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Performance evaluation of the BUDGET model in simulating cotton and wheat yield and soil moisture in Fergana valley

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Abstract

Cotton (*Gossypium hirsutum* L.) and wheat (*Triticum aestivum* L.) are major crops grown in Uzbekistan and water shortage is considered as the main limiting factor for crop growth as well as sustainable economic development. The objective of this study was to adapt and test the ability of the soil water balance model BUDGET (ver. 6.2) to simulate cotton as well as wheat yield and soil water content under current agronomic practices in the Fergana Valley. Crop yield and soil moisture content data, collected and measured from sites in 2010 and 2011, were compared with model simulations. Results showed that the BUDGET can be used to predict cotton yield and soil water content with acceptable accuracy using the *minimum* approach. However, predicted wheat yield was high compared to the observed and reported yield. Overall, relationship between the observed and predicted cotton and wheat yield for both sites combined produced R^2 of 0.91 and 0.15, RMSE of 0.24 and 1.64 t ha⁻¹, relative Nash-Sutcliffe efficiency (E_{rel}) of 0.71 and -5.68 and index of agreement (d) of 0.48 and -0.54, respectively. Similarly, comparison of the observed and simulated soil moisture contents at the top 0-30 cm soil layer and soil water contents in 90 cm profile yielded R^2 of 0.88 and 0.71-0.88, RMSE of 2.74 % vol. and 21.4-28.7 mm, E_{rel} of 0.87 and 0.53-0.81, respectively and d around 1.0. Consequently, the BUDGET can be a valuable tool for simulating both cotton yield and soil water content, particularly considering the fact that the model requires relatively minimal input data. Predicted soil water balance can be used to improve current practice of irrigation water management, whereas simulated soil moisture content can be used to estimate capillary rise from groundwater in the UPFLOW model. However, performance of the model has to be evaluated under a wider range of agro-climatic and soil conditions in the future.

1. Introduction

Aridity of the climate in Uzbekistan makes water resources as the main limiting factor for sustainable economic development. Thus, agriculture, accounting about 90 % withdrawal of total available water resources in Uzbekistan, is impossible without irrigation (Qadir et al., 2009). At present, cotton and wheat are major crops in Uzbekistan, occupying annually about 70-80 % of the irrigated lands (Ibragimov et al., 2011). The furrow

irrigation is the dominated method, which is currently practiced at 98 % of irrigated lands in Uzbekistan (Horst et al., 2005). Indeed, water use is hampered due to its inefficient supply and poor management (Pereira et al., 2009). Moreover, water requirements of major crops are not well known (Evet et al., 2007), contributing to excess water use or aggravating water scarcity situation.

Modeling to cope with the scarcity of water resources is an effective tool to develop new management approaches. Vast researches have been done in the past to model crop yield and soil moisture content under furrow irrigation in Uzbekistan (Cholpankulov et al., 2008; Evet et al., 2007; Horst et al., 2005; 2007; Ibragimov et al., 2007; 2011; Stulina et al., 2005), where irrigation scheduling was based on pre-defined soil water content (usually when soil moisture at the field capacity is depleted up to 60 to 75 %). In contrast, studies conducted at farmer's managed agronomical condition (Forkutsa et al., 2009; Reddy et al., 2013) are dearth. Moreover, there are some differences between actual and pre-defined performances of irrigation water scheduling at the field level. In fact, current irrigation scheduling is not based on pre-defined soil moisture content. Irrigation norms and application modes including required water for planning and distribution are based on Hydromodule zoning (GMR) of the irrigated lands (Kazbekov et al., 2009). The main objective of the present study is to explore the BUDGET in simulating cotton as well as wheat yield and soil moisture under current irrigation water management practices during the cropping period of wheat in 2009-2010 and 2010-2011 and cotton in 2010 and 2011 in Fergana province of Uzbekistan. Hence, findings of the research can be useful for the development of the future strategies to improve current irrigation management in Uzbekistan.

2. Materials and methods

2.1. Location and description of study sites

Two sites, namely Akbarabad in Kuva district and Azizbek in Koshtepa district in Fergana province of Uzbekistan, were selected as research objects.

