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Modeling irrigated cotton with shallow groundwater in the Aral Sea Basin of Uzbekistan: I. Water dynamics

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Abstract In Khorezm, a region located in the Aral Sea basin of Uzbekistan, water use for irrigation of predominantly cotton is high whereas water use efficiency is low. To quantify the seasonal water and salt balance, water application, crop growth, soil water, and groundwater dynamics were studied on a sandy, sandy loam and loamy cotton field in the years 2003 and 2005. To simulate and quantify improved management strategies and update irrigation standards, the soil water model Hydrus-1D was applied. Results showed that shallow groundwater contributed a substantial share (up to 399 mm) to actual evapotranspiration of cotton (estimated at 488–727 mm), which alleviated water stress in response to suboptimal quantities of water applied for irrigation, but enhanced concurrently secondary soil salinization. Thus, pre-season salt leaching becomes a necessity. Nevertheless, as long as farmers face high uncertainty in irrigation water supply, maintaining shallow groundwater tables can be considered as a safety-net against unreliable water delivery. Simulations showed that in 2003 around 200 mm would have been sufficient during pre-season leaching, whereas up to 300 mm of water was applied in reality amounting to an overuse of almost 33%. Using some of this water during the irrigation season would have alleviated season crop-water stress such as in June 2003. Management strategy analyses revealed that crop water uptake would only marginally benefit from a permanent crop residue layer, often recommended as part of conservation agriculture. Such a mulch layer, however, would substantially reduce soil evaporation, capillary rise of groundwater, and consequently secondary soil salinization. The simulations furthermore demonstrated that not relying on the contribution of shallow groundwater to satisfy crop water demand is possible by implementing timely and soil-specific irrigation scheduling. Water use would then not be higher than the current Uzbek irrigation standards. It is argued that if furrow irrigation is to be continued, pure sandy soils, which constitute <5% of the agricultural soils in Khorezm, are best to be taken out of annual cotton production.

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Introduction

During the Soviet Union era, about 8 Mha of land were brought under intensive cultivation by the implementation of large-scale irrigation infrastructure in what today are the five central Asian countries Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan. Following their

independence in 1991, irrigated agriculture remained important. In the Republic of Uzbekistan, agriculture provided 24.0% of the GNP in 2007 (ADB 2008). Agriculture constitutes the main income for the rural population (Müller 2006) and, thus, sustains rural livelihoods. At the end of the last century the total irrigated land in Uzbekistan was estimated at 4.2 Mha (Abdullaev 2003).

One of the most important crops in Uzbekistan is cotton (*Gossypium hirsutum* L.). Uzbekistan, after the USA and India, is the world's third largest exporter of raw cotton. In the last 3 years, annually between 0.97 and 1.05 million metric tons of raw cotton, i.e., $\sim 80\%$ of the total harvest was exported (USDA 2008). About 8% of the cotton in Uzbekistan is produced in Khorezm, one of the twelve administrative units of Uzbekistan located in the western part of Uzbekistan in the Amu Darya Delta.

Countrywide per hectare raw-cotton production in 2005 was estimated at 2.7 Mg (FAOSTAT 2008). Although this was higher than the world average (1.9 Mg ha^{-1}), it is still less than achieved under similar agro-climatic conditions such as in Australia (4.2 Mg ha^{-1}). In view of such moderate yields, irrigation water use is high, although in-field and field-to-field application can vary significantly. Irrigation recommendations for cotton issued by the Central Asian Research Institute of Irrigation (SANIIRI) depend on soil type and range between 500 and 800 mm. Recent studies showed that frequently up to 1,200 mm irrigation water is applied for cotton production (Conrad 2006). Additionally, on average 430 mm of water is applied for pre-season salt leaching on 85% of the irrigated land in Khorezm (Djanibekov 2008). For the whole of Khorezm, between 17,000 and 30,000 m^3 of water per hectare is extracted from the Amu Darya, which is one of the two tributaries to the Aral Sea. For the growing season 2005, Conrad (2006) estimated that the average withdrawal was 2,240 mm. FAO (1997) concluded that around 37% of the diverted river water for irrigation was lost along the way between the source and the irrigated fields.

The excessive diversion of water for irrigation purposes is considered the main reason for the drying up of the Aral Sea, engendering a large-scale ecological catastrophe. Furthermore, the ever-growing demand for water cannot be matched anymore by the supply; Khorezm increasingly experiences years with water availability of <25% of normal (FAO and WFP 2000; Müller 2006). In the course of global warming, the frequency of extreme dry years is estimated to increase and the glaciers feeding the Amu Darya are expected to decrease, underlining also the need for changes in irrigation water management.

Optimal irrigation water management is supposed to address at least three aspects: maintaining favorable soil water content, preventing salinity stress, and saving as much water as possible. Despite the immense amounts of water used in Khorezm, in view of the moderate yields and the pressing problem of soil salinization, optimal management has not been achieved so far.

This paper addresses the combined challenges of the irrigated areas of Central Asia: Water application, crop growth, soil water and groundwater dynamics. These were studied at field level on three fields with different soil textures in the years 2003–2005. Subsequently, the soil water model Hydrus-1D (Šimunek et al. 2005) was applied for in-depth analyses. The objective of the study was threefold: (1) study the significance of major as well as micro-scale differences in soil texture for (micro-basin) water management; (2) simulate current irrigation practices of cotton in Khorezm with the aim to quantify water fluxes and water use efficiencies; (3) simulate and analyze improved management strategies and derive updated irrigation standards.

This publication is complemented by a companion paper focusing on soil salinity management in Khorezm under current and alternative irrigation practices (Forkutsa et al. 2009).

Materials and methods

Location and climate

Experimental data were collected in the Khorezm region located in northwestern Uzbekistan, on the left bank of the Amu Darya River within the transition zone of the Karakum and Kyzylkum deserts. This region is characterized by an arid climate. Hot and dry summers alternate with cold winters. The region receives some precipitation from October to May (~ 100 mm on average; Fig. 1), but neither summer nor winter precipitation plays a significant
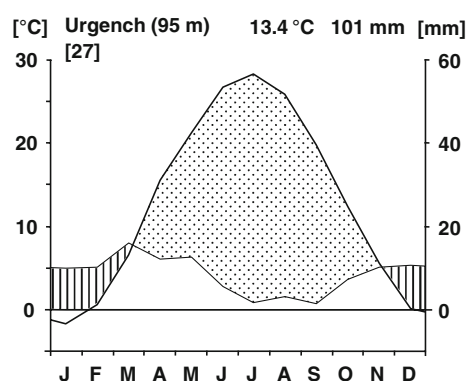
Fig. 1 1980–2006 monthly mean air temperature and monthly precipitation in Khorezm; diagram according to Walter–Lieth notation (Breckle 2002). The parabolic upper line displays air temperature (*left axis*) which is intersected by the lower line representing monthly precipitation (*right axis*)

role in the water balance of the region. In the observation year 2003, with 172 mm, precipitation was almost twice the long-term annual average. In 2005, rainfall (82 mm) was a little lower than usual.

Crop production of mostly cotton, wheat, and rice fully relies on irrigation water that originates from the Amu Darya River. Most of the irrigation network of Khorezm is fed by water stored temporarily in the Tuyamuyun Hydro-engineering Complex, a complex of artificial water reservoirs located upstream of Khorezm.

Experimental data

The study comprised two data sets.

Year 2003 data set

In 2003, a joint farmer-researcher managed experiment was initiated on two cotton fields, one with a sandy loam and the second with a sandy texture. Both fields were located approximately 500 m apart within the research farm of Urgench State University (41°20′39″N, 60°18′60″E) in the Khiva district of Khorezm. The sandy loam field comprised 3.5 ha and the sandy field 3.7 ha. Cotton cultivation was managed by farmers who decided on the amount and timing of irrigation and all other cultivation activities. Farmers considered the sandy field marginal, and not actually suitable for cropping, but were obliged by the

Uzbek state to cultivate cotton to fulfill the "state-order". This implies that the land-user must meet production targets set by the state, while the latter controls the crop distribution on the fields, regulates the supply and prices of water and other inputs, and organizes product processing and, in the case of cotton, the export (Wehrheim and Martius 2008).

