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Remote Sensing and Hydrological Measurements for Irrigation Performance Assessments in a Water User Association in the Lower Amu Darya River Basin

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Abstract Irrigation water management in Central Asia is notorious for its inefficiency. We assessed the operational performance of the irrigation scheme in one Water Users Association (WUA), Shomakhulum, in Khorezm district, Uzbekistan, in 2007 to provide recommendations for strategic water management planning. Relative evapotranspiration (RET), delivery performance ratio (DPR), drainage ratio (DR), depleted fraction (DF), overall consumed ratio (OCR), field application ratio (FAR) and conveyance ratio (CR) were used as performance indicators. The components of the water balance were obtained through remote sensing techniques and hydrological field measurements. The surface energy balance algorithm for land (SEBAL) was applied to MODIS satellite data to derive actual and potential evapotranspiration. Inflows and outflows were quantified with field measurements in the irrigation and drainage network using discharge rating curves. Ponding experiments allowed determining canal seepage losses. Water balances at field level were established for application efficiency estimations. The indicator values were

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then compared to efficiency target values taken from the literature in order to assess the operational capabilities of the irrigation scheme. The general performance of the irrigation scheme is very poor. DPRs exceeding 1.0 indicate that more water is delivered to the system than is demanded. The seasonal DF of 0.4 is lower than the target value of 0.6. Losses during the field application averaged at 57%, which is 24% above target values. Seasonal DR, OCR, CR and RET are 0.55, 0.51, 0.76 and 0.82 against the target values of 0.1, 0.54, 0.84 and 0.75, respectively. We conclude that the distribution mechanism can be considerably improved. Besides improving water distribution (timing and equity) in the network, another recommended intervention would be to increase the DF, particularly by interventions at field level that raise the FAR, which in turn will improve DR and OCR. This can be achieved by introducing modern water management approaches such as laser leveling, double-sided irrigation, and control of inflow through flow-measuring devices installed at farm gates, and adequate water pricing.

Keywords Irrigation performance indicators · SEBAL · Central Asia · Drainage

1 Introduction

In Uzbekistan, 57 km^3 of water per year are withdrawn from the Amu Darya and Syr Darya rivers for irrigation of more than four million hectares of irrigated land (UNDP 2007). Agriculture forms the backbone of Uzbekistan's economy by contributing approximately 24% of the country's gross domestic product and employing 60–70% of its labor force (World Bank 2005; ADB 2008). Therefore, efficient irrigation water use is highly desired, especially in the downstream and middle-stream reaches of the Amu Darya, which frequently experiences insufficient water (Olimjanov and Mamarasulov 2006). While water use efficiency is reported to be very low in Central Asia, site-specific irrigation performance assessments based on primary data are rare.

The scientific approach to evaluate irrigation schemes and water use efficiency within the scheme has undergone various modifications during the last decades. Nevertheless, two aspects have been focused on since the late 1980s: the use of a comprehensive assessment framework and—as part of the framework—spatio-temporal comparisons within an irrigation system, so-called compound measures (Small and Svendsen 1990) or indicators (e.g., Bos et al. 1994; Gorantiwar and Smout 2005). Such irrigation performance indicators usually allow for assessing equity, productivity, adequacy, reliability, and ecological sustainability of irrigation water use (Wolters 1992; Murray-Rust and Snellen 1993). By intelligent combinations of selected indicators it becomes possible to quantify and locate the strengths and weaknesses of an irrigation and drainage system (Bos et al. 2005).

Many indicators require the integration of point measurements with spatially distributed measures such as crop distribution, yields, or water consumption. Recent developments in remote sensing (RS) have made it possible to obtain such information in a spatially distributed way from satellite imagery (Menenti 1990; Vidal and Sagardoy 1995; Gontia and Tiwari 2010; Muthuwatta et al. 2010). The Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen et al. 1998) is widely accepted and validated to obtain evapotranspiration (ET) data for modelling field water consumption. SEBAL enables modeling both, actual ET (ET_a) and potential ET (ET_p) (e.g., Hellegers et al. 2009; Wu et al. 2010) which in turn can be combined to measure relative ET at various scales (Hafeez et al. 2007). However, irrigation performance assessments basically still rely on hydrological in-situ data, which mainly consist of inflow and outflow measurements, or groundwater observations (Bos et al. 2005). Many researchers are relying on secondary data available from local or regional water management institutions (Bastiaanssen and Bandara 2001; Ahmad et al. 2009; Karatas et al. 2009). However, in Central Asia secondary data on hydrological measurements is difficult to access (Chemin et al. 2004; Conrad et al. 2007) and their reliability is often questionable, due to strategic reasons (Mueller 2006; Martius et al. 2009).

The objective of this study was to assess operational performance of the irrigation and drainage system in the central Aral Sea basin using RS and near-real time on-ground hydrological measurements. Special emphasis was put on the identification of bottle-necks in irrigation water distribution within the area managed by a Water Users Association (WUA), by quantifying losses at system, canal, and field levels. Interrelations within a set of irrigation performance indicators (relative ET, delivery performance ratio, drainage ratio, depleted fraction, overall consumed ratio, field application ratio and conveyance ratio) were sought.

