

Remote Sensing Based Hydrological Modeling for Irrigation Performance Assessment in the Lower Reaches of the Amu Darya River in Central Asia

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Keywords: *Irrigation performance assessment, remote sensing, spatially distributed modelling, Uzbekistan*

EXTENDED ABSTRACT

According to FAO standards underperforming irrigation systems are reported from Central Asia, especially for the downstream parts of Amu Darya and Syr Darya. A lack of reliable and consistent data for various reasons, is the major bottleneck to analyse the system functioning and irrigation performance in detail. To overcome these limitations is an important step towards integrated water resource management aiming improved environmental conditions in the Aral Sea Basin. Remote sensing may be a technical advance to contribute reliable and consistent data for a better understanding and assessment of the irrigation complexes at different spatial scales.

This study utilizes satellite images for water balancing and irrigation performance assessments in Khorezm, a 275.000 ha sized hydrological unity, within the lower reaches of the Amu Darya. Agricultural land use was derived from 250 m MODIS NDVI time series. To calculate seasonal actual evapotranspiration (ET_{act}) the widely used SEBAL model was applied to 1 km MODIS data for 63 days of the vegetation period 2005. Discharge measurements were recorded continuously in the irrigation and drainage channel system throughout the vegetation period 2005, covering 82 % of the irrigated land. Relative evapotranspiration (ET_{rel}), depleted fraction (DF) and drainage ratio (DR) were calculated to disclose the functioning of the irrigation system at the scale of major distribution channels.

A decreasing tendency of ET_{act} towards the distal parts of the irrigation system demonstrated decreasing water availability at field complex level. In the downstream parts, crop water demand was not met whereas ET_{rel} indicated water saving

potentials in the upstream locations. But this upstream-downstream gradient of irrigation water supply was not found at the higher distribution level. 24.000 m³ water per ha agricultural land revealed very high water availability in 2005. DR of about 55 % indicated a functioning drainage; however, considering drainage problems observed at field level and given the fact, that capillary rise contributes significantly to irrigation, it could be concluded that the drainage system empties the groundwater body at large scale, which was filled up by percolation losses in the irrigation system. Equally, low DF emphasized the risk of groundwater and soil salinity especially in the distant parts of the irrigation system.

The case study underlined the under-performing irrigation system in the Khorezm region representing the lower reaches of the Amu Darya in Uzbekistan. Adequate water distribution, increased irrigation efficiency, and sustainable water use were identified as major challenges.

1. INTRODUCTION

According to FAO standards, irrigation performance in the lower reaches of the Amu Darya River in Central Asian Uzbekistan is grossly under-performing and a major reason for increasing economic and ecological problems in the Aral Sea region (“Aral Sea dilemma”). Yet, this generalized statement is based upon inconsistent, outdated and unreliable data provided by national structures. These data lack an adequate methodological basis for a more accurate data collection, especially on percolation and seepage losses in rivers and channels and unregistered withdrawals. For the intended and highly demanded introduction of an Integrated Water Resource Management (IWRM) in Central Asia, it is a prerequisite to master these problems which constitutes the present focus of the scientific branch of the Interstate Water Distribution Commission (ICWC-SIC, Dukhovny et al., 2004)

Remote sensing may help filling this gap by improving the understanding and assessment of the irrigation complexes at different spatial scales and may contribute to better-informed decision-making of water resources management. Especially performance indicators based on an accurate estimation of the actual amount of water consumption for different land use types derived from remote sensing data have been found useful to assess the major principles of irrigation management, adequacy, equity, reliability, productivity, and sustainability (Bastiaanssen and Bos, 1999). Bos et al. (2005) added remote sensing parameters such as biomass estimation or soil wetness and assigned those to the group of emerging indicators. However, most basic indicator systems to assess irrigation water use rely on water balances and need quantifications of water flows in the irrigated area.

