, saline return flows to downstream areas, and damages to natural and built infrastructure.

Negative impacts of increased soil salinity on ecosystems include a loss of biodiversity, limitations on crop choices, an increase in invasive species, a loss of pollinator species, river-system health linkages, and ecological impacts. For instance, Qalandarov (2007) carried out a study under saline conditions in the Mirzachul lowlands, downstream of the Syrdarya River basin, next to the Fergana Valley. He observed a low microbiota activity in the saline soils of Uzbekistan and found low populations of ammonificators, oligonitrophils, and actinomycetes, that all play an important role in the soil ecosystem sustainability and resilience. In other settings, salinity limits crop varieties suitable for irrigated soils and affects crop development and yield (Katerji et al., 2003). It also affects river, stream, and wetland ecosystems (Hart et al., 1990), impacts of climate change on river ecosystems (Suen and Lai, 2013), river diversions and ecology (Das et al., 2012), river environmental flow requirements (Sun et al., 2009), tolerance of macro-invertebrate and the ecosystem protection trigger values (Dunlop et al., 2008), sustainability of agricultural landscapes, carbon sequestration and biodiversity values (George et al., 2012), vegetation–groundwater interactions (Humphries et al., 2011), pesticide toxicity, ecosystem functions and ecosystem services (Schafer et al., 2012), bioavailability of Cu and Zn and other essential plant micronutrients (Speelmans et al., 2010), and causes changes in grain ultrastructure, amylase, protein and amino acid profiles under water, salinity, and combined stresses (Ahmed et al., 2013). These myriad ecosystem health linkages do imply that under shallow groundwater conditions salinity has implications for river basin health and ecosystems and thus imposes carrying capacity constrains in terms of water-savings and unlocking the potential of groundwater development for irrigation.

Table 5
Land salinization in Central Asia (Bucknall et al., 2003).

Settings	Irrigated area (ha)	Area affected by salinization	
		(ha)	(%) of irrigated area
Kyrgyz Republic	1,077,100	124,300	11.5
Tajikistan	719,200	115,000	16.0
Kazakhstan	2,313,000	>763,290	>33.0
Turkmenistan	1,744,100	1,672,592	95.9
Uzbekistan	4,280,600	2,140,550	50.1
Central Asia	10,134,000	4,815,732	47.5

Managing salinity has implications for water security as well as for the sustainability of food production and terrestrial and aquatic ecosystems and vital services they provide to the mankind (Tilman et al., 2002). Long-term data on the concentration of total dissolved solids (TDS—an indicator of salinity and river system pollution normally discussed only for freshwater systems, as salinity comprises some of the ions constituting the definition of TDS) show that (a) the salinity has been on the rise over time (1931–2012) in the Amudarya River and (b) the rise in TDS concentrations was relatively low in upper reaches, higher in the midstream, and highest in the downstream reaches of the river (Table 6). While the data for the Syrdarya River show similar temporal trends of salinity patterns across the upper, middle, and lower reaches of the river system, the data also show that salinity is relatively higher, especially in the mid and downstream reaches of the Syrdarya River compared to those of the Amudarya River. Overall, these data show rising salinity and poor health of the river system, which has implications for ecosystem health and environmental water security of the region.

A key dimension of water security is environmental water security, i.e., the status of the water-related environment of river basins that can be assessed using the river heath index. The River Basin Health Index (ADB, 2013) is a composite of four indicators and their sub-indices that include: watershed disturbance (cropland, livestock, wetlands), pollution (salinization, NPK, Hg, TDS, acidification, etc.), water resources development (dams, relative water use compared to supply, agricultural sector water stress, and changes down streams), and biotic factors (non-native species, catch pressure and aquaculture). Data on environmental water security in selected basins and countries show that in Central Asia, agricultural development and salinization have already had major impacts and pose a major stress on the region's rivers and ecosystems (Table 7). For instance, with the development of water resources and irrigation in the region, vast tracts of underdeveloped land were converted into productive agricultural ecosystems, leading to the drying up of the Aral Sea. The vast irrigation development and over irrigation practices have also led to extensive land degradation in the areas irrigated with waters from Amudarya and Syrdarya rivers. According to recent estimates, nearly 50% of the irrigated areas in Central Asia are salt affected, water logged, or both (Qadir et al., 2009). The deterioration and poor health of the rivers and ecosystems potentially threatens the livelihoods of tens of millions who depend on them for food security and incomes.

Table 6
Temporal and spatial change of TDS of the Amudarya River and the Syrdarya River (modified from Abdullaev et al. (2007)).