2 Study Area

The Khorezm province is situated in the northwest of Uzbekistan and has an arid continental climate. The long-term annual average reference evapotranspiration (ET_o) (using Penman–Monteith equation) and precipitation from the official climatic data for the last 25 years in the Khorezm region are 1,338 and 94 mm, respectively (Fig. 1). The resulting difference between crop water demand and precipitation needs to be covered by irrigation water from the Amu Darya River which is the only source of fresh water in the region.

To supply farmers with irrigation water and for socio-technical interventions, 113 WUAs were established until 2006 in the Khorezm region by decree (Bobojonov 2008). For the present study, the WUA Shomakhulum (1,885 ha of farm land) in the southwest of Khorezm (Fig. 2) was selected. The distinct hydrological boundaries

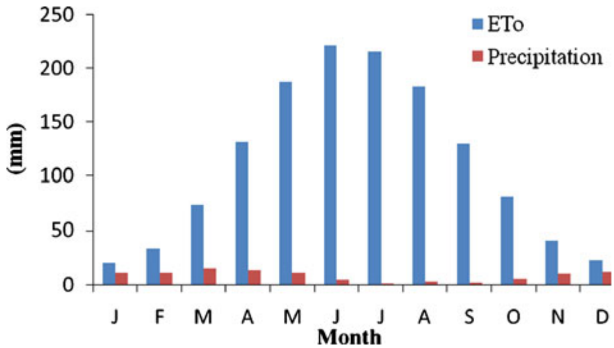

Fig. 1 Monthly values of reference evapotranspiration and precipitation from 1985–2009

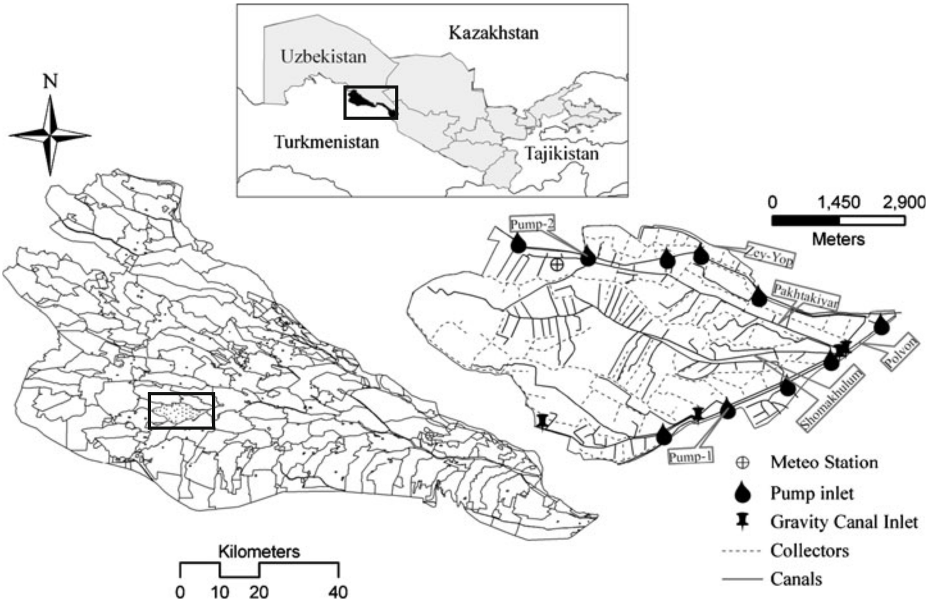

Fig. 2 Location of Shomakhulum water user association with irrigation and drainage system in Khorezm region of Uzbekistan

of Shomakhulum WUA were considered advantageous for water accounting and modeling.

Water is provided to the WUA boundaries by Zey-Yop and Polvon canal. As canals are dug-in, the water needs to be pumped up into the main distributor canals of the WUA, but depending on topography, some farms receive the water by gravity directly from the dug-in canals. About 66% of the total field water supply into Shomakhulum originates from 10 lift irrigation schemes (pumps), whereas the remaining 34% is supplied through gravity canals (Fig. 2). Irrigation network density of the WUA is 83 m ha^{-1}. An open horizontal drainage network is used to remove excess surface and groundwater from the area along with the salts, the latter especially stemming from leaching events prior to the vegetation season. The total length of the drainage system in the WUA is 101 km (drainage network density 54 m ha^{-1}).

3 Material and Methods

The operational performance was assessed against pre-formulated target values (Bos et al. 2005). Appropriate performance indicators were selected from comprehensive lists provided, e.g., in the international commission on irrigation and drainage (ICID) guidelines (ICID 1978). The rationale for selecting these indicators included the feasibility of taking measurements, their accuracy and the cost effectiveness (Bandara 2003). The following subsection shows the conceptual framework established to assess operational irrigation performance in the Shomakhulum

WUA and the indicators selected. We then describe how the parameters were measured and were used to calculate the performance indicators.

3.1 Operational Performance Assessment, Framework and Indicators

In order to quantify the water losses and to localize bottlenecks of water distribution and water use, indicators were combined which allowed for assessing the water flow from both perspectives, supply and demand. Supply, consumption, and drainage were assessed at different scales using the conceptual framework, schematically presented in Fig. 3.

To assess water distribution to and within the canal system, the delivery performance ratio (DPR) was selected.