After tractor-leveling, the sandy loam field was divided into micro-basins of 30 m × 30 m each in mid-February. Both fields were leached twice in March and once in April. In mid-April, the land was ploughed to a depth of 40 cm, followed by leveling and chiseling. The cotton variety *IF-175* was planted 25 April at a density of 8 pl. m^{-2} (spacing 0.6 m × 0.2 m). Both fields were fertilized with 250 kg N ha^{-1} in the form of ammonium nitrate and 65 kg P ha^{-1} as calcium phosphate. Cotton growth on both fields was studied including details on root growth, maximum rooting depth, cotton height, leaf area development, and yield (Coppi 2004). The water and salt balance of the three micro-basins was studied, according to the west–east transect along the slope on the sandy loam field, which was the main irrigation direction within the field (henceforth called location 1–3; Fig. 2), and on one single micro-basin on the sandy field. The transect was set up to study the significance of micro-level soil textural variability and in-field differences in water management with regard to water use efficiency and secondary soil salinization (Forkutsa et al. 2009).

Fig. 2 Scheme of installations on the sandy loam field; *arrows* in canals denote the flow direction
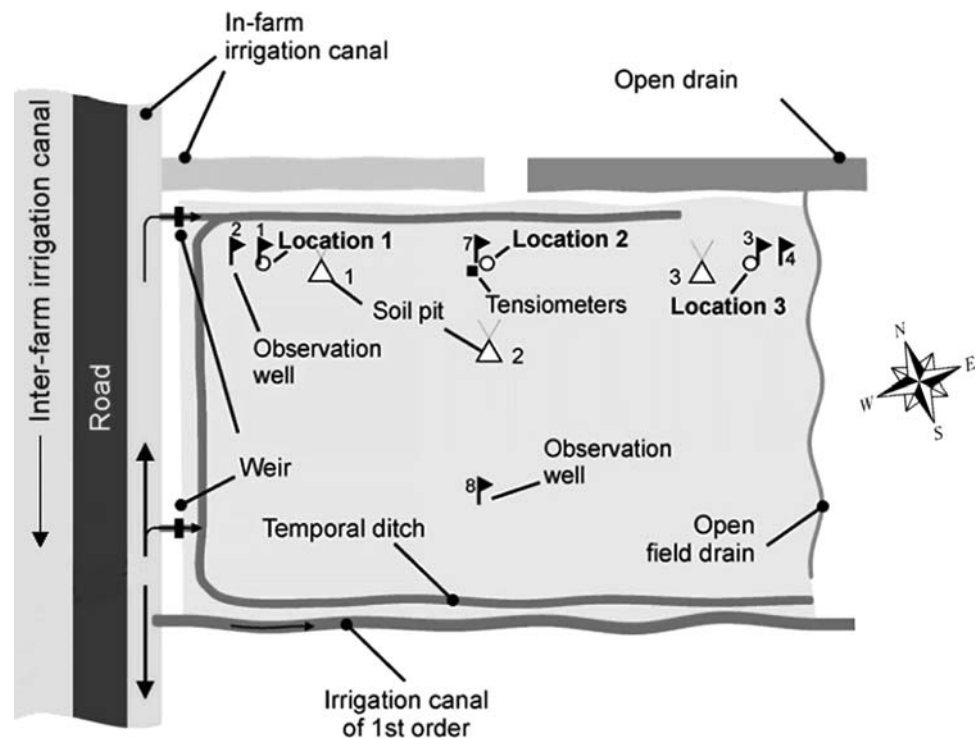
Year 2005 data set

The second data set was generated in 2005 on a completely researcher-managed fertilizer-response trial (factorial block design, four replications) in Urgench district (41°60′25′′ N, 60°51′47′′ E) of Khorezm on a loamy soil. Tillage was similar to that of the sandy and sandy loam fields in 2003. Leaching was carried out once in March and twice in the first half of April. The cotton variety *Khorezm-127* was planted on May 2 on plots of 4.8 m × 10 m (spacing 0.6 m × 0.2 m). The experiment comprised different amounts of N fertilizer as well as various forms and combinations of N-fertilizer and different application dates. The water balance was studied on a plot that had received 160 kg N ha^{-1} as ammonium-nitrate, 175 kg P ha^{-1} as single-super-phosphate, and 125 kg K ha^{-1} as KCl. Cotton growth and N-response were studied in detail by Kienzler (2009).

Water application

Leaching and irrigation water amounts were measured with Cipoletti (or trapezoidal) weirs that were installed before each irrigation event. The side slopes of this weir had a vertical to horizontal ratio of 4:1. The discharge, Q (m^3 s^{-1}), over a Cipoletti weir can be formulated as a function of the weir length, b (m), and the upstream water depth referenced to the weir crest (H; m), whereas H is called "head":

$$Q = 1.86 \times b \times H\sqrt{H}. \tag{1}$$

The accuracy of this type of measurements is about ±5% (Bos 1989; USBR 1997). Head measurements were conducted every minute during the entire irrigation events.

Unfortunately, water amounts applied for leaching on the sandy field could not be measured, as leaching was started by the farmers without notice, and leaching was accompanied with unintended runoff directly into the drain at various parts of the field. Leaching amounts on the loamy field were roughly estimated, based on expert's visual estimation of the level of water in the field and the total duration of water application.

Soil water content and pressure head

On the sandy loam and the sandy field soil water content was determined gravimetrically. To that end, soil samples were taken with a soil auger at 20, 50, 80, and 105 cm depths each time at two (sandy field) or four (sandy loam field) locations. Soil samples were taken 1 day before and 2 days after irrigation and additionally between two irrigation events every fifth day.

Additionally, soil water pressure head was measured with manual tensiometers (Eijkelkamp) on the sandy loam field. Two pairs of tensiometers were installed vertically at 30 and 50 cm soil depth, and 50 cm apart from each other in the center of the field. Readings were taken manually on selected days or more frequently around irrigation events.

In 2005, in the experiment on the loamy field, soil water dynamics was monitored with automatic devices. Soil water content was measured in hourly intervals with factory-calibrated capacitance probes (theta probe, Delta-T Devices, UK). Hanson and Peters (2000) determined the average absolute differences between factory-calibrated theta probe readings and soil moisture contents (manual sampling) for a loamy soil to be 2.5 vol.%. Soil salinity, which could further influence readings, was lower than 2.5 dS m^{-1} during most of the growing season (see Forkutsa et al. 2009), and thus did not influence water content readings. Theta probes were installed at 20, 40, 60, 80, and 100 cm depth. Soil water pressure head was measured in 15-min intervals with pF-meters (Geo-Precision, Germany). These probes determine soil water pressure head as a function of the heat capacitance of the amount of water inside the porous, ceramic head of the probe. A calibration polynomial converts this information into pressure head values. The advantage of the pF-meters is that they cover the whole range of soil water pressure head, from saturation to beyond permanent wilting point (for details see http://www.geo-precision.com/Products/Soil_Sensor__pF-Meter/soil_sensor__pf-meter.html). However, the pF-meters have found wider scientific use only recently. They have not been tested in saline soils and under hot summer climatic conditions as prevail in the study region. Four sensors were installed at the end of May 2005 at 20, 40, 60, and 80 cm soil depth.

Groundwater

The depth of the groundwater table was monitored with six observation wells installed in the sandy loam field, four in the sandy field and ten in the loamy field. The observation wells consisted of 2.5 m long plastic pipes with a diameter of 4 cm. The pipes were closed at the bottom with a metal lid and perforated on one side starting 50 cm above the lower end and wrapped in gauze to protect the perforations from soiling. On the sandy and sandy loam site, the groundwater table depth was measured concurrently with soil-moisture sampling using a hand-operated sounding apparatus (Eijkelkamp). On the loamy site groundwater depth was measured in biweekly intervals.