	Amudarya River			Syrdarya River		
	Upstream	Midstream	Downstream	Upstream	Midstream	Downstream
1932–50	0.379	0.496–0.513	0.513	0.293	0.425	0.485
1951–60	0.395	0.514–0.524	0.524	0.302	0.584	0.698
1961–70	0.402	0.576	0.641	0.307	1.034	1.137
1971–80	0.409	0.59–0.755	0.755	0.321	1.203	1.282
1981–90	0.424	0.572–1.12	1.196	0.346	1.252	1.8
1991–99	0.424	0.572–1.122	1.196	0.359	1.265	1.829
2000–2012			1.113			1.102

Table 7
Environmental water security in selected river basins and countries (ADB, 2013).

Subregion (river basin or country)	Watershed disturbance (% of basin)	Pollution (% of basin)	Resource development (% of basin)	Biotic factors (% of basin)	River health indicator	River health assessment
Central Asia (Syr Darya)	0	31.6	68.4	0	0.30	Poor
Central Asia (Aral Sea)	4.2	6.5	74.1	15,1	0.28	Poor
Esat Asia (Yellow River)	0	29.7	70.3	0	0.19	Bad
Southeast Asia (Mekong)	21	3.6	63.8	11.6	0.27	Poor
Southeast Asia (Vietnam)	38.8	26.7	25.3	4.6	0.27	Poor

Improved management of land and water resources for enhancing food security and livelihoods and protecting ecosystems requires economic incentives and agriculture policies that can address the salinity issue head-on. This justifies public funding for policies for motivating farmers to adopt better water and land management practices and more efficient irrigation technologies. This can enhance the benefits to farmers by lowering the excess irrigation water applications to crops and reducing salinity, a consequent reduction in salt buildup and rise of ground-water table, and reducing negative impacts on ecosystem health. The suite of policy incentives and interventions include: better crop choices, better irrigation practices, practicing deficit irrigation while considering the depth of ground water table, a conjunctive use of canal and groundwater (as shown by this analysis), an improved water use efficiency (Molden et al., 2010), better irrigation technologies, and integrated agro forestry and cropping systems.

4. Conclusion

The results of the study suggest that contributions from shallow groundwater to crop evapotranspiration for winter wheat cultivated areas highly depend on irrigation regimes and land and water management practices. Under high deficit irrigation and rainfed conditions in loam soils, upward fluxes from shallow groundwater exceed 60% of total crop evapotranspiration. Under full irrigation, net upward fluxes are small even when the water table is only at 1.5 m depths below the soil surface. The evaporation fraction of the crop evapotranspiration is minimal and the transpiration fraction maximal for high deficit irrigation under shallow and deep water table conditions, respectively. However, under shallow water conditions, the benefits of deficit irrigation during early stages of crop growth may be followed by crop yield losses during later stages of crop growth, due to the rapid increase in topsoil and root zone salinity. Similar phenomena were observed in late 1980s in irrigated lowlands of Central Asia, where the shift from full to deficit irrigation under shallow water conditions caused salinity buildup and high economic losses to farming communities. Increasing the share of winter wheat on the irrigated lands since the mid 1990s accelerated these processes. Under shallow water conditions, evaporation from lands fallowed after winter wheat harvesting represents up to 45–47% of total evaporation losses. Excessive evaporation losses under shallow groundwater conditions become a source of continuous salinity buildup in the crop root zone.

The results of this study suggest that cultivation of low water-consumptive crops under shallow groundwater conditions does not produce expected water savings. Under shallow water conditions, reduced irrigation applications may be followed by an increase in upward fluxes to the topsoil. The numerical model indicates that for winter wheat, evaporation as a fraction of crop evapotranspiration increases with raising of the water table, while transpiration decreases. Evaporation from fallowed lands after winter wheat harvesting may represent up to 35–39% of total evaporation losses. Evaporation losses increase when the water table is raised and irrigation applications increased. Excessive evaporation losses under shallow groundwater conditions become a source of salinity buildup in the crop root zone. Evapotranspiration is identified as a key driver of groundwater salinity, and Humphries et al. (2011) support this finding. The same amount of water supplied earlier for irrigation of high water-consumptive crops may have to be applied at later stages for irrigation of low water-demanding food crops and leaching of the progressively salinized soils.

The results of this study suggest two alternative approaches that could be proposed to policy-makers to lower the shallow water table and unlock its potential for irrigation in the Valley. The first approach would increase the intensity of drainage, which would allow maintaining salinity levels in the crop root zone, but it would generate return flows to the river in the winter season, when the reservoirs are full in the Syrdarya River midstream. The second approach is the shift from canal irrigation to conjunctive groundwater and canal water use. The increased groundwater extraction will supply the irrigation demand of an intensive cropping system in the Fergana Valley, while saved surface water could be delivered to other users, midstream of the Syrdarya River. To prevent the environmental consequences of intensive farming practices and protecting ecosystem health, a wide scale adoption of water saving technologies has to be put in place. This is another important policy instrument to produce more food crops using available water and is a subject for future research.

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