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

where V_c is actual volume of water (m^3), and V_i (m^3) is intended flow of water. Bos et al. (1991), Clemmens and Bos (1990) and Molden and Gates (1990) judge this

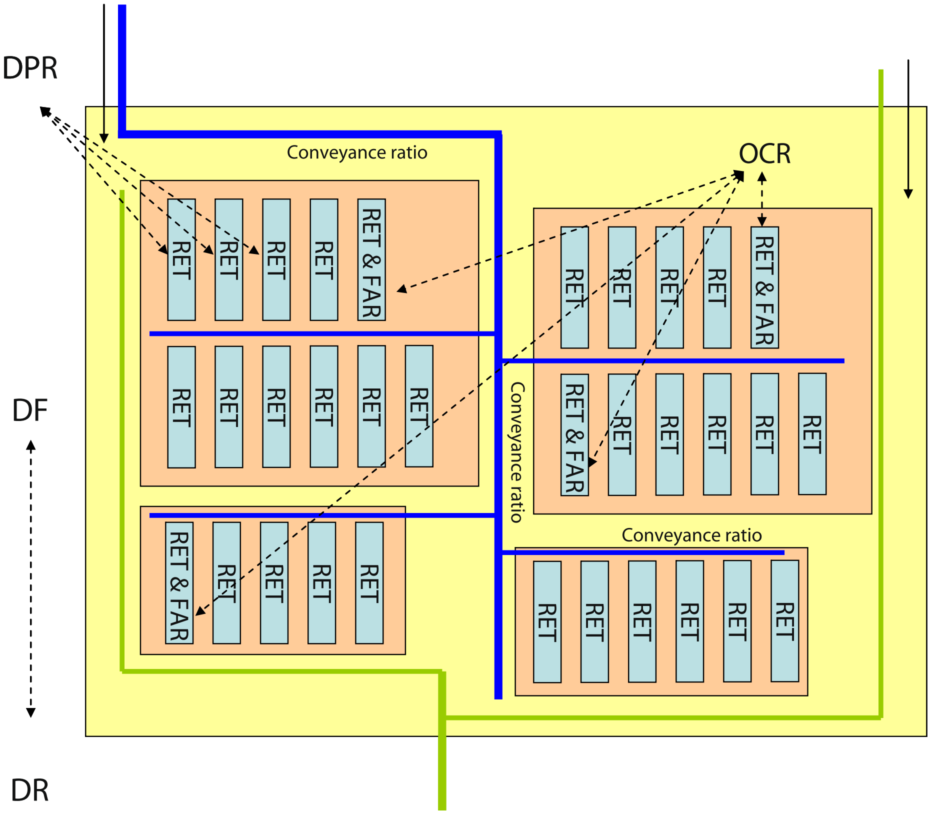

Fig. 3 Conceptual framework for assessing irrigation performance of the WUA. *DPR* delivery performance ratio; *RET* relative evapotranspiration; *DR* drainage ratio; *DF* depleted fraction; *OCR* overall consumed ratio; *FAR* field application ratio; *CR* conveyance ratio

to be the most important indicator for the operational performance of the water distribution in an irrigation scheme. Moreover, DPR allows assessing adequacy, equity and reliability of realizing the water distribution in the irrigation scheme.

DPR was primarily used in combination with relative evapotranspiration (RET):

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

where ET_a and ET_p are actual and potential evapotranspiration, respectively. RET also allows for assessing the adequacy of water supply (Perry 1996). Besides adequacy assessments at different scales, a major purpose of the comparison was to explain spatio-temporal variations of water consumption in the system.

The depleted fraction (DF) was used for tracking the water flow from the system intake to the field. It quantifies the water amount lost during transportation or due to low application efficiencies. Water consumption for crop production (ET_a) is aggregated for the gross command area (including uncultivated land within the hydrological boundaries of the observed irrigation system) and compared to the amount of water available at the system boundaries (Molden and Sakthivadivel 1999):

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

where P_e is effective precipitation (Dastane 1978) within the gross command area, and V_c is the volume of surface water flowing into the command area. Due to the prevailing arid climate, P_e was negligible in the vegetation period.

Due to the local prevalence of shallow groundwater tables, DF also was selected for assessing the risk of rising GW levels and soil salinity. But since GW levels are at the same time influenced by the drainage, the drainage ratio (DR) was included. During long-term observations of a catchment or irrigation scheme, DR and DF should sum up to 1 (Bos et al. 2005). DR is defined as (Bos et al. 1994):

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

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

The overall consumed ratio (OCR) was used for evaluation of the overall system efficiency. OCR quantifies the degree to which the crop irrigation requirements are met by irrigation water in the irrigated area (Bos and Nugteren 1974):

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

For understanding potential discrepancies between water supply and demand in detail, a differentiation was made between the field level and the network level represented, by considering a field application ratio (FAR) and a conveyance ratio (CR). Field application ratio (FAR) was measured several times to quantify water losses in the field and to investigate the high water demand reported for the Khorezm region (Awan 2010). This efficiency indicator is defined as follows (ICID 1978):

$$FAR = \frac{ET_p - P_e}{V_d}$$

where ET_p expresses the water volume required by the crop growing on the investigated field and V_d is volume of water delivered to the field. To measure FAR, we selected two farms in Shomakhulum having different but representative GW levels, soil textures and cropping patterns.

A comparison of OCR with FAR was expected to disclose the status of the irrigation infrastructure and to understand water losses within the WUA. We also calculated conveyance losses in the canal system (conveyance ratio, CR), which is classically defined as the water balance of a canal (Bos et al. 2005). The water delivered to the canal partly reaches the field and partly is lost through evaporation and seepage and eventually by overflow into the drainage system.