This study aims to investigate the functioning of the irrigation system in the Khorezm region which represents one downstream part of the Amu Darya River suffering from the aforementioned unreliability and inconsistency of data for strategic and operational irrigation management. As a consequence, the area is characterized by advancing soil degradation and salinity, owing to rising groundwater tables. For example, throughout the irrigation periods between 1990 and 2002, groundwater tables in Khorezm averaged 1.2 m – 1.5 m below surface reaching critical threshold levels (Ibrakhimov, 2005). Forkutsa (2006) reported from on-field irrigation experiments in the southern part of Khorezm between 17% and 89% of total crop water demand supplied by groundwater. In addition, farmers

compensate water shortages during the growing period by rising groundwater levels to increase capillary rise as a contribution to meet crop water requirements. Consequences are groundwater and soil salinity problems, which result in intensive leaching during the winter times. The specific objectives of this study were (i) to quantify water amounts available for irrigation at the system boundaries, (ii) to assess the adequate water supply on field complexes, and (iii) to identify and explain potential upstream-downstream disparities within the Khorezm region. To achieve these objectives, water balance indicators, including the depleted fraction and drainage ratio, and the relative ET, revealing the adequacy of water distribution, have been addressed. The presented study focused on the regional scale and combined water in- and outflow measurements covering 82% (240,000 ha) of the entire irrigated land with data on land use and actual evapotranspiration (ET_{act}) derived from MODIS remote sensing records.

2. STUDY SITE

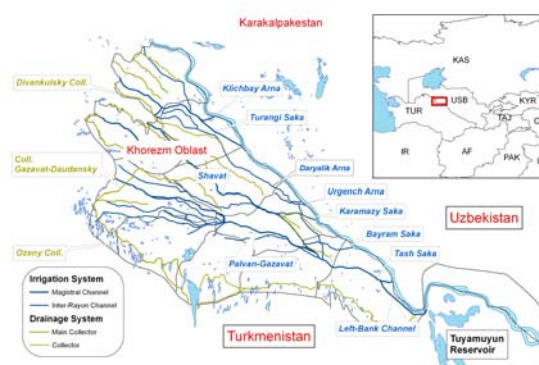


Figure 1. Geographic location of the Khorezm region and main irrigation and drainage network.

The study area is located approximately 225 km south of the remainders of the Aral Sea in Uzbekistan (Figure 1). Khorezm is the upstream part of the lower Amu Darya River floodplain. The climate is extremely continental and necessitates irrigation throughout the whole year. The main crops are cotton, winter wheat, rice and alfalfa.

About 2,750 km² of 5,600 km² land can be irrigated in Khorezm. Six major inlet water constructions supply an extensive, hierarchically constructed network of main, inter-farm and on-farm irrigation channels. The total length of the irrigation and drainage network is 16,233 km and 7,679 km, respectively (Figure 1). The majority of water is distributed to Water User Associations (WUAs) and to single fields through gravity irrigation system. About 95% of the annual water supply in Khorezm (between 3.5 and 5 km³

according to official data) is designated for agricultural purposes (Conrad, 2006). Channel losses by evaporation and seepage are estimated to be higher than 40% (Martius et al., 2004), because water is mostly conveyed from the river to the fields in open, non-lined channels.

3. MATERIALS AND METHODS

Water balances and indicators related to the water balance components provide the necessary overview on the functioning of the irrigation system. According to Molden (1997), water balances of irrigation systems describe the change in the storage (ΔS) as a result of irrigation and drainage inflow (I_{irr} and I_{dr}) and outflow (O_{irr} and O_{dr}), precipitation (P), and ET_{act} :

$$\Delta S = (I_{irr} + I_{dr} + P) - (O_{irr} + O_{dr} + ET_{act}) \quad (1)$$

As major reservoirs within the Khorezm irrigation system are absent, storage comprises the unsaturated and saturated zone since storage changes may occur due to soil moisture and groundwater level differing at the end of the balancing period compared to the beginning of the period. Lateral water flows in Khorezm are less than 19-26 mm per year and therefore negligible (Kats, 1976). At the meteorological station of Yangibazar, 21 mm of rainfall were measured for the entire vegetation period of 2005. This very low value was assumed to be representative for the entire region because of the generally dry climate in combination with the very flat terrain of the Khorezm region. The following sections describe the key parameters and indicators used for performance assessments.

3.1. Remote sensing parameters

MODIS remote sensing data products distributed by the NASA (<http://redhook.gsfc.nasa.gov/~imswww/pub/imswelcome/>) were utilized to model agricultural land use and ET_{act} .

