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THEMATIC ISSUE

Water consumption of agriculture and natural ecosystems at the Amu Darya in Lebap Province, Turkmenistan

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Abstract The Amu Darya River is the major water source for Turkmenistan contributing 88 % to the total amount of surface water available to the country. Lebap Province harbours oases and natural riparian vegetation along the Amu Darya River. In the oases, cotton, wheat, and corn as well as fruit and vegetables are grown under irrigation. While cotton was strongly promoted during Soviet Union times, the wheat area was enlarged after independency of Turkmenistan, in order to secure food self-sufficiency. In the literature, a very high crop water requirement has been reported for cotton in Turkmenistan. In this paper, the objective is to investigate the consumptive water use, i.e. actual evapotranspiration, of the major crops cotton, wheat, and corn, the household plots, and the natural vegetation within Lebap Province of Turkmenistan. Actual evapotranspiration (ET_a) was mapped from Landsat satellite images for the vegetation seasons 2009 and 2010. Additionally, reference ET (ET_o) and crop ET (ET_c) were calculated. ET_a for riparian (Tugai) forests and *Tamarix* shrubs was 907–1,043 and 239–259 mm, respectively. ET_a for the mapped crops cotton, wheat, rice, and gardens was 485–658, 156–350, 685–935, and 416–615 mm, respectively. ET_o was 929 and 979 mm in 2009 and 2010, respectively. ET_c for cotton and rice was 896 mm in 2009 and 925 mm in 2010 and 1,085 mm in 2009 and 1,198 mm in 2010, respectively. The low ET_a values are explained partly by under-estimation through the method applied, partly by low yields of the crops. There is a big gap between the amount of water taken up from the Amu Darya and the water really consumed by the irrigated crops. This low water use efficiency might be due to water losses from channels and high amounts of water needed for soil preparation, i.e. leaching of salts.

Keywords Irrigation · Cotton · Riparian forest · Aral Sea Basin · Central Asia · Remote sensing

Introduction

The Amu Darya River is the major water source for Turkmenistan, since 88 % of all surface water resources in this country stem from the Amu Darya. The river length of the Amu Darya on the territory of Turkmenistan is 744 km. Thereby, the Amu Darya flows through the provinces Lebap and Dashagouz (Fig. 1). The other provinces of Turkmenistan receive water from the Amu Darya through the Karakum Channel, which branches off in Atamyrat, Lebap. Under the arid climate of that region, all agriculture depends on irrigation (Rapajov 2002; Stanchin and Lerman 2005) with the Amu Darya and the Karakum Channel being the major water sources. The headwaters of the Amu Darya lie outside the country, i.e. in Tadzhikistan, Kyrgyzstan, and Afghanistan. Together with Kazakhstan and