Conveyance ratio can be mathematically expressed as product of CR at different hierarchy levels CR_i (i = 1 to n, n = lowest hierarchy level, field canal level):

$$CR = \prod_{i=1}^{n} CR_i$$

In the WUA Shomakhulum, CR was derived by investigating all three hierarchy levels of canals (inter-farm, inter-field, and field canals).

3.2 In Situ Measurements and Remote Sensing Techniques

3.2.1 Water Flow Measurements (V_c and V_{dr})

Four flow measuring stations were installed in major canals (Shomakhulum canal, Pakhtakiyar, Pump-1 and Pump-2), which supply more than 70% of the irrigated area (Fig. 2). To cover the entire area, additional secondary data were used. Daily inflow data at all 14 intake points (Fig. 2) were provided by the WUA office. Intended flow of water or the designed flow rate for the year 2007 vegetation season was collated from a dataset of the Shomakhulum WUA.

Water from the network of open drains is collected in a large collector that takes the drainage water out of the area. It was also necessary to determine the discharge from one major inflow collector running into the WUA. For this purpose, two flow measuring station were established, one at the inflow collector and another at the outflow collector.

The stream-gauging technique was used to measure the actual flow of water in the irrigation canals and the collector. With this method, the height of water in a canal, known as stage or head, is used to determine the discharge or equivalent volume for the given period. To measure the head, automatic water level sensors (**eco**Tech™) were installed in these canals. For different stages, the corresponding value of discharge was calculated from a discharge-water level function (rating curve).

The velocity-area method was applied for measuring stream discharge (Buchanan and Somers 1969). The cross sections were measured from a point of known elevation before and after the vegetation season to correct for disturbance by sedimentation. The canal width was divided into a number of subsections, each containing no more than 5% of the total discharge. For each subsection, canal depth and average velocity were measured.

A current meter was used for velocity measurements. For water depths lower than 1 m average velocity was measured at 0.6 times the total depth. When depths were larger, the current meter was placed at 0.2 and 0.8 times of the section depth (Buchanan and Somers 1969). The product of velocity, depth and width of the section is the discharge through the respective subsection. The sum of the discharge amounts in the subsections equals the total discharge of the canal. Covering the range of discharge variation, total discharge of the canal and corresponding water level were measured simultaneously and the equation for the best-fit-line was used for establishing the rating curve. The volume of water was aggregated on a half-hourly, daily, monthly, and seasonal basis.

3.2.2 Actual and Potential Evapotranspiration Using Satellite Remote Sensing

The Surface Energy Balance Algorithm for Land (SEBAL; Bastiaanssen et al. 1998) was used for modeling ET_a and ET_p. SEBAL has been widely used and validated in various countries (Bastiaanssen et al. 2002). The evaporative fraction (Λ), the output of SEBAL, is determined by the following equation:

$$\Lambda = \frac{\lambda E}{(Q^* - G_0)} = \frac{(Q^* - G_0 - H)}{(Q^* - G_0)} \tag{1}$$

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

$$ET_a = \Lambda \times Rn24 \times 86400 \times 10^3 \left[(2.501 - (0.002361 \times T_0)) \times 10^6\right]^{-1} \tag{2}$$

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

SEBAL applications require thermal remote sensing data. For seasonal estimations of ET_a and ET_p with SEBAL (which are hardly possible to determine by the conventional methods), frequent satellite observations are beneficial. Seven cloud-free Terra-MODIS (Moderate Resolution Imaging Spectroradiometer) overpasses recorded during the vegetation period were selected (Table 1). Spatial resolution of MODIS thermal information is 1 km and allows for SEBAL modeling at a subsystem level.

Beside thermal overpass data, MODIS products representing 8- and 16-day periods were downloaded from the LPDAAC website (see Table 1). The products used for SEBAL included MOD11L2 (land surface temperature), MOD13A2 (normalized difference vegetation index), MOD15A2 (leaf area index), and

Table 1 Overview over the satellite overpasses selected for modeling ET_a and ET_p using SEBAL

Data set	Layer	Spatial resolution	Temporal resolution	Linear interpol.
MOD11L2	Land surface temperature and emissivity	1 km	Overpass	No
MOD13A2	Vegetation indices	1 km	16 day	Yes
MOD15A2	LAI	1 km	8 day	Yes
MOD09Q1	Surface reflectance	250 m	8 day	Yes

MOD09Q1 (surface reflectance). Using the HDF-EOS to GeoTIFF Conversion Tool (HEG), these products were re-projected and gridded into 1 km resolution.

ET_p of a crop can be achieved when there is no restriction due to either biological control or soil water content, which in practice corresponds to the well-watered condition of a crop (Bandara 2003). Here, ET_p was estimated using the Penman–Monteith equation (see e.g. Allen et al. 1996), and 24-h actual evapotranspiration values were derived from the seven MODIS images as described in Eq. 2 (Bastiaanssen and Bandara 2001).

3.2.3 Field Experiment for Determining the Field Application Ratio

Two farms in Shomakhulum having different but representative GW levels, soil textures and cropping patterns were selected to measure FAR. Farm-1 had a total area of 13 ha, where cotton and different types of vegetables were grown on 9 and 4 ha areas, respectively. On Farm-2, cotton (6 ha) and wheat (4.1 ha) were cultivated on a 10.1 ha area. The dominant soil texture at Farm-1 is loam and at Farm-2 is sandy loam.