Time series of 250 m normalized difference vegetation index (NDVI) derived from 8-day MODIS reflectance data facilitated to classify agricultural land use, in particular cotton, winter wheat, and rice (Figure 2). Temporal NDVI signatures showed patterns of vegetation cover and greenness of vegetation throughout the season and therefore disclosed crop rotations with winter wheat (Conrad et al., 2007).

The Surface Energy Balance Algorithm for Land (SEBAL, Bastiaanssen et al., 1998) allowed for modelling ET_{act} solving the surface energy balance:

$$\lambda ET = R_n - G - H \quad (2)$$

which enabled calculating latent heat flux (λET) by subtracting ground heat flux (G) and sensible heat flux (H) from the available energy (net radiation, R_n). It was successfully applied on 1 km MODIS overpass thermal data to model seasonal ET_{act} on 63 of 214 days of the vegetation period 2005 (Conrad et al., 2007). Monthly and seasonal ET_{act} resulted from linear interpolation of the relationship between ET_{act} and reference ET (ASCR-EWRI, 2005).

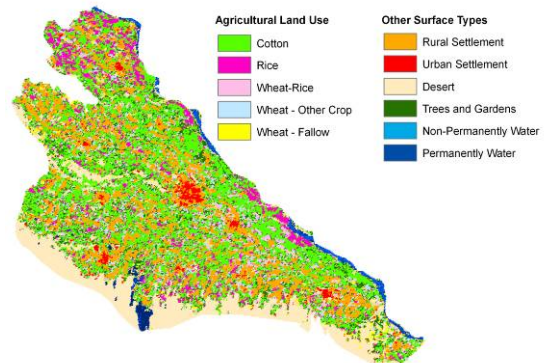


Figure 2. Land use classification, Khorezm 2005

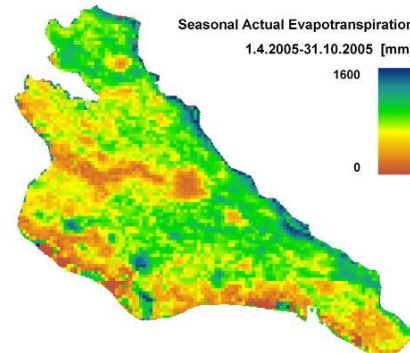


Figure 3. Spatially distributed seasonal ET_{act} , Khorezm, vegetation period 2005

Seasonal ET_{act} of cotton and rice in Khorezm were estimated at 774 mm (2004: 768 mm) and 824 mm (2004: 798 mm), respectively. High standard deviations of approximately 300 mm indicated the spatial variability as shown in Figure 3.

3.2. GIS network analysis

To identify all major water distribution nodes and to analyse the connectivity of the irrigation network, downstream flow-path analysis were carried out using GIS. Channel distances between the major intake points of irrigation water and the boundaries of the WUAs were measured to

identify upstream and downstream parts of the irrigation channel system (Figure 4).

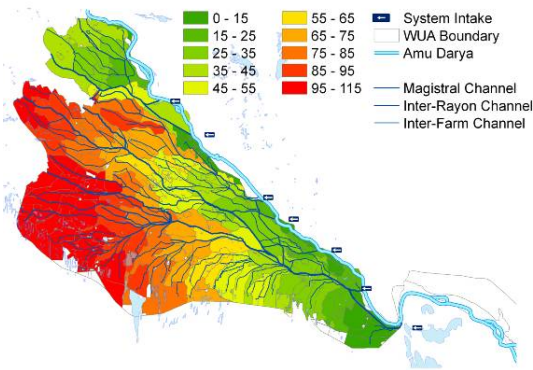


Figure 4. Distances (in km) between system intake nodes and WUA boundaries (channel length).

3.3. Discharge measurements

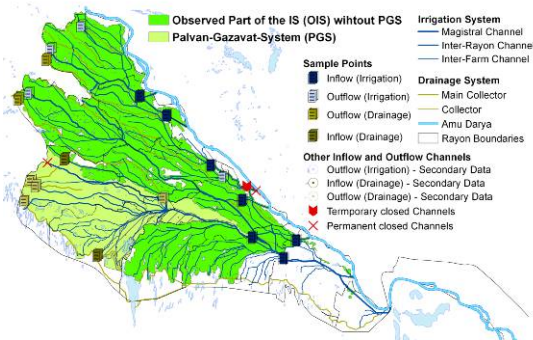


Figure 5. Sample points and hydrological boundaries of the observed part of the irrigation system (OIS) and the Palvan-Gazavat-System.

