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Satellite based calculation of spatially distributed crop water requirements for cotton and wheat cultivation in Fergana Valley, Uzbekistan

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ABSTRACT

This study focuses on the generation of reliable data for improving land and water use in Central Asia. An object-based remote sensing classification is applied and combined with the CropWat model developed by the Food and Agriculture Organization (FAO) to determine crop distribution and water requirements for irrigation of cotton and winter-wheat in Fergana Valley, Uzbekistan. The crop classification is conducted on RapidEye and Landsat data acquired before the onset of the main summer irrigation phases in July using a random forest algorithm. The ClimWat database of FAO is utilized for calculating crop water requirements (CWR) and crop irrigation requirements (CIR).

Classification reveals an overall accuracy of 86.2% and exceeds a producer's (user's) accuracy of 95% (89%) for both, cotton and wheat. In 2010, cotton and winter-wheat are planted on 66.7% of the agricultural area under investigation, whereas orchard areas amount to 15.5%. The CWR modelled for winter-wheat and cotton cultivation revealed 5443 $m^3\ ha^{-1}$ and 9278 $m^3\ ha^{-1}$, respectively. Subtracting effective precipitation leads to CIR of 4133 $m^3\ ha^{-1}$ and 8813 $m^3\ ha^{-1}$. Comparisons of CWR and CIR for the area dominating crops with the total of water officially allocated for irrigation underline the pressure on the water resources in the entire Syr Darya catchment and suggest modifications of the cropping system towards more winter crops. The early season crop maps can be used for water saving as they enable modifications of water allocation plans within the different irrigation subsystems of the valley. The method for mapping spatially distributed CWR and CIR can be transferred to other irrigated areas in Central Asia and beyond.

1. Introduction

Initiated by the Soviet expansion and intensification of crop production starting in 1960 (Létolle, 1993), irrigation of crops on around 8 million ha of land utilizes more than 90% of the annually available 120 km^3 of freshwater in the Aral Sea Basin (ASB) today (Roll et al., 2005). But the peak of productivity along the Amudarya and Syrdarya Rivers achieved by high inputs of water, fertilizers, and pesticides to soils of low natural fertility ended already in the mid1980s (Giese et al., 1998). The permanent overexploitation has resulted in the degradation of croplands due to salinity which caused yields to decline by about 30% already before the break-down of the Soviet Union in 1991 (Létolle, 1993). In the five Central Asian (CA) successor states, Uzbekistan, Kyrgyzstan, Tajikistan, Kazakhstan, and Turkmenistan, approximately 50% of the irrigated land is affected by salinization (Reddy et al., 2013). Moreover, the agricultural sector of these countries is economically incapable to maintain the irrigation and drainage system or to introduce water saving irrigation methods. As a result, land productivity and especially water use efficiency are reported to be low throughout the ASB (e.g. Granit et al., 2010; Tischbein et al., 2013).

The Fergana Valley is a rather typical and maybe the most prominent example of large-scale irrigation systems in Central Asia. Very low field application efficiencies of 49% (Reddy et al., 2013) and contributions of shallow groundwater to irrigation amounting to 23% have been observed in field experiments (Pereira et al., 2009). Despite its upstream location of the major irrigation systems along the Syrdarya River, upstream–downstream disparities of water availability and access to water have been reported within the irrigation system of Fergana Valley (Abdullaev et al., 2009a). These characteristics are similar to other irrigation systems in the ASB (e.g. Dukhovny et al., 2004; El-Magd and Tanton, 2005; Tischbein et al., 2013; Conrad et al., 2013). But the

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irrigation complex is trans-boundary and shared by three countries, Kyrgyzstan, Tajikistan and Uzbekistan. Moreover, the Fergana Valley is the most densely populated region in entire Central Asia with more than 11 million inhabitants and exceeding 500 inhabitants per km^2 in some of its parts (Filcak, 2008). The annual population growth rate in the three Central Asian countries 1998–2015 varies between 1.1% and 1.5% (World Bank, 2013).

Improvements of the water use within Fergana Valley are urgently needed especially in face of still increasing pressure on the water resources, e.g. by impacts of temperature increases expected to be around 1.5–2.5 °C (Lioubimtseva and Henebry, 2009) on snow cover parameters and glacier melting. Diverging prognoses of precipitation patterns show high uncertainties of climate models when predicting future water availability in the upstream catchments (Mannig et al., 2013). However, scenarios of a coupled climate, land-ice and rainfall-runoff model indicated runoff peaks shifting from spring towards the late winter season in the Syrdarya catchment (Siegfried et al., 2012). Another source for increasing pressure is the energy demand of Kyrgyzstan and Tajikistan, which want to make use of the high hydropower potential stored in numerous reservoirs. Most of them were constructed on the territory of today's upstream countries in Soviet times (Rakhmatullaev et al., 2010). Water releases especially during the winter period can reduce water availability at the irrigation system boundaries during the vegetation period (Karimov et al., 2010). For this reason conflicts rose between the states as previously described by Sehring (2008) and an update of the former Soviet inter-provincial distribution schemes is still a matter of dispute 20 years after independence in 1991.