Soil physical properties

To describe the soil genetic layers and assess soil physical properties, at the onset of the experiment, three 1.5 m deep soil pits were dug in the sandy loam field, representing both ends and the middle of the field, one pit in the sandy field, and three pits in the loamy field. Two replicates of undisturbed soil cores were taken from each genetic horizon. Soil bulk density was determined according to Blake and Hartge (1986) and soil texture by sedimentation (Loveland and Whalley 2001).

The vertical distribution of soil texture of the loamy field was quite homogenous (Table 1). Soil bulk density was slightly elevated at 30–45 cm, which might be attributed to some compaction from continuous plowing in the past. A sandy loam topsoil layer overlaid almost pure sand at the sandy field. For the purpose of modeling, genetic layers were aggregated as far as possible, whereas notable differences in texture and bulk density were used as distinguishing criteria.

Meteorological data

In September 2002, an automatic meteorological station (Micromec Multisens-Technetics 2000) was set up about 3 km away from the sandy loam and sandy sites. Half-hourly data of air temperature, relative humidity (Eijkelkamp sensors), incoming short-wave radiation (0.4–1.1 μm; SP-light Pyranometer, Kipp&Zonen), wind speed and direction at 2 m above ground, and precipitation were recorded. A similar data set was generated next to the loamy field in 2005 using an automatic weather station (WatchDog 900ET).

Hydrus-1D

Hydrus-1D (Šimunek et al. 2005) is a software that simulates water and solute transport in the soil. It has been successfully applied in numerous studies (for a review on the history of Hydrus, see Šimunek et al. 2008). Hydrus-1D draws on the Richards equation for simulating soil water

Table 1 Generic layers, soil texture, soil bulk density (BD), and optimized Van Genuchten soil hydraulic parameters

Layer no.	Depth (cm)	Text. class	Sand (%)	Silt	Clay	BD (g cm^{-3})	θ_r (cm cm^{-1})	θ_s	α (cm^{-1})	n (−)	K_s (cm d^{-1})	l (−)	θ_m (cm cm^{-1})
Loam													
1	0–30	Loam	47	37	16	1.45	0.120	0.400	0.022	1.40	17	−0.42	0.4010
2	30–45	Loam	43	43	14	1.64	0.050	0.380	0.026	1.40	15	−0.77	0.3815
3	45–200	Loam	47	36	17	1.58	0.050	0.410	0.020	1.45	15	−0.79	0.4110
Sandy loam, location 1													
1	0–10	Sandy loam	68	24	8	1.32	0.040	0.419	0.109	1.29	45	−0.83	0.4303
2	10–60	Sandy loam	72	20	9	1.49	0.040	0.420	0.054	1.49	40	−0.79	0.4245
3	60–200	Sandy loam	76	19	6	1.72	0.036	0.410	0.051	1.46	35	−1.14	0.4142
Sandy loam location 2													
1	0–11	Sandy loam	74	14	12	1.44	0.049	0.408	0.033	1.52	120	−0.29	0.4100
2	11–26	Sandy loam	69	22	9	1.57	0.040	0.408	0.139	1.27	79	−0.99	0.4224
3	26–85	Sandy loam	72	23	5	1.63	0.036	0.370	0.130	1.23	97	−1.45	0.3825
4	85–200	Loam	41	45	14	1.60	0.042	0.342	0.060	1.45	62	−0.56	0.3459
Sandy loam location 3													
1	0–15	Sandy loam	73	15	12	1.27	0.052	0.453	0.060	1.70	89	−0.77	0.4574
2	15–75	Sandy loam	66	23	11	1.58	0.045	0.410	0.045	1.58	39	−1.25	0.4129
3	75–120	Sandy loam	59	33	8	1.68	0.033	0.380	0.054	1.43	12	−0.66	0.3843
4	120–200	Loam	40	44	16	1.59	0.040	0.343	0.034	1.35	19	−0.40	0.3451
Sand													
1	0–10	Loamy-sand	86	6	8	1.34	0.049	0.441	0.021	3.33	419	0.60	0.4410
2	10–30	Sand	95	4	1	1.62	0.060	0.387	0.025	2.46	355	0.42	0.3871
3	30–60	Sand	90	9	1	1.61	0.043	0.391	0.016	2.00	282	0.50	0.3913
4	60–200	Sand	99	1	0	1.55	0.043	0.391	0.016	2.70	851	0.50	0.3911

θ_r residual water content, θ_s saturated water content, α and n parameters describing the shape of the soil–water-retention and hydraulic conductivity curve, K_s saturated hydraulic conductivity, l pore-connectivity parameter, θ_m fictions term determining the air-entry point (air-entry for all layers = −2 hPa)

dynamics. To parameterize the Richards equation, Hydrus-1D uses, among others, the modified Mualem-van-Genuchten model (Vogel and Císlerová 1988) to describe soil water retention and soil hydraulic conductivity. Vogel and Císlerová (1988) modified the original Van Genuchten model (Van Genuchten 1980) to allow for non-zero capillary height, i.e., an air-entry value (h_e) up to which saturation is maintained.

For the influence of soil water and solute stress on transpiration (root water uptake), Hydrus requires potential evaporation (top boundary) and transpiration (sink term in the Richards equation) as separate inputs in time steps which can be either per day, hour, or minute. We used daily time steps. The top boundary conditions are additionally defined by irrigation and precipitation. Here in correspondence with field conditions, "ponding", i.e., water building up on the soil surface, was allowed to take place. The bottom boundary conditions were governed by shallow groundwater, and thus measured groundwater table depths were used to describe the bottom boundary of the soil profile. Groundwater depths were linearly interpolated to obtain daily model inputs.

Root growth was also simulated, for which repeated measurements of maximum rooting depth served as inputs.

For the determination of the root water uptake the method proposed by Feddes et al. (1978) and modified by Van Genuchten (1987) to include multiplicative water and osmotic stress was applied. The inherent water stress reduction term was parameterized with the function proposed by Feddes et al. (1978) using the following values for h_1–h_4: $h_1 = -10$ hPa, $h_2 = 25$ hPa, $h_{3high} = -200$ hPa, $h_{3low} = -6{,}000$ hPa, and $h_4 = 14{,}000$ hPa, as suggested by Taylor and Ashcroft (1972).

Inverse modeling of soil hydraulic properties

The Rosetta software (Schaap et al. 2001) was applied to predict the van Genuchten (1980) water retention parameters θ_r, α and n, and the saturated hydraulic conductivity (K_s) from soil texture and bulk density. The resulting hydraulic properties were calibrated to site-specific conditions by inverse estimation. Therefore, observed data on soil moisture and pressure head and in the case of the sandy and sandy loam field, soil salinity at 20 cm soil depth (see parallel publication for details) were used. Differences between observed and simulated data were minimized by the Levenberg–Marquardt nonlinear minimization method. The Van Genuchten parameters were optimized sequentially layer by layer from the top to the bottom and parameter by parameter in the order θ_r, , n, K_s, l. The whole procedure was repeated until no further reduction in the sum of squares of the residual was obtained. θ_s, as a rather easy-to-measure parameter, was not included into the

inverse estimation but set to observed values. Including the soil salinity data from 20 cm soil depth into the inverse estimation allowed for a more robust estimation of the Van Genuchten soil hydraulic parameters of the top soil layer, because salinization of the top soil is a direct consequence of the ability of the soil to enable capillary rise of water and soil evaporation.

FAO-56 evapotranspiration

Crop evapotranspiration, ET_c, was estimated with the dual approach version of the FAO-56 Penman–Monteith equation (Allen et al. 1998) using recorded meteorological data. ET_c is derived from the reference evapotranspiration (ET_0) using basal crop (K_{cb}) and soil evaporation (K_e) coefficients:

$$ET_c = (K_{cb} + K_e) \times ET_0. \tag{2}$$

Since crop growth on the sandy and sandy loam field was below optimum (Coppi 2004), leaf area index (LAI) data were used to adjust the crop coefficient. More details on this approach as well as on the definition of K_e are given by Allen et al. (1998).