Discharge measurements at 21 sites covered 82 % of the entire irrigation system of Khorezm throughout the 2005 vegetation period. The Palvan-Gazavat-Subsystem (PGS) located in the distant portion of the irrigation network was studied separately (Figure 5). Rating curves (discharge-water level-function), which were established for each site allowed for transferring water levels recorded automatically to discharges. The rating curves were derived from simultaneous measurements of the water level cross-section and the spatial distribution of velocity in the cross-section using a current meter. Current meter measurements were conducted in verticals representing parts of the cross-section and at 20% and 80% of the water depth for each vertical. The precision of the discharge measurements were calculated approximate to 7 % by applying an approach of federal office for environmental protection of Baden-Wuerttemberg, Germany

(LUBW, 2002), to the characteristics of the considered monitoring sites.

3.4. Performance assessments

Relative ET (ET_{rel}) can be used to indicate crop water deficits and to give an approximation of the adequacy of water supply (Bos et al., 2005). The relationship between ET_{act} and crop potential ET (ET_{crop}) is given as:

$$ET_{rel} = \frac{ET_{act}}{ET_{crop}} \quad (3)$$

where ET_{crop} resulted from crop coefficients, provided by the Central Asian Scientific Research Institute of Irrigation (SANIIRI), multiplied with daily reference ET for small crops according to ASCE-EWRI (2005).

According to Bos et al. (2005), ET_{rel} belongs to the so-called emerging indicators, because it requires satellite measurements for large scale assessments. Its level of detail depends on the spatial resolution of the satellite data. Hence, the 1 km MODIS data used in this study represented field complexes rather than single fields. Therefore, 250 m land use classification MODIS was utilized to increase the accuracy of the results. Only 1 km pixels with more than 80% agricultural area on sub-pixel level were included. 250 m ET_{crop} was summarized to get an indication of the expected value.

The depleted fraction (DF) opposes the actual water use of the cross command area (ET_{act}) and the amount of available surface water. DF is defined by the following equation:

$$DF = \frac{ET_{act}}{P + I_{irr} - O_{irr}} \quad (4)$$

where $I_{irr} - O_{irr}$ equals the irrigation water supplied to the command area. It allows detailed spatio-temporal comparisons of water consumption within subsections of the irrigation network (Molden, 1997). For arid regions decreases in DF below an average value of 0.6 (Bastiaanssen et al., 2001) indicate the rise of groundwater tables and the risk of reaching critical groundwater levels followed by accelerating soil salinity.

The drainage ratio (DR) is defined as the amount of drainage water divided by the amount of water entering the irrigation system. The degree to which water is used in a water basin discloses further water resources which can be utilized e.g. for agriculture.

4. RESULTS AND DISCUSSION

ET_{rel} showed a decreasing tendency towards the distant parts of the irrigation system (Figure 6). Most WUAs located in remote parts of the channel system (distance classes > 65 km) did not reach the average ET_{rel} of 0.95, which can be understood as a benchmark for adequate water supply. (Bos et al., 2005). However, only in the lowest downstream parts (distance class " > 95 km"), ET_{rel} dropped under a critical value of 0.75 suggested by Bos (2004) for most crops. Here, the crop water demand was very likely not met.

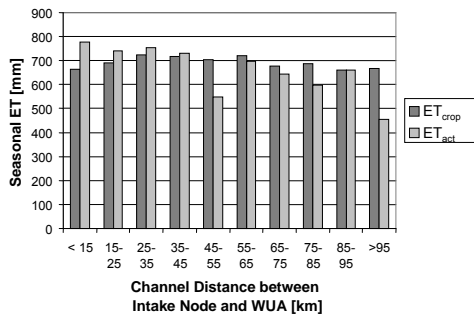


Figure 6. Seasonal ET_{act} (mm) and ET_{crop} (mm) for the distance classes (Figure 4) which were used as input to compute ET_{rel} .