The climatic condition of the study sites is characterized by data from the meteorological station "Fergana". The long-term (1970-2011) average annual temperature and precipitation are +14.3 °C and 181 mm, respectively. During the study period (2009-

2011), annual precipitation ranged from 172 mm in 2009 to 229 mm in 2011 with 35 % falling in summer period (April-September). In contrast, 80 to 82 % of annual evapotranspiration (1100-1200 mm) occurs during summer period.

Six fields in Akbarabad (C-164, C-165, C-172, C-174, C-176, C-180&181) with total area of 82.5 ha and two fields in Azizbek (C-13&14 and C-15&16) with total area of 36.5 ha were selected for investigation.

The lands at the sites are located within the GMR V and VIII, mainly flat and slopes are 0.002-0.005, northward. Soils, according to FAO and Russian classifications, are Calcic Gleysols and sierozem-meadow with infiltration rate ranging from 0.2-3.9 m day⁻¹ to 0.2-2.0 m day⁻¹ in Akbarabad and Azizbek, respectively.

2.2. Agronomic practices and field measurements

The main crop rotation in the sites during the study period comprised cotton and wheat as well as secondary crops (not considered in current study) following wheat harvest. In 2010 and 2011 the cotton varieties “An-35” and “C-6524” were sown on the beds of the leveled field with sowing depth, beds width and seeding rate of 3-6 cm, 60 cm and 25-32 kg ha⁻¹ in Akbarabad and 4-6 cm, 90 cm and 30-40 kg ha⁻¹ in Azizbek, respectively. Winter wheat variety “Kuma” in Akbarabad and “Kroshka” in Azizbek were broadcast sown in 2009 and 2010 at a seeding rate of 200-210 and 220-250 kg ha⁻¹, respectively, incorporated by cultivator into cotton stubble.

Irrigation of cotton was performed with an alternate furrow irrigation (except charging irrigation), whereas wheat was irrigated by each furrow. The amount and salinity of irrigation water applied to the fields was measured in-situ.

In general, all agronomical practices (tillage, weeding, irrigation and fertilization) in the sites were decided by the farmers. Crop yield was taken from farmers and additionally weighted manually at harvest at plot size of 1 m² within 3-5 different locations of each field in 2011. The leaf area index (LAI) of cotton and wheat at the stage of full canopy cover was measured using hand held LAI meter (AccuPAR LP80, Decagon Devices, Inc.) in 2011. 14 soil samples from two pits (7 horizons in each) were collected in 2011 between C-164 and C-172 (AKpit-1) and C-176 (AKpit-2) in Akbarabad for soil physical and chemical analysis. The soil texture data for Azizbek site (C- 13, AZpit-1, 9 horizons)

were obtained from the past research work (Stulina et al., 2005). Hence, soil data from AKpit-1 was assumed to be representative for the fields, such as C-164, C-165 and C-172, and AKpit-2 for C-174, C-176 and C-180&181, whereas AZpit-1 for C-13&14 and C-15&16. Based on the fraction of sand, silt and clay (Fig. 1), soils, according to USDA classification, were classified as loam (L), sandy loam (SL) and silty loam (ZL).