Management strategy analyses

Four different strategies were simulated:

(1) rescheduling irrigation;
(2) reduced soil evaporation in response to a surface crop residue (mulch) layer;
(3) the effects of the introduction of an improved groundwater drainage system; and
(4) a combination of the three previous analyses, with the aim to layout irrigation requirements for an improved productions system that builds on improved drainage and a surface residue layer.

One of the premises for analysis 1 was that the total amount of irrigation water should not be increased. In analysis 2, for the sake of simplicity, we assumed that a mulch layer could reduce potential soil evaporation by 50%. In analysis 3, we assumed that the drainage system could be improved in such a way that the groundwater could be lowered to below 2 m soil depth. Therefore, based on observations of long-term regional groundwater dynamics (Ibrakhimov 2004), a new seasonal course of the groundwater level was constructed. In the integrative management strategy analysis 4, amount and timing of leaching and irrigation was altered to prevent any major stress due to crop-water and -salinity (see parallel publication, Forkutsa et al. 2009). Water stress was measured by the relative transpiration rate (T_a/T_p). Irrigation amount and timing was adjusted so that T_a/T_p did not fall below ~0.8

from May until the end of August. Additionally, for the sandy field it was assumed that cotton could potentially grow as vigorously as observed at location 1 on the sandy loam soil. Consequently T_p and maximum rooting depth for the sandy field was adjusted to equal observations of this location.

Statistical evaluations

The goodness of the simulation results was assessed by the root mean square error (RMSE) between observations and simulation results, which is

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (\text{observed}_i - \text{simulated}_i)^2}{n}}. \quad (3)$$

Results

Cotton growth and yield

Cotton development on the sandy loam and sandy fields in 2003 was heterogeneous. Some spots in the fields showed a high abundance of weeds. For the sake of simplicity, and because of lacking information, in the simulation, weeds were treated like cotton with regard to water uptake characteristics. Also LAI of weeds and cotton was merged in the simulations. Maximum LAI values used for the sandy loam field were 1.62, 1.24 and 0.88 $m^2\ m^{-2}$ for location 1, 2, and 3, respectively, and that of the sandy field was 0.27 $m^2\ m^{-2}$.

Raw-cotton yield, i.e., cotton lint and seeds of in total three to four cotton picks, on the sandy loam and sandy field, was on average 1.7 and 0.08 Mg ha^{-1}, respectively. Corresponding aboveground biomass and harvest index were 4.6 and 0.32 Mg ha^{-1}, and 0.37 and 0.25 on the two fields, respectively.

Raw cotton yield in 2005 on the loamy field on average was 4.46 Mg ha^{-1}, which is close to the yield potential of *Khorezm-127* (Sommer et al. 2008). Total aboveground biomass at first pick was 10.8 Mg ha^{-1} and the overall harvest index 0.41. LAI peaked at 2.74 $m^2\ m^{-2}$ on 6 August.

Groundwater

Groundwater depth varied considerably over time and also spatially (Fig. 3).

In some cases groundwater table increased in response to irrigation, but usually groundwater already increased one to several days before the irrigation event, in response to the filling of inter- and inner-farm irrigation canals, which caused immediate large-scale recharge by seepage of water from these unlined canals.
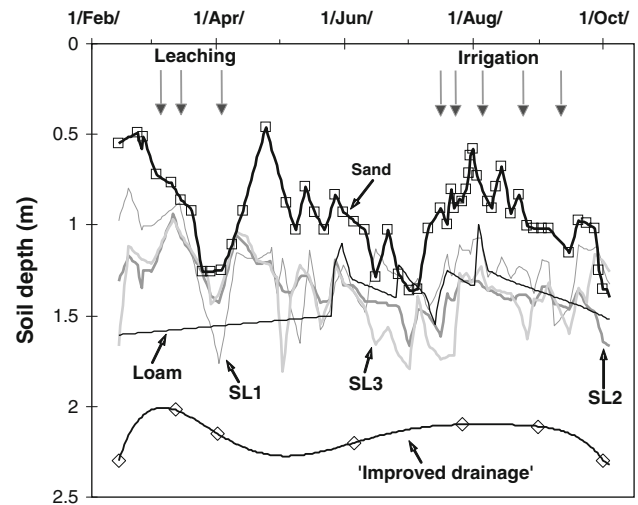
Fig. 3 Groundwater dynamics for the sandy, sandy loam (SL, three different locations), and loamy fields as well as for the 'improved drainage' scenario; *squares* indicate times of observation of groundwater at the sandy field, intermittent periods linearly interpolated; for the sandy loam field leaching and irrigation dates are denoted by arrows at the top; diamonds (improved drainage curve) indicate points that were used to draw this curve using polynomial regression analysis

Groundwater of the sandy field most times was above 1 m depth and sometimes passed 0.6 m.

Leaching and irrigation

On the sandy loam field, a total of 258–300 mm water was applied for leaching (Table 2). Location 1, 2, and 3 were leached in parallel and thus obtained equal amounts of water, with the exception of the third leaching event where location 3 received about 40 mm less than the other two locations. We estimated that the loamy field received 210 mm of leaching water in total.

The sandy loam field was irrigated five times. Altogether between 268 and 407 mm was irrigated with less water applied to the micro-basins at the east end of the field including location 3. Due to shallow groundwater in the sandy field it was not irrigated at all.

The loamy field was irrigated six times, with single irrigations sometimes extending over 2 days. In total only 295 mm was applied, which is well below the amount of 640 mm given as norm for these types of soil (and environment) by the Uzbek Hydro-Mod scheme (SOYUSNIHI 1992).

Inverse calibration (model optimization)

Results of the inverse Van Genuchten parameter estimation followed common trends, with comparably higher values for n and K_s for the coarse textured, sandy soil (Table 1).

Table 2 Amount and date of application of water for pre-season leaching and irrigation on the loamy field (in 2005) and, for three micro-basins in the sandy loam field (in 2003)

Loam		Sandy loam			
Date	Amount (mm)	Date	Location 1 Amount (mm)	Location 2	Location 3
Leaching					
15/April	70[a]	4–5/March	120	120	120
2/April	70[a]	14–15/March	78	78	78
12/April	70[a]	3/April	102	102	60
Sum	210		300	300	258
Irrigation					
26–27/May	59	16–17/July	66	73	77
25–26/June	59	23/July	68	118	49
12/July	37	05/Aug	97	90	64
16/July	40	23–25/Aug	130	64	45
28–29/July	49	9–13/Sept	46	42	33
15–16/Aug	52				
Sum	295		407	387	268

[a] Estimated

Observed soil water pressure heads of 60 and 80 cm of the loamy field were excluded from the inverse optimization after preliminary test runs. In comparison to the corresponding soil moisture data, pressure heads at those depths were unreasonably and systematically low, pointing towards technical problems (most likely poor calibration) of the pF-meter devices that were used for these measurements.

With the final sets of soil hydraulic parameters observed, soil moisture and pressure head dynamics could be well predicted, as is exemplarily shown for the sandy loam field at location 2 and the sandy field (Fig. 4) as well as for 20 cm depth for the loamy field (Fig. 5).

Some of the rapid fluctuations of groundwater at the sandy loam field, visible indirectly through the fast increase and subsequent decline in soil moisture (e.g., in August and September), were not captured in the simulations. This would have required a parameterization of the lower boundary with high-resolution data obtained by continuous, automated monitoring of groundwater depth. Some of the differences between observed and simulated soil moisture at 105 cm at the sandy field have to be attributed to uncertainties in the gravimetric soil moisture determination of, in most cases, completely saturated soil samples with in that case 99% sand content.