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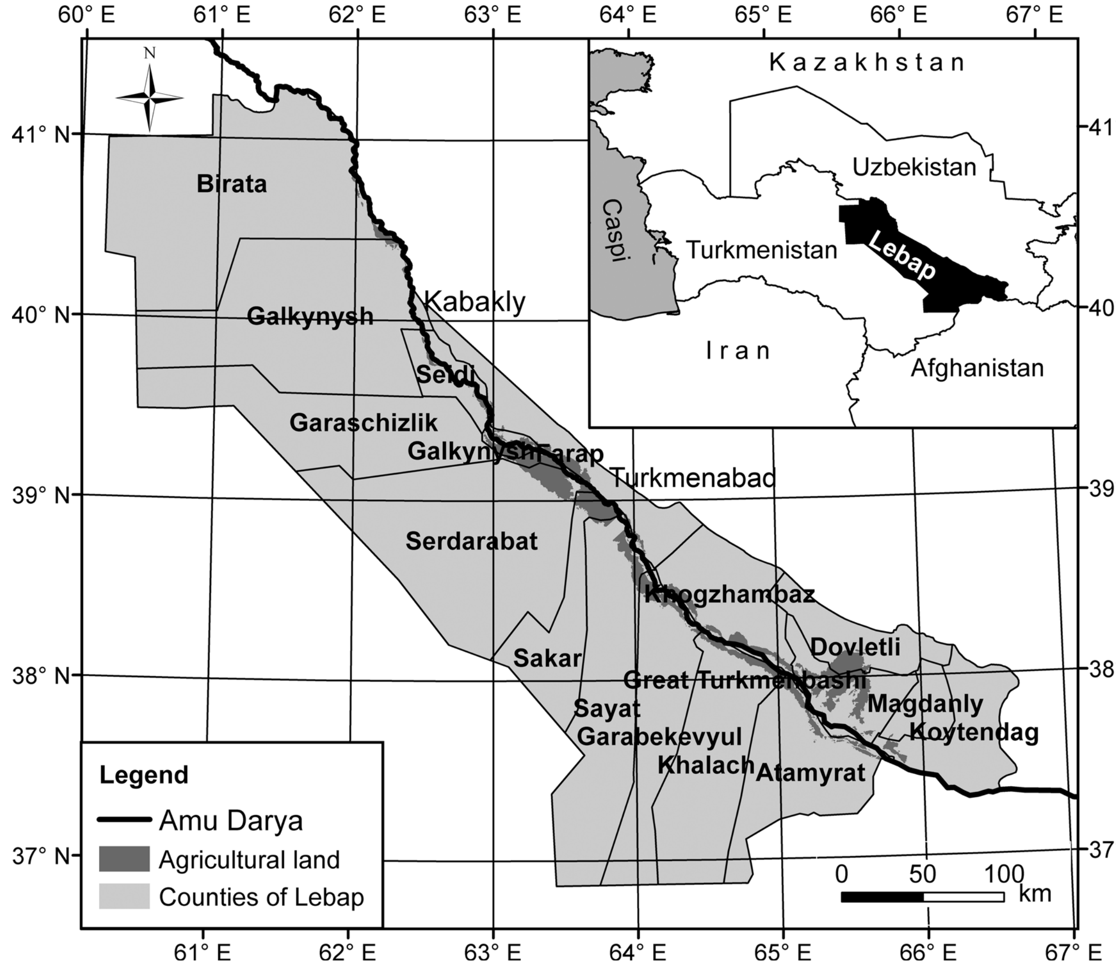

Fig. 1 Map of Lebap Province with its counties and distribution of agriculture

Uzbekistan, Turkmenistan belongs to the countries in Central Asia which lie downstream from the headwaters and whose water consumption exceeds their own water resources (Abdolvand et al. 2014) and which are very vulnerable to climate change and decisions on water management upstream outside their country's borders (Lioubimtseva 2014). The disputes and conflicts between countries due to this situation are analysed by Abdolvand et al. (2014), while Janusz-Pawletta (2014) analyses the development of governance of the transboundary water resources in Central Asia. It is expected that river runoff will decrease in the course of climate change, while water demand will increase, which will aggravate the competition for water between countries as well as different water users like agriculture, industry and settlements, and natural ecosystems (Palmer et al. 2008; Groll et al. 2014). Furthermore, after the collapse of the Soviet Union the operation mode of water reservoirs upstream in Kyrgyzstan and Tadzhikistan was changed (Rakhmatullaev et al. 2013). During Soviet Union times, the reservoirs were operated to release water during the irrigation period. After independence, the water from some reservoirs in Kyrgyzstan and Tadzhikistan has been released in winter, in order to generate electricity. A similar competition for scarce water resources is also found in the Tarim Basin, Xinjiang, China (Feike et al. 2014). Against this background, it is necessary to understand the current water consumption, in order to be able to indicate possible options to reduce water consumption.

Turkmenistan is entitled to withdraw annually 22 km^3 of water from the Amu Darya (Rapajov 2002; FAO 2013; http://www.icwc-aral.uz/). In 2010, 4.9 km^3 were diverted from the Amu Darya in Lebap Province (pers. comm. 2012). Thereby, 90 % of the water diverted off the Amu Darya are used for irrigation (Stanchin and Lerman 2005; FAO 2013). Additional groundwater exploitation plays a minor role (Rakhmatullaev et al. 2010). The major crops grown in Lebap are cotton, wheat, and corn. Cotton was strongly promoted during Soviet times (Glantz 1999), while after independency the wheat area was expanded, in order to become food self-sufficient (Ovezberdyyeva 2009). Now, in whole Turkmenistan wheat is planted on

917,000 ha, followed by cotton, which is planted on 652,000 ha (FAO 2013). The recent development in Turkmenistan is similar to other river basins in Central Asia in terms that crop land area has been increased until now and cotton is one of the a major crops (Feike et al. 2014).