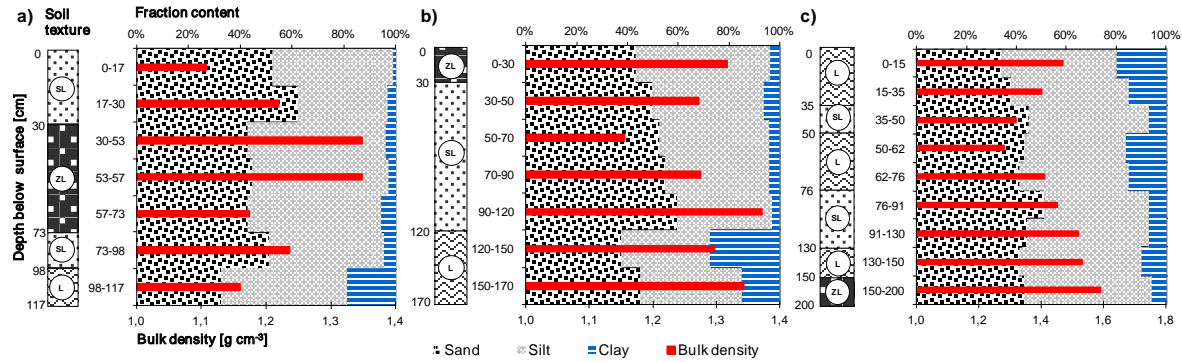


Figure 1: Soil texture, fraction content and bulk density in Akbarabad site - AKpit-1 (a) and AKpit-2 (b) and Azizbek site - AZpit-1 (c).

The soil samples to measure soil water content were collected using hand operated auger (Eijkelkamp, Giesbeek, the Netherlands) at 30, 60, and 90 cm depths on the ridge of the furrows at the center of cotton and wheat fields before as well as after irrigation in 2011. In addition, hourly soil moisture content was continuously recorded using soil moisture sensor (Decagon EC-5), which was wired to a Decagon Em50 series data logger. The sensors were installed at the center of cotton field (C-13) at 20, 40 and 60 cm depths on the ridge of the furrow in 2011.

2.3. Model BUDGET

Model description

The BUDGET constitutes a set of subroutines describing various processes involved in water extraction by plant roots and water movement in the soil profile. The model considers water storage in a soil profile affected by infiltration of rain and irrigation water including withdrawal of water by crop evapotranspiration and percolation for a given period (Raes, 2002). Simulations are performed in daily time-steps. Finite difference technique is used to solve one-dimensional vertical water flow and root water uptake. Estimation of infiltration and percolation rates is based on exponential drainage function.

Calculation of transpiration and separation of soil evaporation from evapotranspiration is based on the ground cover at maximum crop canopy, whereas on-site LAI measurements can be used to adjust ground canopy cover at specific growth stages. Relative yield decline, due to water stress during the growing stages, is based on yield response factor (K_y). Three approaches, such as *seasonal*, *minimal* and *multiplicative* approaches are considered in the BUDGET to estimate expected crop yield. Further details of the subroutines, concepts, rationale, approaches and procedures used to simulate the processes in the BUDGET are given in its Reference Manual (Raes, 2002).

Model input

The inputs of the model consist of climate, crop, soil and irrigation management data. Calculated daily reference evapotranspiration (ET_o) and daily rainfall recorded at the “Fergana” weather station were used as climate input parameters in the model. ET_o was calculated using “ ET_o Calculator” (Raes, 2009a) based on the FAO Penman-Monteith equation (Allen et al., 1998).

The length of crop growth stages (including the sensitivity stages), dual crop coefficient (k_{cb}), soil water depletion fraction for no stress (p), salinity tolerance values (S_T) and K_y for cotton and wheat were derived from indicative values presented by Allen et al. (1998), Ayers and Westcot (1994) and Doorenbos and Kassam (1979). The growing stages of crops were adjusted to local conditions based on the field observations. The 40/30/20/10 percent water extraction pattern (S_{max}) over the crop roots were selected, which assumes the greatest root water uptake near the soil surface and declines with the increase of the depth. The S_{max} at the top and at the bottom of the soil profile was assumed to be 3.5 and 0.5 mm day⁻¹ for cotton and 2.4 and 0.6 mm day⁻¹ for wheat, which are within the range of the model default crop parameters. The soil water content at the anaerobiosis point was taken as 5 % vol. below the soil water content at saturation (Raes 2009b). The soil hydraulic parameters, such as soil moisture at field capacity (θ_{FC}) and wilting point (θ_{WP}) were measured at the laboratory of Scientific Research Institute of Irrigation and Water Problems (SRIWP), Tashkent. In addition, soil moisture content at θ_{FC} , θ_{WP} and saturation (θ_s) were calculated through pedotransfer functions (PTF) in the SPAW model developed by Saxton and Rawls (2006). The saturated hydraulic

conductivity (K_{sat}) was calculated using the Rosetta model (Schaap et al., 2001). Sets of soil data from AKpit-1, AKpit-2 and AZpit-1 were separately used to calculate K_{sat} in Rosetta through five hierarchical Artificial Neural Network (ANN) models (for more details refer to Schaap et al., 2001). The drainage characteristic (τ) was calculated as a function of K_{sat} (Raes, 2002). Five soil compartments were considered as soil input data and thus weighted average values of θ_s , θ_{FC} , θ_{WP} and τ and effective K_{sat} (Radcliffe and Simunek, 2010) were aggregated from 7 layers of AKpit-1 and AKpit-2 and 9 of AZpit-1.