Some deviation between observed and simulated pressured head of the loamy field could not be avoided. The pF-meter at 20 cm recorded desiccation at the end of June and July and beginning of October, reaching minimum pressure heads of around −2,000 hPa. These were also the periods when soil moisture at 20 cm depth dropped to its seasonal minimum, but these data were only moderately corresponding with pressure heads parameterized by the inverse modeling procedure (Table 1), not surpassing −500 hPa

(compare simulated line in lower (Fig. 5). Deviating patterns of observed soil moisture and pressure head might be related to small-scale heterogeneity in response to an inhomogeneous application of irrigation water; a common issue under furrow-irrigated conditions.

The RMSE between observed and simulated pressured heads on the loamy field at the soil depth of 20 cm with 494 hPa was high (Table 3). The RMSE between observed and simulated pressure heads at location 2 of the sandy loam field disclosed a closer match of observed and simulated pressure head (data not shown), though also here the fit was not overwhelmingly high. The RMSE between observed and simulated soil moisture ranged between 0.012 and 0.053 cm cm^{-1}, with slightly higher RMSEs for the 105-cm layer but generally no noteworthy trend with depth or over the range of considered textures.

Soil water dynamics, crop water balance, and irrigation efficiency

The impact of irrigation during the five to six events on topsoil water contents was clearly notable on the sandy loam and the loamy fields (Figs. 4, 5). The three leaching events of the sandy loam-field were discernible only via simulation, whereas the observed picture was blurred, due to the lower temporal resolution of measurements. Unusually high rainfall during 8–14 May 2003, 53 mm in total, temporarily increased soil moisture at 20 cm depth. Groundwater notably influenced soil moisture dynamics at 80 and 105 cm depth in the sandy loam field.

Water dynamics was different in the sandy field: temporary peaks even in topsoil moisture content were exclusively driven by groundwater fluctuations. Soil moisture at 20 cm never dropped below 0.11 cm cm^{-1},
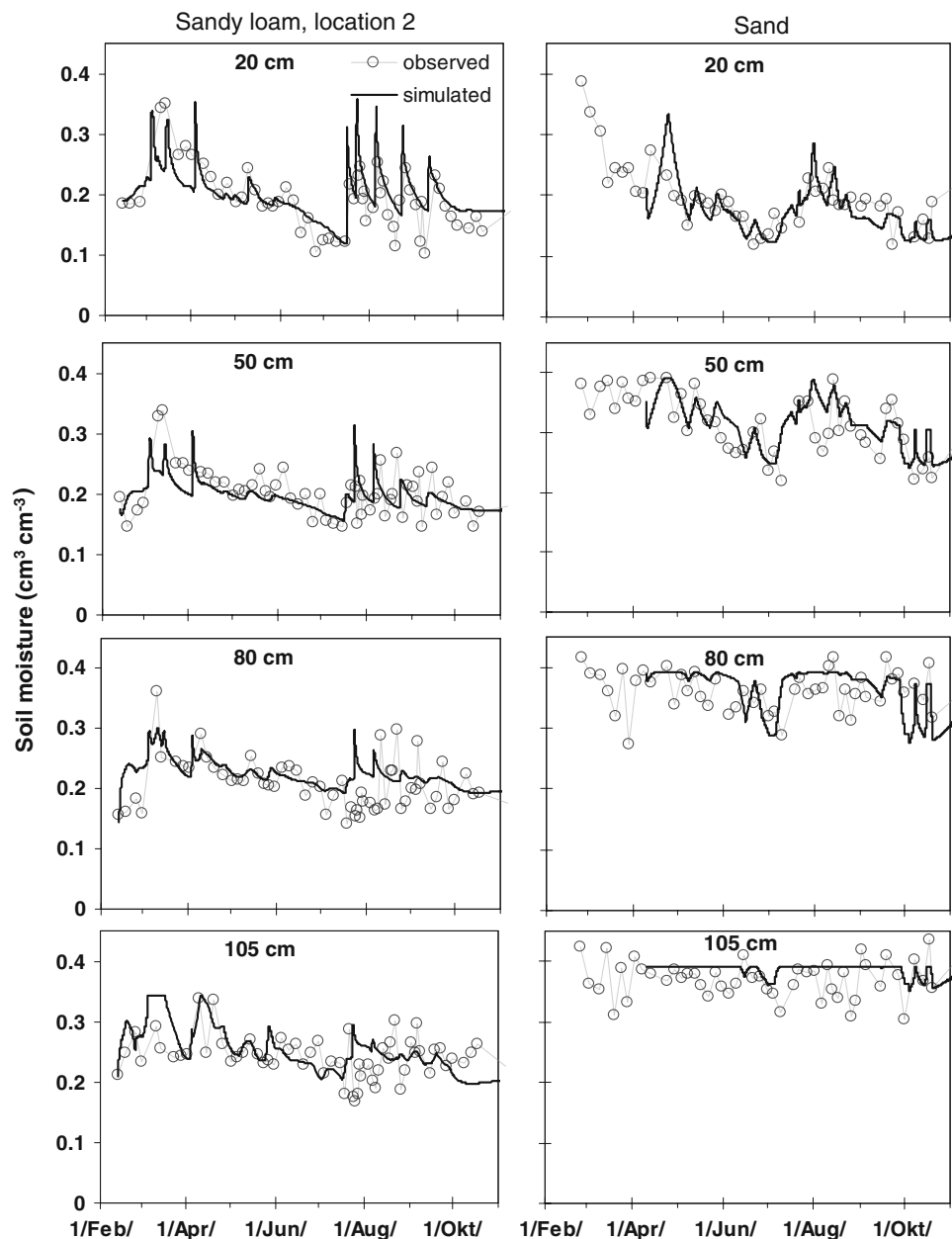
which is equal to a soil water potential of approximately -200 hPa, but rather hovered around 0.19 cm cm^{-1} (~ -100 hPa) despite the fact that the sandy field was not irrigated at all. Thus a strong upward movement of groundwater must have taken place.

Simulation results allowed establishing a detailed water balance for the loamy and sandy fields as well as for the three locations on the sandy loam field (Table 4). The field preparation period from 15 February to 19 April, i.e., 1 week after the last leaching and a few days before cotton planting, which included water application for salt leaching, was distinguished from the cotton cropping season.

As intended, leaching caused a strong downward movement of water across the boundary of 80 cm depth, i.e., below maximum rooting depths of cotton, as is indicated by the negative values for groundwater contribution. Due to their lighter texture but also simply because more water was applied, downward movement of water in response to leaching of the three locations of the sandy loam field was higher than that of the loamy field.

During the cotton growing period between 86 and 493 mm of rainfall and/or irrigation water infiltrated into the soils of the three fields. Actual transpiration on the sandy loam field was highest at location 1 and lowest at
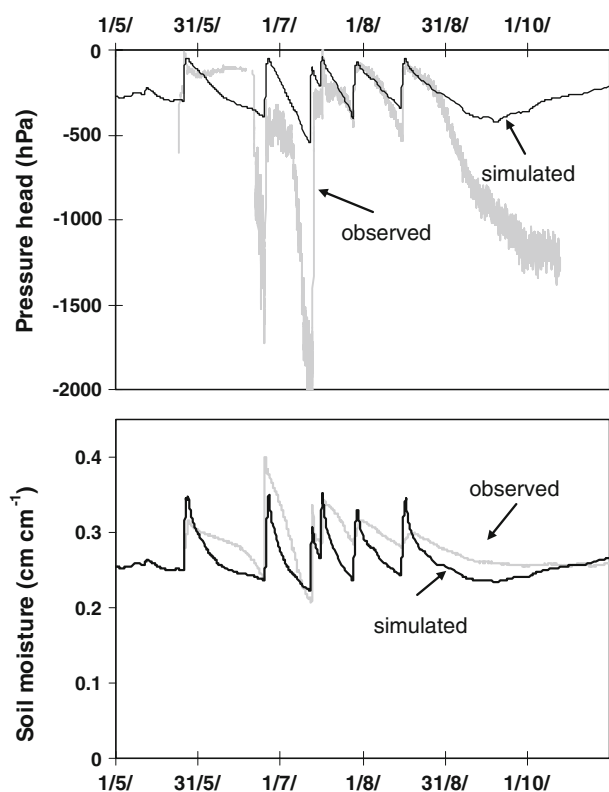
Fig. 5 Observed (*gray line*) and simulated (*black lines*) soil moisture and pressure head at 20 cm depth of the loamy field from May until October 2005

location 3 following the decreasing levels of total irrigation. Cotton growth was poor on the (marginal) sandy field and thus actual transpiration was low on this field. The opposite was the case for the researcher-managed loamy field, where actual transpiration reached 479 mm.