Agricultural land is leased to farmers from the government. Farmers, i.e. leaseholders have to plant cotton, wheat, or corn, depending on State orders. The inputs needed, e.g. seeds and fertilizer, are provided by governmental agencies at fixed prices. Water is allocated centrally and provided to farmers for free. On the so-called household plots, farmers grow vegetables and fruit for their own consumption or for the market without State orders (Stanchin and Lerman 2003; FAO 2013).

The consumptive use of water is the evapotranspiration (ET) of a certain crop or vegetation. The crop evapotranspiration (ET_c) can be calculated with the FAO Penman–Monteith equation (Allen et al. 1998), if meteorological data, i.e. radiation, temperature, air humidity, and wind speed, and crop coefficients are known. ET_c calculation requires a certain density of climate stations and access to these meteorological data. With the FAO Penman–Monteith equation (Allen et al. 1998) a so-called reference ET (ET_o) is calculated. ET_o is the evapotranspiration of a well watered 12 cm short grass vegetation. This ET_o can be converted into ET of certain crops (ET_c) by multiplying ET_o with the relevant crop coefficient (K_c). These crop coefficients refer to well-managed crops without water or other stress (Allen et al. 1998). Alternatively, the actual ET (i.e. ET_a), also from water stressed crops or vegetation without known crop coefficients, can be determined through climate station data using the Bowen ratio method (e.g. Malek and Bingham 1993; Minderlein and Menzel 2013), lysimeters (e.g. Zheleznyh and Risbekov 1987; Sammis 1981), eddy co-variance measurement devices (e.g. Cleverly et al. 2002), or as residual of the water balance equation (e.g. Reddy et al. 2012). These methods measure ET_a at a specific point but do not cover large or remote areas (Kalma et al. 2008).

In order to overcome this limitation, methods have been developed to estimate input parameters needed for the ET_c calculation from remote sensing data as widely discussed by D'Urso (2010). The Penman–Monteith equation (Allan et al. 1998) was rearranged in a way that albedo and leaf area index (LAI) become input factors, which can be assessed from remote sensing data. Wind speed, air temperature, and air humidity still need to be provided from climate stations. Furthermore, relationships between crop coefficients and the normalized vegetation index (NDVI) were developed (D'Urso 2010).

Another group of algorithms has been developed, which maps the actual ET_a on the basis of the thermal channel of satellite images (i.e. Landsat, MODIS, or ASTER), e.g. surface energy balance algorithm (SEBAL) after Bastiaanssen (1995); Bastiaanssen et al. (2002, 2005), mapping evapotranspiration with internalized calibration (METRIC) after Allen et al. (2005), surface energy balance system (SEBS) after Su (2002), and simplified surface energy balance index (S-SEBI) after Roerink et al. (2000), Sobrino et al. (2005, 2007), as reviewed by Gowda et al. (2007, 2008). The former approaches require climate data from not-water-stressed vegetation. As we were not able to obtain climate data from vegetation, which was never water stressed through the study period, we decided to follow the S-SEBI approach as it does not need climate data as input data.

In contrast to the sheer ET_a, crop water requirement refers to the amount of water, which is needed to cover the deficit between evapotranspiration of a certain crop and precipitation, plus the amount of water, which is lost from channels or needed for soil preparation (FAO 2013). The crop water requirement of cotton for Turkmenistan is given with 1,025 mm per season (Chapagain et al. 2006). Thus, Chapagain et al. (2006) calculated a virtual water content of 6,010 m^3/t seed cotton for Turkmenistan, while the world's average only was 3,644 m^3/t seed cotton.

This paper aims at investigating the consumptive water use of cotton, wheat, corn, household plots, and the natural vegetation within Lebap Province of Turkmenistan. The actual evapotranspiration is mapped through remote sensing after the S-SEBI approach (Roeringk et al. 2000), in order to retrieve ET_a data from the whole Lebap Province.

As the natural riparian vegetation of the Amu Darya within Turkmenistan and the major crops of the country are represented in the area of Lebap, this province was chosen for this study. Along the Amu Darya in Lebap, remnants of the natural riparian vegetation, i.e. Tugai vegetation, are distributed mainly on river islands and accreting slopes of the river. Part of the Tugai vegetation lies within the Amu Darya State Reserve, e.g. the core zone Kabakly, which comprises Tugai forests and Tugai shrub vegetation. The term Tugai refers to riparian vegetation of Central Asia. This vegetation consists of forests, i.e. Tugai forests, reed beds, and shrub vegetation. The Tugai forests are dominated by the tree species *Populus euphratica*. The reed beds are *Phragmites australis* stands, while the shrub vegetation is dominated by *Tamarix* species and halophytes such as *Halostachys caspica* or *Halocnemum strobilaceum*.