Model calibration

Crop parameters of cotton and wheat were considered in calibration of the model using field measurements conducted at C-13&14 and C-180&181 in Azizbek and Akbarabad sites in 2011, and tested for other fields with respective soil parameters. Calibration of crop parameters consisted of determining the k_{cb} , K_y , rooting depths and sensitivity stages that lead to the best fit of the observed crop yield. Calibration of soil parameters considered selection of θ_{FC} , θ_{WP} and K_{sat} from measured and predicted values that lead to the closest match between simulated and observed soil moisture.

2.4. Model evaluation

In this study, the model output, such as crop yield and soil moisture was considered for the evaluation of the model. The determination coefficient (R^2), root mean square error (RMSE), relative Nash-Sutcliffe efficiency (E_{rel} , Krause et al., 2005) and the index of agreement (d, Willmot et al., 1981) were used as the error statistics to evaluate model outputs.

3. Results and discussions

3.1. Irrigation management and crop yield

Six fields out of ten, especially C-174 in 2010 and C-13&14 in 2011 cultivated with cotton were under-irrigated, which created water stress condition and impacted crop yield. However, high yield of cotton under less irrigation amount in C-174 comparing to C-13&14 can be explained by relatively high rainfall in 2010 (107 mm) and different agronomical management. In contrast, winter wheat in majority of the fields was over-irrigated, where, according to Abdullaev et al. (2009), evapotranspiration during the

growing period was not considered. In general, three to four irrigations with total irrigation amount 280-500 mm and five to seven irrigations of 380-960 mm, applied during the growing period of cotton and wheat, respectively (Tab.1). The irrigation depth and amount are along the line (except wheat irrigation at C-180) with recommended amount by the GMR (Stulina, 2010). Moreover, they correspond with observations of Bezborodov et al. (2010) and Devokta et al. (2013). The average salinity of irrigation water in Akbarabad and Azizbek sites was 1.13 dS m^{-1} and 0.68 dS m^{-1} , respectively.

Table 1: Area, growing period, precipitation, potential evapotranspiration, irrigation and yields of cotton and wheat grown at fields in Azizbek and Akbarabad in 2009-2011

Year	Field ID	Crop type ¹	Area (ha)	Sowing - harvesting dates ²	P ³ (mm)	ET _o ⁴ (mm)	Irrigation: amount (mm) x number (n)		Yield (t ha ⁻¹)
							Recom. ⁵	Obs. ⁶	
2009-2010	C-13&14	Wheat	20.2	14.10.09-21.06.10	215	522	460x6	483x5	3.10
	C-172	Wheat	7	05.10.09-21.06.10	215	542	460x6	411x5	3.50
	C-176	Wheat	10	05.10.09-21.06.10	215	542	460x6 (320x4)	382x5	4.00
2010	C-15&16 π	Cotton	16.3	19.04.10-15.10.10	93	798	490x4	357x4	3.42
	C-165	Cotton	13	14.04.10-05.10.10	89	793	490x4	332x3	3.04
	C-174 π	Cotton	13	06.04.10-17.10.10	107	842	490x4 (340x4)	253x3	3.39
	C-180&181	Cotton	26.5	07.04.10-15.10.10	107	834	340x4	288x3	2.10
2010-2011	C-15&16	Wheat	16.3	15.10.10-21.06.11	99	576	460x6	718x7	4.89
	C-180&181	Wheat	26.5	20.10.10-15.06.11	96	541	460x6 (320x4)	960x6	3.52
2011	C-13&14 π	Cotton	20.2	15.04.11-11.10.11	33	889	490x4	280x3	2.84
	C-164	Cotton	13	05.04.11-07.10.11	33	920	490x4	488x4	3.20
	C-165	Cotton	13	04.04.11-03.10.11	33	914	490x4	483x4	3.79
	C-172	Cotton	7	04.04.11-06.10.11	33	918	490x4	435x3	2.15
	C-174 π	Cotton	13	04.04.11-30.09.11	33	905	490x4 (340x4)	498x3	3.20
	C-176	Cotton	10	04.04.11-09.10.11	33	835	490x4 (340x4)	473x4	3.80