Among others one starting point for improvement could be a better matching of water demands to the availability within the irrigation system irrespectively of external pressure on water resources. Reddy et al. (2013) assigned low field application efficiencies to high application rates accompanied with runoff losses up to 64%. Suggestions are made, even for increasing irrigation efficiencies by introducing suitable water application strategies (Horst et al., 2005; Webber et al., 2006) or improving irrigation scheduling (Pereira et al., 2009). However, the extrapolation of this findings and potential water saving options from field to system level would require area wide information in a spatially explicit way. For some of the parameters (e.g. soil moisture) exhaustive field surveys would be necessary, but with known land use patterns, at least area wide crop water requirements (CWR) and, utilizing meteorological measurements, crop irrigation requirements (CIR) could be calculated at the field level. Aggregated to sub-system level allocation plans and water distribution in the channel system can be optimized (El Nahry et al., 2011). But due to missing and unreliable data in the land and water sector in entire Central Asia (Giese and Mossig, 2004; Oberkircher, 2010), area-wide CWR/CIR calculations would most likely comprise uncertainties: In addition, the sparse information is mostly available in a tabular way. The latter hinders the location based analyses and the implementation of solutions at different scales.

Remote sensing in combination with Geographical Information Systems (GIS) has shown the potential for improving data situations in irrigation management (Bastiaanssen and Bos, 1999; D'Urso et al., 2010). Satellite remote sensing is for instance an accurate, time and cost-efficient tool for mapping crop distribution at different scales (e.g. GEOSS, 2009; Wardlow et al., 2010; Conrad et al., 2011). The accuracy for instance relies on the spatial resolution of the available satellite data which needs to match the heterogeneity of the agricultural landscape (Wardlow and Egbert, 2008; Conrad et al., 2010). Multi-temporal approaches can return high mapping accuracies (Barrett and Curtis, 1992), however, studies by Murakami et al. (2001) and VanNiel and McVicar (2004) outline the suitability of selecting a few but optimal temporal windows for accurately distinguishing between different crops. For water saving within a vegetation period, initial crop classifications would be helpful to adjust water allocation plans and refine water distribution schedules in the early irrigation season (Oberkircher, 2010).

Calculations of CWR and CIR are usually based on the crop specific reference evapotranspiration (ET_c, Allen et al., 1998). It can be obtained at different levels of detail via crop coefficients based on agro-meteorological data, soil and plant information e.g. as implemented in the CropWat model designed by the FAO (Smith et al., 1996). For mapping extensive areas, this approach has been frequently linked with remotely sensed crop maps. Rao et al. (2001) analyzed the CIR of different crops using Landsat-TM 5 satellite images with a spatial resolution of 30 m for crop mapping and the CropWat model for CWR assessments. Casa et al. (2009) utilized a similar approach for mapping CWR in central Italy based on a crop map from four Landsat ETM+ images. Also the field based approach has been supplemented with remote sensing information. Er-Raki et al. (2010) derived multi-temporal vegetation indices using a handheld spectrometer for simulating spatially distributed ET_c on experimental sites in Morocco. Extrapolations to multi-temporal Landsat TM spectral data were investigated by D'Urso and Menenti (1995). Thermal Landsat observations were included into CWR estimations e.g. by El-Magd and Tanton (2005) in the Kyzyl-Orda region of Kazakhstan. Thermal information also enables the calculation of ET_c solely based on remote sensing data (Tasumi and Allen, 2007; Ahmed et al., 2010; El Nahry et al., 2011). However, the fact that multi-temporal thermal data covering a complete vegetation period with spatial resolution suitable to match the field sizes are rare limits the derivation of ET_c in the different growth phases (Casa et al., 2009).

This study aims at quantifying and assessing irrigation water use for cotton and wheat in the Fergana Valley by combining crop classifications with calculations of CWR and CIR. Methodological focus is set on early season mapping of the major crops, as accurate maps already before main irrigation phases are seen as one option to save water as they allow for within-season adjustments of water allocation plans. Thus, bi-temporal 6.5 m RapidEye data acquired in May and June 2010 and one Landsat TM5 scene recorded in early July 2010 were utilized. Due to the unavailability of digital cadaster maps, field boundaries were derived via segmentation of RapidEye data. The widely used 'random forest' algorithm is selected for classifying crop distribution. CWR and CIR assessments are conducted with CropWat based on meteorological data from ClimWat data base and local knowledge. The results are discussed in the light of water saving options and potentials for increasing water use efficiency in the Fergana Valley.

2. Study area

The Fergana Valley, situated in the south-eastern part of Uzbekistan (Fig. 1) is bordered by two mountains, the Tien Shan in the north and the Alai in the south (Filcak, 2008). The climate can be classified as continental with 100–200 mm average annual precipitation and a potential evapotranspiration of up to 1300 mm (Umarov et al., 2010). The average temperature in the valley ranges from −3.9 °C to 3.9 °C in January to 20.2 °C to 34.7 °C in July (Table 4).

The Fergana Valley forms the upper to mid-reach of the Syrdarya basin. It generates almost 70% of the valleys surface water and his tributaries Naryn and Karadarya. The river's nourishment is classified as mixed snow-glacial and is formed in the surrounding mountains (Savoskul et al., 2003).

The Fergana Valley is one of the most important areas for agriculture in Central Asia (Abdullaev et al., 2009a). It represents one large-scale cotton production system of the former Soviet Union, with 1.653 million ha irrigated land (including homesteads: 193 ha, SIC-ICWC, 2011). Around 70% of the 11,342,000 inhabitants (Reddy et al., 2012) still depend on income from the agricultural sector and agriculture contributes approximately 24% to the country's gross domestic product (Bichsel, 2009).

The Uzbek part of the Valley consists of three provinces (Oblasts): Fergana, Namangan and Andijan, of which about 1 million ha is under