Seasonal ET_{rel} higher than one as found in the upstream parts of the irrigation system indicate uncertainties, which partly result from stiff crop coefficients or crop development stages applied. Despite the relatively small area, environmental conditions may vary throughout the region. This is strongly supported by the recently estimated crop coefficients and growth periods derived from field experiments in Khorezm (Forkutsa 2006), which differ widely from the official SANIIRI values used for this study.

A long term analysis of ET_{act} in combination with crop growth or productivity indicators would lead to spatially distributed ET_{crop} and therefore to more plausible benchmarks than those derived from single point observations as previously shown by Tasumi and Allen (2007). However, applying an expected value of 0.95 ET_{rel} disclosed potentials for water savings in the upstream parts and suboptimal water supply for WUAs located downstream in the irrigation channel system.

The water withdrawals measured in the Observed part of the Irrigation System (OIS) exhibited an opposite trend (Table 1). The PGS located in the outer reach of the channel system received around $30,000 \text{ m}^3\text{ha}^{-1}$ in the vegetation period 2005, whereas significantly lower amounts were extracted in the surrounding parts (OIS-PGS).

Table 1. Water intake related to agricultural area (ha) for the Observed part of the Irrigation System (OIS), the Palvan-Gazavat System (PGS), and the difference between OIS and PGS.

Vegetation period	Area [ha]	Agric. Area [ha]	Withdrawal/Agric. Area [m^3/ha]
2005			
OIS	337,541	204,822	23,933
PGS	83,163	49,820	29,834
OIS-PGS	254,378	155,002	19,460

Three different interpretations are plausible: First, the water demand in the PGS is generally higher than in the other parts of Khorezm, possibly due to high losses in channels. Second, the oversupply in the upstream parts, as indicated by ET_{rel} , forced the water managers to bypass water to the remote parts of the irrigation system, but this assumption could not be verified. Infrastructure problems are a third explanation, because the PGS was formerly designed to transport water to the Daushauz region (Turkmenistan). A certain level of water flow could be necessary to enable water distribution in the extremely flat terrain of the PGS.

Table 2. Water balance and performance indicators for the OIS, the PGS, and the OIS-PGS.

1.4.2005 – 30.9.2005	OIS	PGS	OIS-PGS
$I_{irr} - O_{irr} [\text{km}^3]$	4.73	1.46	2.97
Drainage [km^3]	2.73	0.80	1.93
P [km^3]	0.07	0.02	0.05
$ET_{act} [\text{km}^3]$	2.21	0.56	1.64
$\Delta S [\text{km}^3]$	-0.14	0.12	-0.55
Drainage Ratio [m^3/m^3]	0.58	0.55	0.65
Depleted Fraction [m^3/m^3]	0.46	0.38	0.54

Water withdrawal for the OIS excelled 4.7 km^3 (Table 2). Precipitation contributed approximately 1.5% to the total supplied crop water. Based on the results of the DR, more than 55% of the incoming water ended up in the drainage system. Compared to the critical minimum of 0.15 (Bos et al., 2005), the water use potential in Khorezm was high, but high salt concentrations made the water nearly unsuitable for further irrigation.

On regional scale and regarding the entire vegetation period the drainage seemed to work properly. This, however, is contradictory to observations on field and WUA level, where defects of the drainage system are recurrently reported as a critical problem at least in sub-units and referring to the temporal appropriateness of

drainage (Ibrakhimov, 2005). ET_{act} amounted in comparison to the withdrawals as relatively low, especially in the PGS. Groundwater levels and soil moisture decreased, because the vegetation period started in the late leaching phase, when groundwater levels and soil moisture were usually high. The opposite situation in the PGS was analysed in more detail utilizing performance indicators on monthly base.

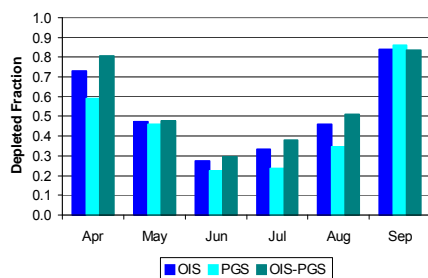


Figure 7. Monthly depleted fraction (DF) of the OIS, PGS, and OIS-PGS, vegetation period 2005.