¹ intermediate crops after wheat harvest were not included; ² last harvest date was taken for cotton; ³ precipitation (P) during the growing period ("Fergana" weather station); ⁴ potential evapotranspiration (ET_o) during the growing period (calculated using "ET_o calculator"); ⁵ recommended total amount and number of irrigation according to GMR V (values in parenthesis pertain to GMR VIII) according to Stulina (2010); ⁶ gross irrigation within the growing period. Note, charging irrigation in cotton fields (indicated by symbol π) was used in the BUDGET as pre-sowing irrigation.

Cotton yield, measured during the study period and reported by farmers, is within the range of average yield reported by Provincial Statistical Department (Oblstat, 2012). However, average wheat yield reported by farmers (Tab.1) has deviated from those measured at the sites as well as from those reported by Oblstat (2012) for the districts

where the sites are located (Fig. 2). Hence, wheat yield measured at the field was used to compare with modeled yield.

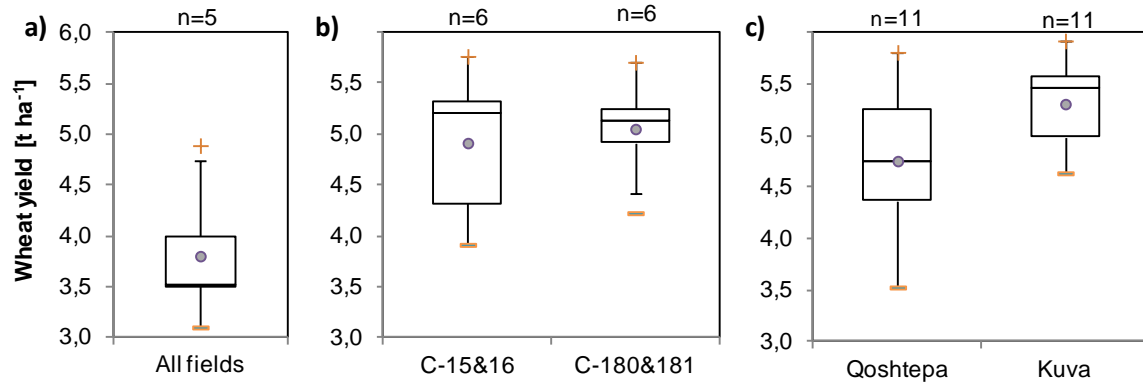


Figure 2: Box plots describing grain yield of winter wheat reported by farmers (a), field measured (b) and averaged in districts for 2000-2010 (c) and number of samples n . Line and dot inside the box: median and mean value; box: 25th-75th percentiles (interquartile range); whiskers: data values less than or equal 1.5 times the interquartile range, plus and minus: maximum and minimum values.

3.2. Soil moisture content

Results of comparison between simulated and observed soil moisture contents (SMC) between two irrigations of cotton (field C-13&14) cultivated in Azizbek in 2011 are plotted in Fig. 3. The simulated SMC using laboratory measured θ_{FC} (pF 2.0) and θ_{WP} (pF 4.2) and corresponding K_{sat} calculated using the Rosetta (ANN5) as input gave better result (Fig. 3a) comparing to those inputs calculated using the SPAW (Fig. 3b).

It should be noted that statistical analysis (Tab. 2) in terms of R^2 , E_{rel} and d are almost similar in both soil inputs (Fig. 4a and b, right). However, RMSE of 2.72 % volume was 3-fold lower when θ_{FC} and θ_{WP} were based on the laboratory measured soil inputs. This can be explained by underestimation of θ_{FC} and θ_{WP} in the SPAW. Hence, laboratory measured soil hydraulic parameters were used as default soil input data for further model simulations.