Study region

The study region is the province (Velayat) Lebap in the northwest of Turkmenistan, which is shown in Fig. 1. Most

Table 1 Climate data of Turkmenabad (N39.05° E063.36°, elevation 192 m above sea level), 25-year average

Climate feature	Value
Annual average air temperature	15.5 °C
Average January air temperature	1 °C
Average July air temperature	29.3 °C
Annual average precipitation	129.5 mm
Annual average relative air humidity	54.7 %
Annual average wind speed	3.1 m/s

of the area of Lebap lies in the Karakum Desert. Only along the Amu Darya River, which flows through the entire length of Lebap from southeast to northwest, agriculture and riparian, i.e. Tugai, vegetation is distributed.

The climate is arid and continental as shown in Table 1 (www.weatherbase.com). Under such arid climate conditions, agriculture depends on irrigation, while most species of the riparian Tugai vegetation are adapted to exploit the groundwater (Gries et al. 2003; Thomas et al. 2006; Thevs et al. 2008).

Monthly air temperature, relative air humidity, and wind speed measured at the climate station Kabakly (cf. methods section underneath) from 2009 to 2010 follow the trends of Turkmenabad (Fig. 2). The climate station Turkmenabad is located at the airport, which may explain the higher wind speed compared to Kabakly.

Like in other river basins of Central Asia, e.g. the Tarim Basin, the major source of irrigation water here is the Amu Darya. The Amu Darya also refills the groundwater layer, from which the natural vegetation takes up water (cf. Hou et al. 2007, Chen et al. (2014) and Tayierjiang et al. (2014), both submitted to this volume for the Tarim River). The Amu Darya carries water all year round with annual summer floods in the period from May to August. The average annual runoff at Kerki, i.e. where the Amu Darya enters Turkmenistan, was 45.9 km^3 from 1988 to 2007 with a maximum of 64.4 km^3 in 1998 and a minimum of 28 km^3 in 2001. The largest average monthly runoff during this period was measured in July with 14.4 km^3 (pers. comm. Bakhtiyarov 2006).

The major crops grown in Lebap are cotton, wheat, corn, and rice. Cotton and rice are planted during April and harvested during late summer and autumn. Wheat is grown as winter wheat, i.e. it is planted during September and harvested in June of the following year. On a part of the wheat fields, corn is planted as second crop right after the wheat harvest. Corn is harvested in September and October (Ovezberdyyeva 2009).

The natural vegetation along the Amu Darya is a mosaic of riparian forests, reed beds, and shrub vegetation. This vegetation is called Tugai vegetation (Treshkin 2001; Ogar 2003). The Tugai forests are dominated by *P. euphratica* as tree species. Tugai forests on sites with high groundwater level (not deeper than 3 m) have an understory vegetation of *P. australis, Apocynum venetum, Glycyrrhiza glabra, Halimodendron halodendron* (Ogar 2003; Thevs et al. 2008). With deeper groundwater levels, the understory vegetation becomes sparser and also the tree density and crown coverage of *P. euphratica* decreases. The Tugai forests are distributed in a mosaic together with reed beds and shrub vegetation. The reed beds are built by *P. australis*. The shrub vegetation is dominated by *Tamarix* species, which often are distributed further away from the river course on sites with deeper groundwater levels. Such Tugai vegetation complexes mainly are distributed on accreting slopes in the inner curves of the Amu Darya or on river islets.

In 1982, the Amu Darya State Reserve was established, in order to protect Tugai forests and other Tugai vegetation from logging and grazing. Today, one core zone is located in Kabakly, i.e. the northern part of Seydi County (Ministry of Nature Protection of Turkmenistan 2002). There, Tugai forests next to the river course of the Amu Darya on groundwater levels of 2 m have a tree density of more than 850 trees per hectare and a standing biomass of up to 58.4 t/ha (Thevs et al. 2012). Tugai forests more than half a kilometre away from the Amu Darya River have tree densities of <700 trees per hectare and a standing biomass