Low DFs indicated the risk of shallow, saline groundwater tables and soil salinity throughout the OIS (Figure 8). In particular between May and August, all observed parts of the irrigation system fell below the lower critical values of 0.5 suggested by Bos (2004). Also a lower critical minimum of 0.4 suggested by Bandara (2006) was missed during June and July, when two out of the three main irrigation phases take place in the OIS. Obviously high amounts of freshwater supplied at the system boundaries got lost for irrigation due to channel losses or inappropriate irrigation at field level. This aligns very well with channel losses and low application efficiencies reported by Martius et al., (2004) and Forkutsa (2005), respectively. Direct linkage between irrigation and drainage due to deficits concerning the coordination of irrigation activities between field and network level as well as within the irrigation network operation observed in the fields could also contribute to the low DFs. All three possibilities are plausible even though exact quantifications are outstanding due to limited data. Figure 9 shows that the leaching period in spring resulted in high DR (April). In the initial irrigation phases between May and July DR achieves a level of 0.45 in the OIS followed by a slight increase towards the shut down of the irrigation water supply during the harvest period in September.

The sum of DF and DR as an indicator for monthly storage changes discloses the large-scale system functioning of the irrigation period 2005. In general during the main irrigation phases between June and July soil moisture and groundwater tables increased significantly. But from July onwards

variations of DR and DF were lower in the OIS-PGS than in the PGS. In the OIS-PGS the DR level of 0.65 in July, August and September indicate a balanced drainage system. But with regard to the high amounts of water supplied to the system in 2005 the appropriate use of freshwater could be scrutinized again.

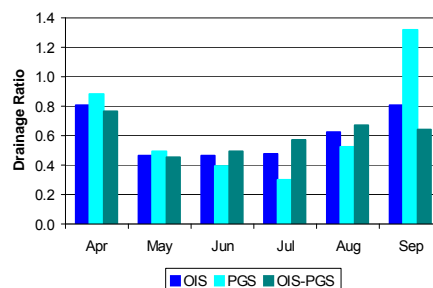


Figure 8. Monthly drainage ratio (DR) of the OIS, PGS, and OIS-PGS, vegetation period 2005.

The distant part (PGS) seemed to be in a more critical situation than the OIS-PGS. Throughout the main irrigation phases in June and July DR fell below 0.25. Concurrently decreasing DR indicated high water supply to the storage, which coincides with generally high groundwater tables in the PGS in the same period (Ibrakhimov, 2005). This situation can be explained by drainage backlogs caused by the very flat relief in the outer part of the irrigation system. As soon as the water supply is reduced, the groundwater storage starts to be emptied by the drainage system (lowering of groundwater table). The DR of about 1.3 measured in September indicates that situation, because the high discharge in the drainage fed by an emptying groundwater storage exceeds the reduced input of irrigation water to the system.

5. CONCLUSIONS

The case study of Khorezm underlined a low irrigation performance in the downstream regions of the Amu Darya River in Uzbekistan. Despite disregarded leaching periods between November and March immense water withdrawals were recorded in the vegetation period 2005. Low DF disclosed high water losses especially in the downstream parts of the irrigation system. Combined with in-situ observations showing that a certain percentage of field water consumption (ET_{act}) was contributed by capillary rise, low irrigation efficiency can be concluded for 2005. For an exact quantification of irrigation efficiency rates, however, modelling variations of the storage variables is an outstanding task.

Remote sensing showed a high ability to contribute hydrological surface parameters for regions suffering from reliable data such as Central Asia. In geographical regions with low atmospheric disturbances such as cloud cover or aerosols and therefore with a high number of suitable MODIS overpasses, half-monthly ET_{act} observations become possible. A fast access to such remote sensing products can support operational water distribution, because it enables water managers to localize over- and undersupply in time. Another future perspective is to link these remote sensing products with models simulating the water distribution. The presented approach is portable to regions with similar agro-climatic conditions such as the irrigation systems of the Amu Darya and Syr Darya Rivers in Central Asia or beyond.

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