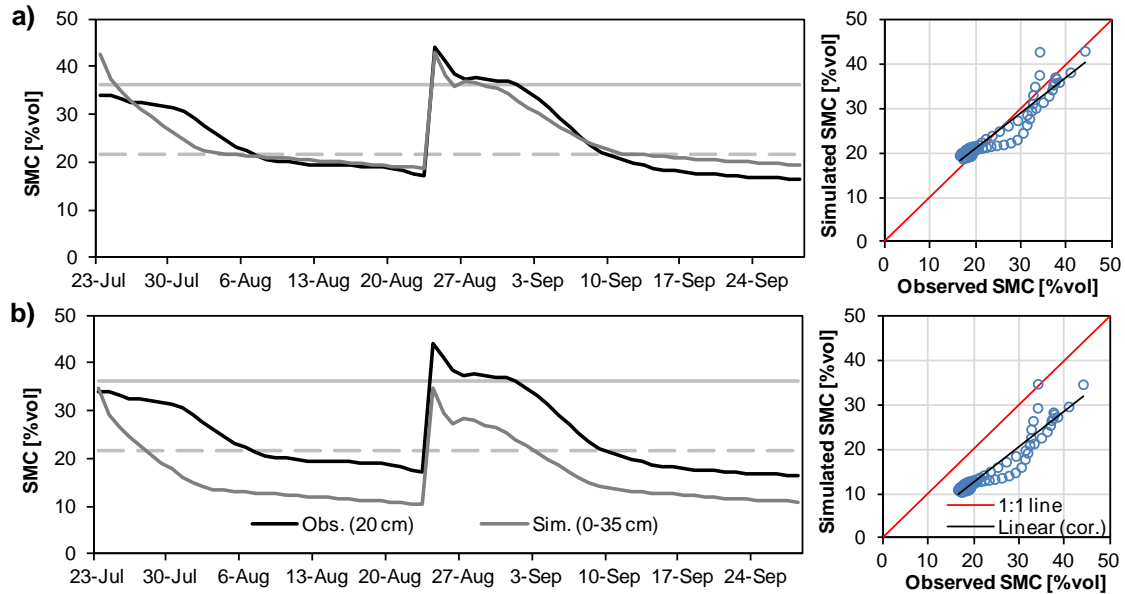


Figure 3: Relationship between simulated and observed soil moisture content at the top 0-30 cm layer for C-13&14 in Azizbek site. Straight and dashed horizontal lines represent soil moisture at θ_{FC} and θ_{WP} , respectively: using laboratory measured soil input (a) and the SPAW calculated soil input (b).

Table 2: Statistical comparison of observed and modeled soil moisture content (0-30 cm) and total soil water content (0–90 cm layer) for all sites (2011)

Variable	Field	R^2 (-)	RMSE	E_{rel} (-)	d (-)	Refer to
Soil moisture content (%vol.) ¹	C-13&14	0.88	2.72	0.87	0.99	Fig. 3a
		0.87	8.84	0.99	0.98	Fig. 3b
Soil water content in 90 cm (mm) ²	C-165	0.88	21.36	0.78	0.99	Fig. 4a
	C-174	0.71	28.72	0.53	0.99	Fig. 4b
	C-180&181	0.75	22.82	0.59	0.99	Fig. 4c

¹ between two irrigations; ² for growing period (the unit of RMSE corresponds to the variable's unit).