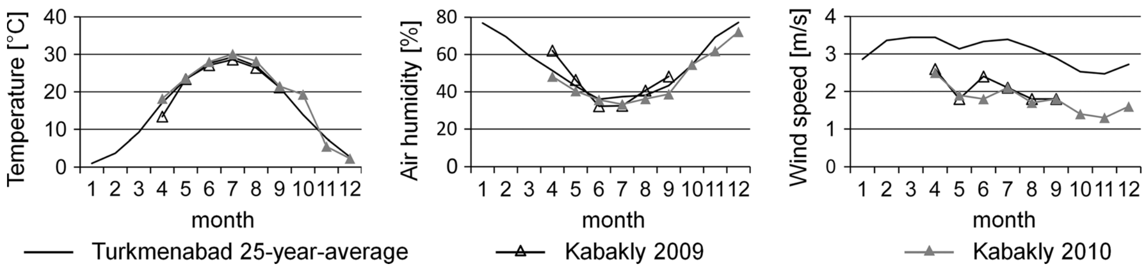

Fig. 2 Monthly average air temperature (*left*), relative air humidity (*centre*), and wind speed (*right*) from Turkmenabad (25-year average) and Kabakly 2009 and 2010. Data for Turkmenabad were taken from (www.weatherbase.com), while data from Kabakly were recorded by a climate station established within this study

Table 2 Counties by Landsat image path and row coverage

Landsat image path/row	Counties covered
156/034	Koytendag, Atamyrat, Magdanly, Khalach, Khogzhambaz, Dovleti, Great Turkmenbashi
157/033	Garabekevyul, Sayat, Sakar, Serdarabat, Farap, Galkynysh (southern part), Garaschilik
158/032	Seydi, Galkynysh (northern part), Birata

Table 3 Landsat images used for the supervised land-cover classification

Path/row	Image date	Day of the year (DOY)
156/034	2010-04-16	106
156/034	2010-06-03	154
156/034	2010-09-07	250
157/033	2010-04-25	115
157/033	2010-07-14	195
157/033	2010-10-02	275
158/032	2010-04-23	113
158/032	2010-07-12	193
158/032	2010-09-14	257

of 26.5 t/ha and less (Thevs et al. 2012). Later in this text, the former and latter Tugai forest is referred to as Tugai forest 1 and 3, respectively.

The river oases and the Tugai vegetation within Lebap Province are covered by three Landsat scenes with the path and row: path 156 row 34, path 157 row 33, and path 158 row 32. In Table 2, the Landsat scenes and the counties covered by each scene are listed.

Methods

Land-cover mapping

The land-cover mapping of Labap Province was performed for 2010 through a supervised classification of Landsat 5 satellite images. Landsat 5 was chosen, in order to avoid the strips of empty pixels as delivered by Landsat 7 after May 2003 due to the Scan Line Corrector failure (SCL-off). In a first step, the areas with agriculture and villages were digitized manually into two shape files. Afterwards, for each of the three Landsat scene, which cover Lebap Province, an image from May, July, and September 2010 were selected, respectively (Table 3). The near infrared (NIR) and visible red (RED) channel of each of these three images were grouped together and undergone a supervised classification. Thus, a time series was classified (cf. Fiorentino et al. 2010). The ground truth data were representative fields of cotton, wheat, wheat-corn, fallow, rice, open water, and reed. The supervised classification, as well as all other image processing, were done with the software package GRASS-GIS 6.4.2. Maps presented in this study were made with ArcGIS 9.3.

Evapotranspiration mapping

In this paper, the actual evapotranspiration (ET_a) of the agricultural land and the natural vegetation along the Amu Darya River in Lebap Province was mapped for the vegetation seasons 2009 and 2010, in order to retrieve the amounts of water consumed by irrigation agriculture and natural vegetation. The vegetation seasons were defined as the time span from 1st of April to 31st of October in each year, because cotton, as the major crop in the study area, is planted at the beginning of April and harvested until end of October. *P. euphratica,* as one dominant species of the natural vegetation, flowers in April, while leaves shoot in Mai and fall until end of October. In November, the daily average temperatures fall below 10 °C. Only in April, daily average temperatures rise above 0 °C with night frosts occurring until March (www.weatherbase.com). Therefore, for this study the ET_a for this vegetation seasons was used as the annual ET_a for cotton, rice, and the natural vegetation. For wheat, the ET_a from 15th of September until 31st of October 2009 and 1st of April 2010 until 15th of June 2010 was used, while for wheat-corn the ET_a from 15th of September until 31st of October 2009 and 1st of April 2010 until 31st of October 2010 was used. In this study, the ET_a was mapped from Landsat 5 and Landsat 7 satellite images.