Five irrigation events were monitored during the irrigation season 2007 at both farms. At each farm's main inflow point, 2-m-long uniform concrete cross sections with a width of 1 m were constructed to facilitate the discharge measurements (described above). Net water demand for each irrigation event was calculated as the difference between field capacity and soil moisture prior to irrigation.

Two pits of 1 m^3 volume were dug in the middle of each farm and soil samples taken from the pits at 0–20, 20–40, 40–60, 60–90 and 90–120 cm depths. At each depth, soil moisture characteristic curve, soil bulk density, soil texture, and soil moisture were measured.

The soil moisture characteristics was established (Fig. 4) using the Richards pressure membrane method (Klute 1986). Soil bulk density was determined according to the method by Blake and Hartge (1986). The average bulk density was 1.5 g cm^{-3}

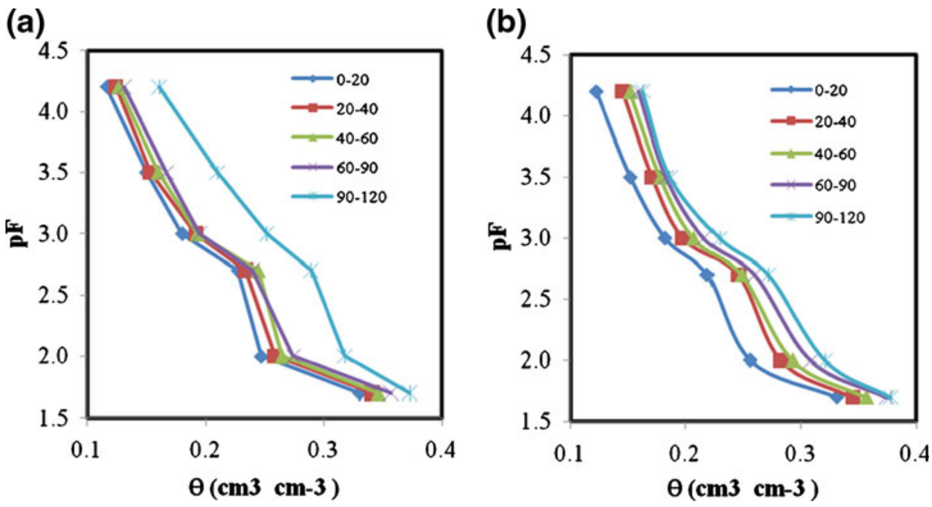

Fig. 4 Soil retention curve for **a** Farm-1 and **b** Farm-2

(standard deviation of 0.09) at Farm-1 and 1.46 g cm^{-3} (standard deviation of 0.08) at Farm-2. Soil texture was determined using the gravimetric method (Loveland and Whalley 2001) from the same depth at 16 regular grids over the farms. Samples for soil moisture, determined by the gravimetric method on a dry basis, were taken one day before and 4 to 6 days after the irrigation events depending on the soil moisture status on the farms.

3.2.4 Ponding Experiments for Measuring Conveyance Ratio

Six ponding experiments were conducted following the guidelines by Rohwer and Stout (1948). For these experiments, a canal segment was closed at both ends and water level measurements were taken for a certain time period to allow estimations of conveyance losses through seepage. Six canals representing all three canal hierarchies in the WUA were selected: two inter-farm canals (Site-1 and Site-2), three farm canals (Site-3, Site-4 and Site-5) and one in field canal (Site-6). In addition to canal hierarchy, the permeability of the soil immediately below the wetted perimeter of the canals was considered for site selection, because it significantly affects canal seepage (Rohwer and Stout 1948). To classify the soil texture, soil samples were taken from three different locations near the canals from 0–15, 15–30, 30–60, 60–90 and 90–120 cm beneath the soil surface till the GW level was reached.

Uniform canal segments were selected for the experiments in each canal reach. The length of the ponds varied from 40–120 m depending on the hierarchy of the canals, water filling capacity, easiness of dam construction, and uniform lengths. Nevertheless, the ponds were long enough to make the sum of the pond end areas a very small percentage (not more than 3%) of the total wetted area.

In earthen canals, it is difficult to find a regular cross section with a typical geometric shape. To describe the geometry of the canal segments, the most representative cross section in the ponds was measured by elevation points taken at each 25 cm segment per width. A best-fit trend line was added to the surveyed points to find the polynomial equation for calculating the geometric components of the pond. Using the coordinates (x,y) of the polynomial developed for the cross sections of all the ponding sites, the wetted perimeter was determined for each 1-cm depth with the aid of Pythagoras theorem, and the results were summarized.

Data loggers were installed in the middle of each test reach to record changes in water levels in 5-min intervals. In areas with shallow GW tables, confirmation of the GW level is very important because GW levels have a direct influence on seepage rates (Bouwer 2002). Therefore, three observation wells about 20, 10 and 5 m apart in a line rectangular to the canal reach were installed to monitor GW fluctuation.

To determine the longitudinal slope of the canals, profile surveys were taken with an engineering level. Observation wells, data loggers in the middle of the pond, cross sections of the pond and longitudinal slope were surveyed in one local system of elevation. Losses were then determined for each canal reach and time-step converting the water level drop into a loss of water volume using the above mentioned water level-volume function. Considering evaporation and rainfall per time-step allows estimating the seepage rate (seepage per time-step). The seepage rates were then related to a unit of wetted area as recommended by ICID (1967), Kraatz (1977), Byrnes and Webster (1981), Wachyan and Rushton (1987), Frevert and Ribbens (1988) and McLeod (1993).