The picture was more complex regarding cumulative actual evaporation. The finer-textured loamy soil facilitated upward movement of water and soil evaporation (248 mm),

especially as irrigation amounts were comparably low. Given its course soil texture, the sandy soil had the lowest potential for upward movement of water. However, contrary to theory, simulations revealed that this soil in fact had the highest cumulative soil evaporation (347 mm), due to the very shallow groundwater and because no irrigation water was applied. Consequently, the groundwater contribution to ET_a, with 399 mm, was highest on the sandy field followed by 382 mm for the loamy field. It decreased with increasing amounts of irrigation on the sandy loam field from 106 mm in the east of the field (location 3) to 79–86 mm in the west (location 1 and 2). ET_a over the cotton growing season added up to between 488 and 727 mm.

Disaggregating seasonal water fluxes with regard to irrigation timing and amounts revealed some insights into irrigation efficiencies. None of the six irrigation events on the loamy field caused a subsequent downward movement of water beyond 80 cm depth. From an irrigation-engineering point of view, application efficiency was 100% throughout. This was not the case for the sandy loam field, where depending on the location and the amounts of irrigation water applied on micro-basin level, two (location 2 and 3) or four (location 1) out of five irrigation events caused at notable downward movement of water beyond 80 cm and an intermittent decrease in cumulative water flux at 80 cm (Fig. 6).

Simulations showed that transpiration of cotton plants on the sandy loam field must have been hampered by water stress from June onwards, increasing in severity until the first irrigation event July 16. Relative transpiration rate (T_a/T_p) dropped to around (locations 1 and 2) or even below (location 3) 0.6 at all three locations during this period (Fig. 7).

Water stress (re-) appeared later in the season at location 1 and 2 of this field, but not at location 3. Plant establishment was poor and growth was less vigorous in this part of the field

Table 3 Root mean square error between observed and simulated soil moisture (θ; cm cm^{-1}) and soil water pressure head (h; hPa)

Soil depth (cm)	Loam		Sandy loam				Sand
	θ (cm cm^{-1})	h (hPa)	Loc. 1	Loc. 2		Loc. 3 θ (cm cm^{-1})	θ (cm cm^{-1})
			θ (cm cm^{-1})	θ (cm cm^{-1})	h (hPa)		
20	0.028	494	0.022	0.033	276	0.029	0.042
40[a]/50	0.038	383	0.025	0.037	190	0.031	0.039
60	0.022	137	n.d.	n.d.	n.d.	n.d.	n.d.
80	0.023	101	0.029	0.046	n.d.	0.025	0.040
105	0.012	n.d.	0.045	0.042	n.d.	0.053	0.031
N	4,200	8,814	58	59	59	59	40

N of underlying data sets in the last row, based on hourly (θ), quarter-hourly (h) measuring intervals for the loam, and intervals of one to several days for the sandy loam and sand; *n.d.* not determined

[a] Loam only

Table 4 Water balance of the loamy, sandy loam and sandy field for the field preparation (leaching) period, and the cotton cropping season; infiltration is the sum of precipitation, leaching, and irrigation

Field/period	Infiltration	T_p	T_a	E_p	E_a	ET_a	Store change, 0–80 cm	Groundwater contribution
	(mm)							
Loam								
15/Feb–19/April	235	0	0	94	94	94	2	−139
20/Apr–4/October	322	489	479	342	248	727	−24	382
Sandy loam, location 1								
15/Feb–19/April	341	0	0	119	109	109	−7	−238
20/Apr–4/October	493	442	398	348	190	588	−10	86
Sandy loam, location 2								
15/Feb–19/April	341	0	0	119	119	119	4	−217
20/Apr–4/October	473	394	352	348	222	574	−22	79
Sandy loam, location 3								
15/Feb–19/April	299	0	0	119	117	117	21	−161
20/Apr–4/October	354	334	291	343	197	488	−28	106
Sand								
15/Feb–19/April	n.d.	0	0	n.d.	n.d.		n.d.	n.d.
20/Apr–4/October	86	182	181	368	347	528	−43[a]	399

T_a, T_p actual or potential transpiration, E_a, E_p actual or potential soil evaporation; negative numbers denote a reduction or a downward movement of water; *n.d.* not determined; groundwater contribution = $T_a + E_a −$ infiltration + store-change
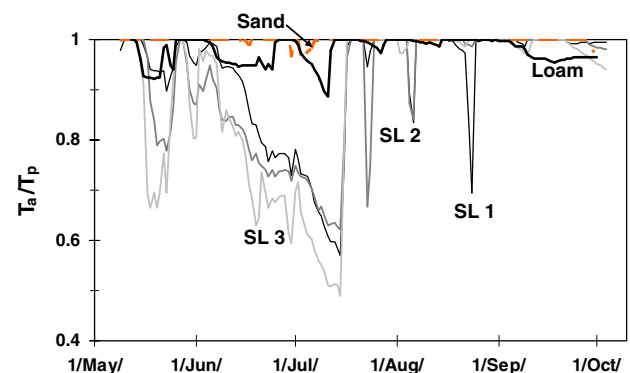
[a] 0–30 cm
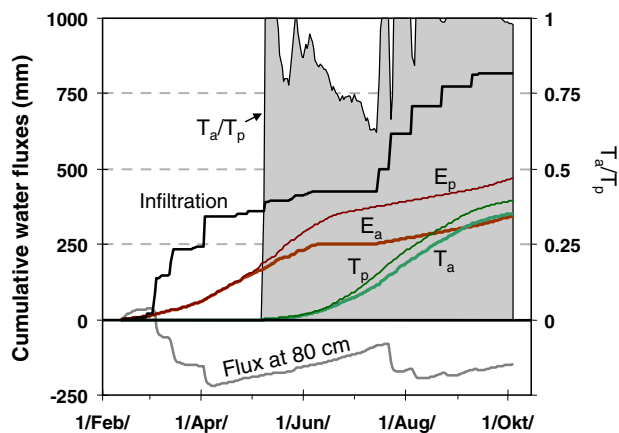
Fig. 6 Cumulative water fluxes (mm; *left axis*) and relative transpiration rate (T_a/T_p, *gray-shaded area*; right axis) for location 2 of the sandy loam field; a decreasing cumulative flux at 80 cm depth denotes a downward movement of water in response to leaching or irrigation

Fig. 7 Relative transpiration rate (T_a/T_p) of the three locations of the sandy loam (*SL*) field, and the loamy and sandy field during the cotton growing season

with lower leaf area index and consequently lower potential transpiration as parameterized via the K_{cb} coefficient.

Relative transpiration rate was either not or only slightly below 1 on the sandy and loamy field. On the sandy soil, this was due to poor plant establishment, low *LAI* and K_{cb}, lowering T_p to an amount that could be sustained by mere upward movement of water. On the loamy field, plant growth was close-to optimal, as was soil water supply.

Management strategy analyses

Rescheduling irrigation

The observations in combination with modeling showed that the third leaching event (102 or 60 mm) was actually unnecessary which is explained in more detail in our parallel publication (Forkutsa et al. 2009). The obvious solution was to postpone this water application, i.e., rather use it for irrigation. Simulating an application of half of this amount on June 14 and the second half on July 2 increased the relative transpiration rate during the period

end-June to beginning of July over that of the original scheme. The effect was comparably limited at location 3, where only 60 mm of water had been applied for the third leaching (and thus could be re-distributed). While water stress from late June to beginning of July could be alleviated, the opposite was the case for May to early June, where water stress increased at location 3. Total transpiration of cotton at locations 1–3 of the sandy loam field under rescheduled irrigation increased from previously 398, 352, and 291 mm (see Table 4) to 430, 378, and 311 mm, respectively.