Soil water contents (SWC), at the 90 cm of soil profile for cotton (C-165 and C-174) and winter wheat (C-180&1881) cultivated in Akbarabad in 2011, are plotted in Fig. 4. Results presented in Tab. 2 show that the R^2 values ranging from 0.71 to 0.88 indicate large fraction of the variation of observations is explained by the model. The RMSE has value of 21.4 mm for C-165 and 28.7 mm for C-174. The efficiency and agreement indices, E_{rel} and d, have values 0.53-0.78 and around 1.0, respectively. The low goodness of fit in terms of RMSE and E_{rel} can be explained, as soil parameters were not calibrated and used as selective basis from the available and calculated data. In general, the SWC

simulated by the BUDGET are in line with the observed data (Fig. 4). Moreover, the model is able to simulate SWC above θ_{FC} , which have been confirmed by rising groundwater table after irrigations (not shown in this paper). Studies of soil moisture simulations, by Stulina et al. (2005) and Cholpankulov et al. (2008) using RZWQM and ISAREG models, respectively, yielded similar results. However, the first requires a detailed set of input parameters, whereas the latter does not consider SWC above the θ_{FC} .

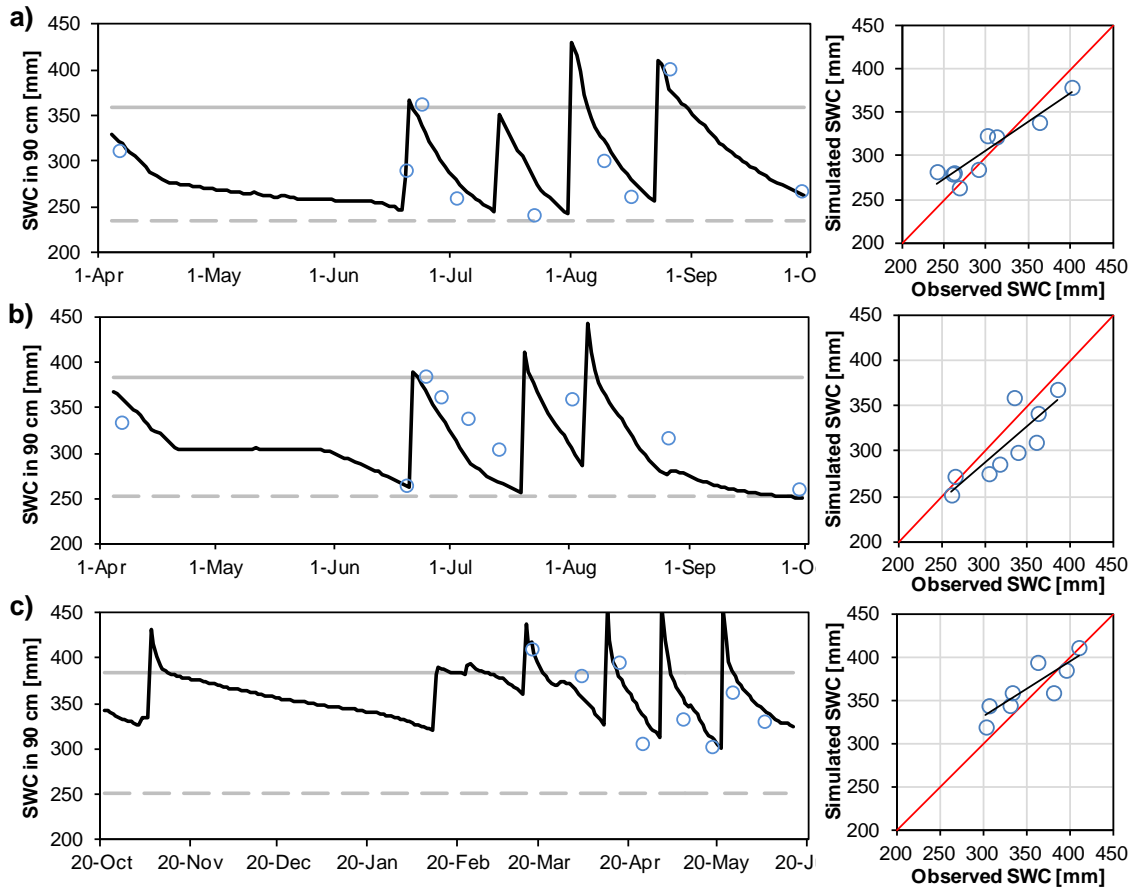


Figure 4: The simulated (full line) and observed (dot) soil water content (left) and their comparison (right) in 90 cm of cotton for C-165 (a) and C-174 (b) and winter wheat for C-180&181 (c) in Akbarabad (straight and dashed horizontal lines represent soil moisture at θ_{FC} and θ_{WP} , respectively).