Table 2 Water balance components for WUA Shomakhulum during the 2007 vegetation season

Month	Actual inflow (mm)	Intended inflow (mm)	Total outflow (mm)	Actual ET (mm)	Potential ET (mm)	Precipitation (mm)
April	94	84	101	35	85	41
May	246	148	154	118	138	4
June	245	242	115	191	175	9
July	451	308	247	104	164	1
August	456	255	219	124	140	0
September	97	110	45	89	102	0
Seasonal	1,589	1,147	881	661	804	55

4 Results and Discussion

The performance assessments for the Shomakhulum WUA focused on (1) water availability at system boundaries and at field level, (2) water distribution within the system, and (3) water use efficiency at both, field and system level. Water balance components used to determine the irrigation performance indicators are given in Table 2. The analysis of the indicators according to the conceptual framework is described in the following sections.

4.1 Relative Evapotranspiration and Delivery Performance Ratio

The DPR indicates that water availability in the irrigation system of the WUA was high during the vegetation period 2007. Figure 5a shows that the water supply

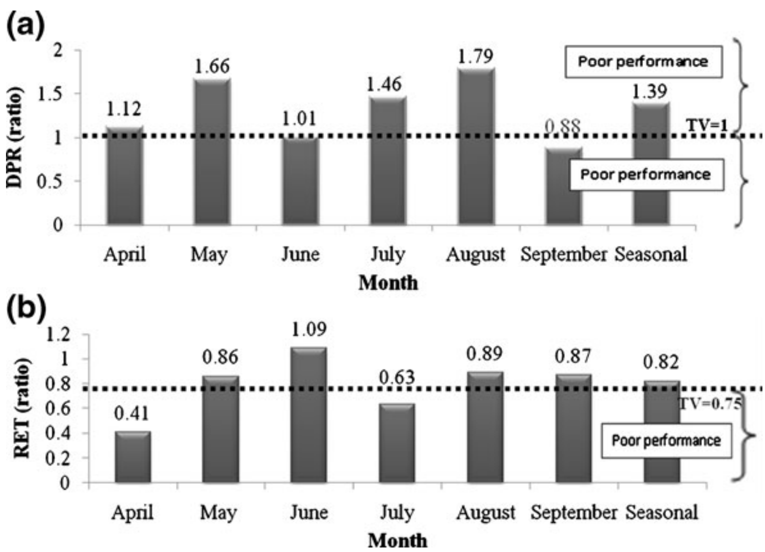

Fig. 5 Behavior of performance indicators during the 2007 vegetation season in Shomakhulum WUA: **a** DPR and **b** RET

generally exceeded the demand, as monthly DPR values are always above the target value except in September. One of the reasons for higher DPR could be that high-water-demand crops such as rice were grown, which are not officially accounted for in the water demand calculations. Conrad et al. (2010) confirmed that rice fields were present and covered approximately 7.5% of the irrigated lands in the WUA. This is much lower than the regional average, and we therefore expected that the analysis of water use and consumption in the WUA would disclose other reasons for the high water intake.

Water supply at the system boundaries was high in contrast to water consumption at field level (Fig. 5b). Monthly RET values between 0.75 and 1.0 indicate adequate water supply at field level. Monthly RET values were above 0.8 in all months except for April and July: comparison of RET with DPR indicated enormous water losses in the system through distribution and field application mechanisms. That RET exceeded the value of 1.0 in June might be due to errors associated with the presence of other sources of evaporation such as irrigation canals and flooding of rice fields in the pixels.

4.2 Drainage Ratio and Depleted Fraction

The analysis of the performance indicators DR and DF was expected to explain part of the discrepancy between water supply at system and field level. The seasonal drainage ratio is 55% (weighed average) which means that 55% of the water supplied to the WUA ended up in the drains (Fig. 6a). Highest DR values were recorded in April 2007, which can be explained by the drainage of water, applied for salt leaching purposes, and which was mostly drained to the groundwater before the vegetation

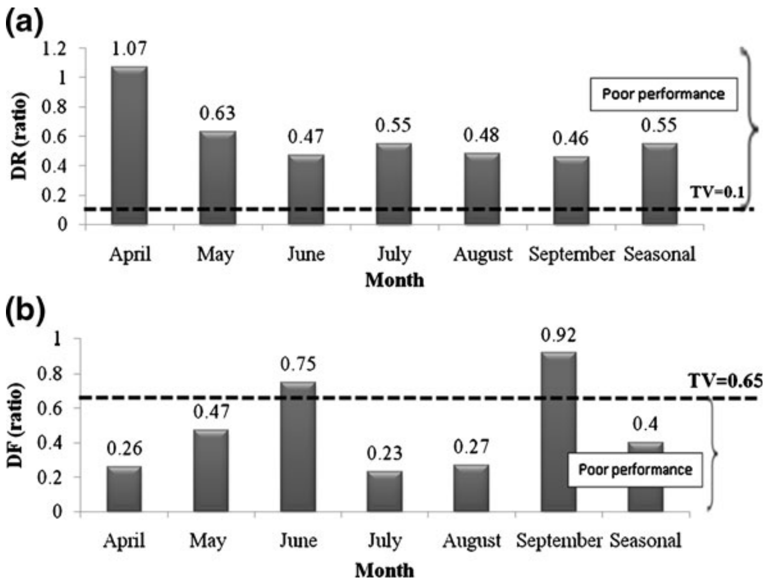

Fig. 6 Behavior of the performance indicators during the 2007 vegetation season in Shomakhulum WUA: **a** DR and **b** DF

period. But also after draining, the leaching water DR exceeded a critical value of 10% (Bandara 2006). Two main reasons were found to explain the high DR values:

1. Part of the delivered water is drained out from the canal system during the vegetation season: most of the canals of the observed WUA end in drainage collectors. But infrastructure is poor (closing constructions at the end of the irrigation canals are missing), and water management is often uncoordinated. The water supply through pumps has a fixed average discharge of 0.5 m^3 s^{-1} and is not flexible. Water is usually shared between a group of 4–5 farmers. However, as water is not always used at the same time (Abdullaev 2009), given the fixed pump discharge, more water than needed is pumped into the canal, and the unused part goes directly into the drain. Poor canal design also forces the farmers to discharge water into the drains to protect the earthen canals against damage from high discharge.
2. Part of the water which is delivered to the cropped area is discharged into the drains during application as farmers continuously drain water out from rice fields to decrease soil and water temperature and to reduce the risk of fungal infections of the rice stem.

The depleted fraction (DF) was below the target value of 65% for most part of the season, which further indicates high losses of water (Fig. 6b). Only in June and September, the DF was in an acceptable range. In the main irrigation periods of July and August, only 23% and 27% of the applied water, respectively, were consumed for crop production.

The multi-temporal comparisons of both indicators, DR and DF, allowed for a better tracing of the movement of water from the irrigation canals to the fields and groundwater, and finally to the drainage collectors. DR and DF (Fig. 6) should sum up to near to 1.0 when storage does not change (i.e. the sum of soil moisture content and groundwater level change remains stable). However, especially in the main irrigation periods, the total was decreased, indicating that a high amount of water was increasing soil moisture content/or accessing the groundwater. The latter has been reported to occur regularly in entire Khorezm (Ibrakhimov et al. 2007).

There is always a natural temporal delay between inflow and outflow within any observed hydrological boundaries. The enormous water movement to the storage in July and August, when water supply is at highest level, shows however, the variability of this delay in Shomokhulum. The WUA is located in the very flat south-west of Khorezm, where drainage problems at regional level occur (Conrad 2006). Obviously the drainage is unable to remove the water which was excessively supplied during both months, when intakes where much higher than demand (Table 2). Moreover, surveys of the drains revealed that farmers start blocking the drains in periods of high water demand to retain soil moisture in the root zone, which obviously worsened the situation during July and August.

The situation in September underlines the large role that groundwater contribution plays for irrigation in Central Asia, which was also reported by Forkutsa (2006), Forkutsa et al. (2009a, b) and Conrad et al. (2007) for the Khorezm region, and by Pereira et al. (2009) for irrigation systems in the upstream region of the Syr Darya River. However, one negative ecological impact indicated by DR and DF is the risk of increasing soil and GW salinity (Bos et al. 2005), risks also well documented for the Khorezm region (Ibrakhimov et al. 2007).

Although, the DF values indicate an increased amount of water in the system after the vegetation season, only long-term observations (summer and winter season) and quantification of lateral flows would reveal a complete view of the drainage situation in the WUA. Despite poor DR and DF during the vegetation season which highlights the problem of water distribution and the drainage situation in the main irrigation phases of July and August, the DF and DR totals for the entire vegetation period sum up to 0.95 which is nearly the target value of 1.0.

It has to be noted that DR and DF do not distinguish the level at which the losses occur, i.e. either in the canal system or during field application; therefore the focus of the following section is to trace these losses in the WUA Shomakhulum.

4.3 Field Application Ratio, Conveyance Ratio, and Overall Consumed Ratio

4.3.1 Conveyance Ratio

Table 3 shows the results from the ponding experiments, the respective soil types, and the basic information of the measured cross sections. Data from the experiment at Site1 in the inter-farm canal was discarded from the analysis, due to the interference of the GW level with the full supply level (FSL) of the canal. The shallow GW conditions not only restricted the seepage of the water from the canal, but also caused the ex-filtration of the shallow GW into the canal.

The losses in the irrigation network of Shomakhulum ranged from 23–26% (the range is based on the average of the minimum and maximum values within the same hierarchy of canals) during the vegetation season (Table 3). The losses in inter-farm and farm channels are comparatively low. Surprisingly, the conveyance losses were generally lower than expected at all hierarchy levels. Especially in months of low DF, e.g. July (23%), this is tantamount to high losses.

The low seepage rates in almost all canals can be explained by silt deposits at the canal bottom and shallow GW conditions particularly in the inter-farm canals.

However, losses in the field channels could be reduced. An average CR of 76% was calculated for the irrigation network in the WUA Shomakhulum. Jurriens et al. (2001) reported that a CR of 84% can be achieved for an irrigation network with well-managed earthen canals.