Introducing a surface residue layer (reducing potential E)

The effect of a permanent residue surface layer that would reduce potential soil evaporation by 50% on total actual soil evaporation during the cotton cropping season was considerable. E_a of the loamy and sandy loam soil in comparison to the corresponding evaporation of a surface residue-free soil (Table 4) was reduced by 26–34% (Table 5). Evaporation of the sandy soil was even reduced by 48%.

Crop water uptake (transpiration) could, however, not particularly benefit from water which was saved from evaporation, and the percentage increase of T_a was negligibly low (Table 5). This was because part of this water remained unavailable to the plants (held at a pressure head below permanent wilting point). It was rather the contribution from groundwater to actual evapotranspiration that diminished, as pressure head gradient in the topsoil dropped. This reduction in upward movement of soil water had considerable beneficial effect on soil salinity (Forkutsa et al. 2009).

Table 5 Simulating the influence of a surface residue cover on actual transpiration and evaporation of the loamy, sandy loam, and sandy field during the cotton cropping season (20 Apr–4 Oct)

Field	T_a	E_a	Store change, 0–80 cm	Ground-water contribution	Change in[a]	
	(mm)				T_a (%)	E_a
Loam	484	165	−31	296	1	−34
Sandy loam,						
location 1	401	140	−12	37	1	−26
location 2	356	152	−26	8	1	−32
location 3	299	143	−33	54	3	−28
Sand	181	180	−44	230	0	−48

T_a actual transpiration, E_a actual soil evaporation

Negative numbers denote a reduction or a downward movement of water; groundwater contribution = T_a − infiltration + store-change; data for infiltration, see Table 4

[a] As compared to surface residue-free conditions in Table 4

Table 6 Influence of an improved drainage on actual transpiration and evaporation of the loamy, sandy loam, and sandy fields during cotton cropping season (20/Apr–4/Oct)

Field	T_a	E_a	Store change, 0–80 cm	Groundwater contribution	Change in[a]	
	(mm)				T_a (%)	E_a
Loam	357	171	−58	148	−26	−31
Sandy loam,						
location 1	326	164	−28	−30	−18	−14
location 2	293	178	−19	−20	−17	−20
location 3	248	155	−41	7	−15	−22
Sand	62	48	0	23	−66	−86

T_a actual transpiration, E_a actual soil evaporation

Negative numbers denote a reduction or a downward movement of water; groundwater contribution = $T_a + E_a$ − infiltration + store-change; data for infiltration, see Table 4

[a] As compared to groundwater-influenced conditions in Table 4

### Improved groundwater drainage system

Implementing an improved drainage system in the management strategy analysis was realized by lowering the groundwater table to at least 2 m depth. The assumed seasonal course is displayed in Fig. 3. Under the current irrigation management an improved drainage of the groundwater would drastically impact the soil water balance and crop growth. Simulation results showed that, depending on the previous reliance of crop growth on water from groundwater, actual transpiration was in part significantly reduced (Table 6).

Improved productions system

Simulations of an optimized leaching and irrigation management scheme indicated that 200–230 mm of water, split over two events, would be sufficient for a proper leaching of salts out of the sandy and sandy loam soil profile, if the drainage system functioned properly and the groundwater table was lowered.

For optimal growth on the sandy, sandy loam and loamy fields, cotton required around 690, 580, and 650 mm of irrigation water, respectively. As expected, distribution and single amounts differed markedly between fields. The loamy and sandy loam fields required eight irrigation events starting mid May every 12–19 days, with each time between 60 mm (May) and 100 mm (August) water applied. On the sandy soil cotton would have to be irrigated much more frequently, according to our simulations at least 24 times every 4–8 days starting with the planting of cotton. Simulations showed that only between 25 and 30 mm should ideally be irrigated every single event. Higher single
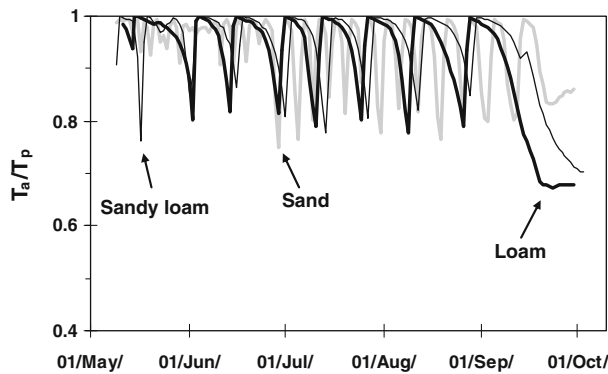
Fig. 8 Relative transpiration rate (T_a/T_p) of cotton grown under improved drainage conditions on a sandy, sandy loam and loamy soil with a surface residue layer under optimal (furrow) irrigation management

amounts would almost exclusively contribute to an increased drainage of water from a sandy soil with high hydraulic conductivity and low water holding capacity.

Under conditions as outlined above, the relative transpiration rate of cotton would never fall below ~ 0.8 from May until the end of August on any of the three fields (Fig. 8).

Discussion

Monitoring irrigated cropping of cotton in Khorezm, Uzbekistan, disclosed some peculiarities: farmer-managed cotton cropping on the sandy field in 2003 fully relied on the contribution from groundwater, yet with quite a limited production of raw-cotton (0.08 Mg ha^{-1}). Similarly, only 295 mm of water was irrigated at the researcher-managed loamy field in 2005. Reasons for applying irrigation water amounts below Uzbek irrigation recommendations are twofold: First of all, farmers considered the sandy field as a marginal site and consequently little attention was paid to optimal plant performance and yield. Second, irrigation timing by farmers in Khorezm is presently to a major extent based on the availability of irrigation water, as well as on their visual perception of the soil water status in situ (or indirectly by plant water status). Given that irrigation scheduling based on this perception did not produce any significant plant–water stress in 2005 underlines the robustness of such management.

The results of the simulations and those of Kurambaev (1969), confirmed that cotton may grow in the desert climate of Khorezm without any irrigation, under the premise that the groundwater level can be kept at 1 m and the water is only slightly saline. The calculated groundwater contribution (382 mm) to ET$_a$ (727 mm) of cotton on the loamy field is in the range of reported values. Rakhimbaev, e.g.,

(cited in Felitsiant 1964) observed that cotton could take up as much as 45.5% of the total water consumption from the groundwater providing an average depth of 1 m below the surface. Atashev et al. (1966) concluded that in Khorezm, cotton acquired 25–49% of total consumed water from the shallow groundwater under the irrigation schemes of that time. Based on findings of lysimeters studies in sandy loam soils, cotton received 57% of the transpired water from groundwater at 0.9 m depth (Hoffman and Hall 1996).

Actual evapotranspiration from April to October (488–727 mm) was well within the range of values reported by Ibragimov et al. (2007) for cotton grown in northeastern Uzbekistan (432–739 mm). Our maximum value was also only slightly lower than the ET$_a$ of fully irrigated cotton (775 mm) grown in Texas, USA, reported by Howell et al. (2004).

There is continuous debate whether the contribution of groundwater to crop water use, in particular as an unmanaged sub-surface irrigation, is a viable strategy for crop production in Khorezm and other irrigated regions in Central Asia. From the perspective merely of the field *water* balance, this appears the case. In this regard, shallow groundwater tables can be considered a safety-net against unreliable delivery of irrigation water to individual farms and fields, which is unfortunately rather the rule than the exception in Khorezm (Müller 2006). This explains the occasional blocking of on-farm drains by local farmers as to raise the groundwater table, a practice that had previously been reported by Jabbarov et al. (1977). However, the downside of this sub-surface irrigation is the increased secondary soil salinization (Forkutsa et al. 2009), which requires annual pre-season salt leaching.