On the basis of the S-SEBI, developed by Roerink et al. (2000), the latent heat flux can be calculated as:

$$\mathrm{LE} = \Lambda(R_n - -G) \tag{1}$$

with LE, Λ, R_n, and G being latent heat flux (W/m^2), evaporative fraction, net radiation (W/m^2), and soil heat flux (W/m^2), respectively. When calculating daily values instead of instantaneous values, the daily sum of the soil heat flux is set to zero (Sobrino et al. 2005, 2007) so that the Eq. 1 is simplified for daily values:

$$\mathrm{LE}_d = \Lambda_d R_{nd} \tag{2}$$

with LE_d, Λ_d, and R_{nd} referring to daily latent heat flux sum (MJ), daily evaporative fraction, and daily net radiation sum (MJ).

If the daily net radiation (R_{nd}) is converted into evapotranspiration, i.e. potential evapotranspiration (ET_{pot}), ET_a, can be calculated as follows (Senay et al. 2007):

$$\mathrm{ET_a} = \Lambda\,\mathrm{ET_{pot}} \tag{3}$$

We estimated R_{nd}, and thus also ET_{pot}, on the basis of day of the year (DOY), latitude, transmissivity of the atmosphere, land surface temperature, and albedo, applying the module i.evapo.potrad (http://grasswiki.osgeo.org/wiki/AddOns/GRASS_6#GIPE) of the software package GRASS-GIS 6.4 (http://grass.fbk.eu/). The albedo was calculated from the six Landsat channels according to the Landsat 7 Science Data Users Handbook (http://landsathandbook.gsfc.nasa.gov/pdfs/Landsat7_Handbook.pdf). The thermal channels of Landsat 7 and Landsat 5, respectively, were converted into Kelvin after Landsat 7 Science Data Users Handbook, too. The transmissivity was estimated from the data of a climate station set up in Kabakly (Fig. 1). Therefore, the daily extraterrestrial radiation R_a was calculated for the position of the climate station (Allen et al. 1998) and the transmissivity was calculated as:

$$t = \frac{R_s}{R_a} \tag{4}$$

with t, R_a, and R_s being the transmissivity, extraterrestrial radiation, and incoming solar radiation measured at the climate station, respectively. As the data series recorded by the climate station were interrupted for a number of days during the vegetation periods 2009 and 2010, transmissivity values could not be calculated for every Landsat image included into this study. Therefore, the mean of all transmissivity values from the vegetation seasons 2009 and 2010, i.e. 0.6, was used to calculate $\mathrm{ET_{pot}}$ for both years 2009 and 2010.

The evaporative fraction (Λ) is the part of the $\mathrm{ET_{pot}}$, which is realized as $\mathrm{ET_a}$. Thus, over a well-watered vegetation, e.g. wetland vegetation, we can assume $\Lambda \approx 1$ and $\mathrm{ET_a} \approx \mathrm{ET_{pot}}$. The land surface temperature is low, because the net radiation is consumed by evapotranspiration. In contrast, at places without any vegetation or other moisture Λ and $\mathrm{ET_a}$ are zero. Here, the land surface temperature is high, because the net radiation goes into the sensible heat flux. Between these two extremes it is assumed that Λ and land surface temperature have a linear relationship (Roerink et al. 2000; Senay et al. 2007).

The evaporative fraction is calculated as follows:

$$\Lambda = \frac{\mathrm{TH} - \mathrm{Tx}}{\mathrm{TH} - \mathrm{TC}} \tag{5}$$

thereby, TH, TC, and Tx refer to the land surface temperatures at the hot pixel, cold pixel, and pixel, for which Λ is calculated, respectively. Cold pixels were chosen from wetlands with dense reed vegetation interrupted by small open waters, which do not fall dry during the vegetation season. Hot pixels were selected from areas free of vegetation but lying adjacent to the riparian vegetation or irrigated fields. At the hot pixels, $\Lambda = 0$ and $\mathrm{ET_a} = 0$. Thus, all the radiation is converted into sensible heat flux so that the land surface temperature is high. For each day, for which a Landsat 7 or Landsat 5 scene was available, a daily $\mathrm{ET_a}$ map was produced. These $\mathrm{ET_a}$ maps were linearly interpolated and summed to $\mathrm{ET_a}$ maps for the vegetation season and seasons of wheat and wheat-corn, respectively.