4.3.2 Field Application Ratio

FAR was found to be far below the target value (0.67) in all irrigation events (Fig. 7b) which confirmed that high losses were from the fields and thus caused low DF. The

Table 3 Conveyance losses in the irrigation network in WUA Shomakhulum

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

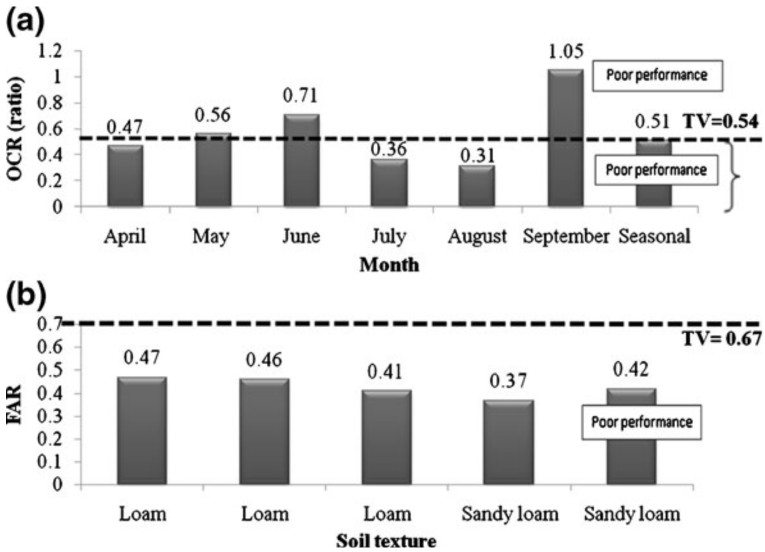

Fig. 7 Behavior of the performance indicators during the 2007 vegetation season in Shomakhulum WUA: **a** OCR and **b** FAR

farmers applied much more water than required. On loamy soils, an average of 55% of the entire water was lost during the application, the sandy loam soils revealed higher losses (Fig. 7b).

Large field sizes and irregular leveling, and especially the farmers' excessive water use to cope with the unreliable water supply in the canal system, resulted in the observed low efficiency. The farmers' preference is for water security rather than water saving. This is the major difference between the view by external observers who focus on water saving and salinity control, and the farmers who focus on reliability of crop production, which explains their need for water at any costs (Oberkircher and Ismailova, submitted). The lack of any flow measuring devices also means no proper control on the irrigation water use exists.

The technology-centered 'mantra' that better engineering and management in the region will improve the FAR makes sense as recent advancements in modern technologies to improve FAR still are not implemented in the region. However, it is necessary to understand the reasons why these modern technologies are still not being implemented in the region. Recently Bekchanov et al. (2010) presented a socio-economic analysis in the study area regarding constrains in implementing modern techniques. They studied the potential and viable use of laser-guided land leveling for cotton, drip irrigation for tomato, and improved furrow irrigation practices (surge flow, double furrow, alternate dry furrow, and short furrow) for cotton cultivation. Their study shows that there is an inverse relationship between water use improvement potential and financial feasibility of various water-saving options, i.e., the more water-efficient the technology is, the more capital intensive it becomes. They concluded that, as farmers are typically poor and there are no currently government incentives to introduce high-cost water-wise options such as laser-guided leveling, drip irrigation, and surge irrigation, the best current approach is the low-cost approaches. Short and double flow techniques and alternate dry furrow system would have a high potential in irrigated cotton production due to their insignificant implementation costs and reduced water use. Likewise, Paluasheva (2005) reported that double flow irrigation has a great potential in the region for increasing the FAR. To improve the application ratio in furrow irrigation systems, currently practiced on more than 98% of the irrigated area in the region, Horst et al. (2005) proposed to operate at higher inflow rates than those currently used.

Bobojonov et al. (2008) further argued that underdevelopment of farmer-to-market links in the study region reduces the chances for farmers to obtaining adequate prices of their products, which restricts them not to invest in their production. And Bobojonov (2008) reported that inadequate water pricing is another factor that does discourage farmers from adopting expensive water saving technologies. However, a larger problem is that extension services in the region are virtually absent which restricts the farmers' awareness of the technological alternatives and innovations (Bekchanov et al. 2009).

4.3.3 Overall Consumed Ratio

Throughout the season, the overall consumed ratio (OCR) is below the target value except in June and September (Fig. 7a). The increased OCR in these two months results in higher DF and hence lower DR. Thus, an increase in the OCR would improve both the DF and DR. OCR is therefore an important strategic indicator (Bos 1997).

5 Conclusions and Recommendations

Oversupply of water and occasional crop water stress with huge outflows from the drains reflected by DPR, RET and DR indicators, respectively, show the inadequacy, inequity and unreliability of the irrigation scheme in the WUA. These indicators also point to the bottlenecks in water distribution. The OCR and DF are below the target values, which show the inefficiency at system levels. The detailed investigation of inefficiency aspects by tracing the efficiency at irrigation network (CR) and at farm level (FAR) shows that losses on the fields are the main reasons for low OCR and DF values. Therefore, to improve the efficiency of the system, measures needs to be taken at farm level. The inefficient use of water at farm level is partly due to insecurity of water availability which explains the farmers' opportunist behavior to apply water 'as much as they can', and partly due to the lack of modern water-saving technologies. The implementation of water-saving technologies is restricted to low-cost options. Another reason for low FAR are the high operational losses, which could be reduced by institutionalizing the involvement of farmers in water distribution planning. Although the establishment of WUAs was done with this purpose in mind, they are mostly not managed to achieve greater participation (Zavgorodnyaya 2006).

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