3.3. Yield estimations

Fig. 5 shows the relationship between the observed and modeled yield of cotton (seed and lint yields together) and wheat (grain yield) for all the fields combined. The results in this figure refer to simulations performed with the *minimal* approach (Raes et al., 2002),

considering the relative transpiration ($T_{\text{actual}}/T_{\text{crop}}$). The potential (maximum) yield of cotton was reckoned to be 4.65 and 4.5 t ha⁻¹ for varieties of “C-6524” and “AN-35”, respectively (Ibragimov et al., 2008), whereas yield of wheat 6.0 t ha⁻¹ which have been observed during 2000-2010 in Fergana province (OblStat, 2012).

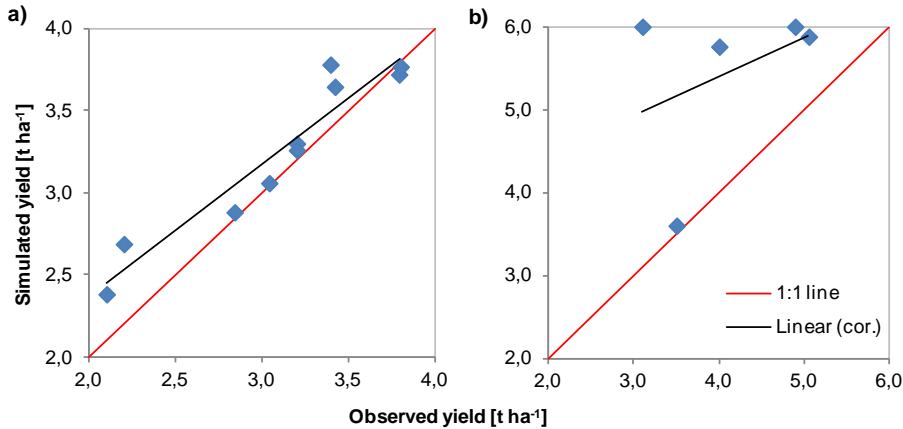


Figure 5: Relationship between observed and modeled yield of cotton (a) and wheat (b) for all the sites combined.

Observed and modeled cotton yield was correlated well giving the R^2 of 0.91, the RMSE of 0.24 t ha⁻¹, the E_{rel} of 0.71 and d of 0.48 (Tab. 3). However, the model has over-estimated wheat yield resulting poor correlation and high statistical errors. Hence, model can be used to simulate crop yield decline accurately under water stress condition (Raes et al., 2006), which was a case regarding cotton irrigation in the sites.

Table 3: Statistical comparison of observed and modeled cotton and wheat yield for all the sites combined (2010-2011)

Variable	R^2 (-)	RMSE	E_{rel} (-)	d (-)	Refer to
Cotton	0,91	0,24	0,71	0,48	Fig. 5a
Winter wheat	0,15	1,64	-5,68	-0,54	Fig. 5b

4. Conclusions

The current wheat irrigation practiced in Fergana province compared with recommended norms by the GMR shows high non-beneficial/highly unsustainable water use, where actual crop water requirement, contributions from groundwater and use of the available soil water are not taken into account. Hence, it makes high water loss as deep percolation and rise of groundwater level.

Simulations of soil water content were performed using two sets of data, e.g., measured physical soil parameters and estimated one with the help of pedotransfer functions (PTF). Results show that caution is needed to use soil parameters directly derived from PTF, which leads to miss-estimation of soil moisture content, where even statistical estimators (R^2 , E_{rel} and d) are similar. In general, the Budget can simulate soil water content and cotton yield with relative accuracy under current farmer-managed field condition in Fergana valley. Hence, the model can be a useful tool to develop an irrigation strategy under water deficit conditions that guarantee an optimal response to the applied water. Nevertheless, this work describes the first attempt to use the BUDGET for Central Asian conditions, further performance of the model is needed to consider wider range of soil, crop and management conditions.

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