When comparing the observed groundwater dynamics with the irrigation schedule it becomes obvious that groundwater is not only driven by actual field-level application of irrigation water. Sub-regional water re-distribution and temporal filling of mostly unlined irrigation canals cause lateral movement of groundwater. As data presented by Ibrakhimov (2004) show, Khorezm-wide groundwater tables are lowest in winter. Tables rise in spring with the start of cropping activities (pre-season leaching) with a first minimum in March–April and a second in July–August when irrigation water requirement (for cotton and rice) and accompanying system losses are highest. Groundwater slowly drops thereafter, with some delay, when a second summer crop like maize is grown.

Regional groundwater dynamics, independent from field-level management, offer some challenges to soil water simulations, or crop-growth modeling in general. For field-level irrigation scenario analyses the groundwater dynamics, i.e., the lower boundary, cannot easily be predicted. In our case, this concerns analysis 1 (rescheduling of irrigation). However, we assumed that the error involved in

shifting only one single leaching event without adapting groundwater dynamics should be marginal.

Although previous studies in northeastern Uzbekistan assumed that upward movement of water was negligible for cotton growth (Ibragimov et al. 2007; Kamilov et al. 2003), it should be clear from our results that upward or downward movement of water cannot be neglected in Khorezm and that an accurate water balance could not have been established without the aid of modeling.

The measurements of soil water potentials with the pF-meters in part did not produce useful results. Further tests will have to show whether technical (calibration) problems or the influence of micro-scale differences in soil water regime are responsible for results deviating largely from indirectly (via soil moisture) calculated dynamics. Nevertheless, model calibration resulted in sufficient simulation-accuracy witnessed by the low RMSEs for simulated soil moistures, which were basically in the range of measurement accuracies given by the manufacturer for the capacitance probes. Furthermore, the rapid changes in soil moisture at greater depths in response to groundwater level fluctuations show the need for automated equipment to measure groundwater dynamics at high temporal resolution. This is especially true for studies that focus on the importance of shallow groundwater at daily resolution or at even higher precision.

Hydrus-1D does not include feedback algorithms of water-stress on crop-growth, leaf area development, and yield, unlike most well-known crop-models. The ameliorating or deteriorating effects of certain irrigation strategies on crop-growth could therefore only be indirectly derived via the effects on T_a. This is definitely a bottleneck and switching to some of those crop models might be an alternative, unless accurate crop growth prediction is of less interest.

The management strategy analyses highlighted various issues. Visual impression and simulations showed that plant growth on the sandy loam field in 2003 was constrained by water stress from mid-June to mid-July. Farmers explained that irrigation was delayed because water was unavailable in June. Our simulations confirmed that water was sub-optimally distributed, e.g., the third leaching event was unnecessary. Had this irrigation been postponed, it would have benefitted cotton growth and most likely also yield. Two reasons why fields were leached three times: (1) farmers schedule leaching according to availability of water in the system rather than with the aim to save water for later; and (2) the amounts of applied water and its effect on soil salinity are not measured and thus not understood. Based on experience gained elsewhere, three leaching events are often prescribed. As information is lacking and water for free, farmers stay on the safer side. On the other hand, the limited effect of postponing the third leaching on T_a at location 3 of the sandy loam field suggested that too little water was provided to this micro-basin and little could be done by rescheduling to improve the situation under furrow-irrigated conditions. Abandoning furrow irrigation and switching to drip-irrigation systems would offer ways to substantially reduce irrigation amounts, but currently seems financially infeasible.

Optimal irrigation of cotton, and more specifically the beneficial effects of a delayed first irrigation, has been subject of debate for decades (Stockton et al. 1961; Grimes et al. 1978; Dhankar et al. 1980; Wanjura et al. 1996; Buttar et al. 2007). In our study, the first irrigation in 2003 took place 87 days after planting. Water stress was partly alleviated by some precipitation in May. Nevertheless, the first irrigation was 30–45 days late according to the studies cited above.

The assumed 50% reduction of potential evaporation can be achieved by a surface mulch of 1.3–2.3 Mg ha^{-1} crop residues, depending on the residue area-to-mass relationship as well as the homogeneity of distribution and overlap (see, e.g., Steiner 1989). Our results suggest that the often claimed improvement of crop water availability and crop production under conservation agriculture with a permanent residue layer (Unger 1986; Steiner 1994; Fabrizzi et al. 2005; Sommer et al. 2007) may not automatically apply for irrigated conditions with shallow groundwater such as in Khorezm. Nevertheless, a residue layer has its merits with regard to the positive effect of reduced soil evaporation and secondary soil salinization (Forkutsa et al. 2009).

Improving the drainage system to reduce secondary soil salinization caused by capillary rise of groundwater, does not seem advisable without adapting irrigation amounts and frequencies. This became evident by the largely reduced actual transpiration as compared to groundwater-sustained conditions (Table 6).

The amounts and frequencies of irrigation derived from the HYDRUS-1D simulation for an 'improved production system' matched well the current recommendations in Uzbekistan, such as by the Hydro-Mod scheme (Soyusnihi 1992). The latter are based on intensive, multi-year field testing. Our study proved that simulations can substitute for intensive field studies on alternative irrigation management, once the underlying model has been calibrated (by field tests). The results of an 'improved productions system' clearly showed that the absence of a shallow groundwater table and contribution to satisfy crop water demand can be coped with by a timely and soil-texture-specific irrigation scheduling without applying more water than currently foreseen.

On the other hand, to improve the drainage system of Khorezm in such a way that groundwater tables drop by the

70–140 cm on average, as was realized in the 'improved production system' management strategy analysis, would require substantial investments. A first step would be to improve the irrigation canals to reduce extremely high seepage losses. Conrad (2006) calculated that on average for all of Khorezm between 1,700 and 3,000 mm is diverted from the Amu Darya of which a considerable part is lost by seepage before it reaches the field.

Our results indicated that sandy soils are rather unsuitable for furrow irrigation when groundwater is below 2 m. Cropping such soils only makes sense when applying relatively small but frequent amounts of water. Thus, this simulated "best management option" is technically impossible under furrow irrigation and could only be realized by implementing a drip-irrigation scheme. In fact, <5% of the agricultural soils in Khorezm are sand. Taking them out of annual crop production seems to be the better alternative since the loss of production potential is limited but the potential for saving water high. The land freed from cultivation could alternatively be used for small-scale forestry (cf. Khamzina et al. 2008; Lamers and Khamzina 2008).

Conclusions

Hydrus-1D proved to be a valuable tool to simulate and quantify the water balance of irrigated cotton under the current conditions of shallow groundwater and for possible production (irrigation and drainage engineering) alternatives.

Shallow groundwater tables in Uzbekistan are the results of massive losses in the large-scale, irrigation system. Leaking irrigation canals combined with ill-functioning drains provoke the groundwater level to rise and thus create a situation of "unmanaged" subsurface irrigation in Khorezm. A considerable share of the crop water requirement of cotton is met by this water source, complementing the unreliable delivery of irrigation water at field-level. However, groundwater contribution to crop water uptake provokes secondary soil salinization. In consequence, annual pre-season salt leaching becomes crucial, negating in-season irrigation water savings.

Simulation findings confirmed that irrigation water was sub-optimally distributed, with excessive and ineffective pre-season leaching. Simulations also highlighted the scope for reducing the amount of water for leaching, if an improved drainage system were to be installed. Furthermore, crop growth could be improved, as evidenced by a higher actual transpiration, if the irrigation scheduling was optimized. Improving the drainage system alone, without concurrently adapting irrigation amounts and frequencies, does not seem advisable. Furthermore, the often

proclaimed improvement of crop water availability and crop production under conservation agriculture with a permanent residue layer may apply less under irrigated conditions with shallow groundwater as experienced in Khorezm. A residue layer, however, improves soil salinity (Forkutsa et al. 2009).

Further research at landscape level has to show what is required to improve the drainage system of Khorezm in such a way that groundwater tables drop by roughly 70–140 cm on average, as is necessary to provide proper soil water drainage.

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