In Kabakly, a climate station was operated, in order to calculate $\mathrm{ET_a}$ and to validate the Landsat $\mathrm{ET_a}$. Furthermore, $\mathrm{ET_o}$ and $\mathrm{ET_c}$ of reed swamp, cotton, and rice were calculated from data of this climate station after Allan et al. (1998). The climate station was located on the ground of the ranger station in Kabakly due to security reasons, i.e. at the edge of the riparian forest. The climate station was equipped with sensors for incoming and outgoing radiation (pyranometers CMP3, Kipp & Zonen) and ventilated air temperature/humidity sensors in two different heights so that $\mathrm{ET_a}$ was calculated with the Bowen ratio method (Malek and Bingham 1993). One air temperature/humidity sensor was mounted 2 m above soil surface, while the other sensors were mounted 10 m above surface. Electricity supply came from 12 V car accumulators, which were charged by the nearby ranger station.

Retrieve $\mathrm{ET_a}$ of irrigated agriculture and natural vegetation

In 2009, a Quickbird satellite image was purchased, which covers the core zone Kabakly of the Amu Darya State Reserve and adjacent areas with Tugai vegetation and irrigated fields. In the area covered by this Quickbird satellite image, field visits could be conducted in 2009 and 2010 (Ovezberdyyeva 2009; Thevs et al. 2012), during which farmland was visited and forests were investigated. Within this study, daily $\mathrm{ET_a}$ and $\mathrm{ET_a}$ of the vegetation seasons was recorded at randomly picked points in the following land-cover types: Tugai forest adjacent to the Amu Darya (Tugai forest 1 and 3), Tugai forests further than half a kilometre from the river (Tugai forest 2 and 4), Tugai shrub, reed, and cotton.

Furthermore, the mean $\mathrm{ET_a}$ values for each land-cover class from each county, respectively, were inferred from the $\mathrm{ET_a}$ maps. Thereby, the $\mathrm{ET_a}$ of the vegetation season 2010 was inferred, except for wheat and wheat-corn, as explained above in the previous section.

Results

Land-cover classification

Within the agricultural land, wheat covers the largest area with 1,455.2 km^2 in 2010, followed by cotton and fallow with 1,196.3 and 482.5 km^2, respectively. Gardens, fields with wheat followed by corn, and rice only cover 133.7, 182.4, and 3.3 km^2, respectively (Table 4). Reed-dominated Tugai vegetation only covers 395.4 km^2, while Tugai-dominated by forests and shrubs cover 2,169.2 km^2.

Evapotranspiration mapping

At the climate station, during the vegetation seasons 2009 and 2010 an ET_a of 711 and 694 mm was measured, respectively (Table 5). The Landsat ET_a only was 588 mm in 2009 and 636 in 2010 mm at the position of the climate station.

In the vicinity of Kabakly, the highest ET_a was found on dense Tugai forests, i.e. Tugai forest 1 and 3 (Table 4) ranging from 907 to 1,043 mm. The mean ET_a of reed pixels was 711 and 882 mm in 2009 and 2010, respectively. Though, the ET_a of reed pixels ranged from 979 to 499 mm in 2009 and 1,172 to 681 mm in 2010, showing a much higher standard deviation than the other land covers listed in Table 6. These maxima of the ET_a of reed are the same range as the ET_c calculated for reed given in Table 5. Tugai shrub only showed ET_a values of 239 and 259 mm in 2009 and 2010, respectively. The mean ET_a of cotton is surprisingly low with only 528 mm in 2010 (Table 6).

Looking at the ET_a development during the vegetation season, the ET_a of the natural vegetation types listed in Table 6 increases during spring until summer and decreases over time during autumn. In contrast, the ET_a of cotton remains low during spring until beginning of June and increases sharply during June. Like the others, it decreases during autumn (Fig. 3).

The ET_a mean values by county and by land cover for 2010 are given in Table 7. ET_a of cotton ranges from 485 mm (in Seydi) to 658 mm (in Koytendag). Thereby, there is a decreasing trend from upstream, e.g. Koytendag and Dovleti, towards downstream, e.g. Seydi and Birata. These ET_a values are well below the ET_c of cotton of 870 and 925 mm in 2009 and 2010, respectively (Table 5). The ET_a values for wheat-corn range from 876 to 533 mm, also with the lowest values downstream in Birata. Rice is only grown on a small area in the three counties Galkynysh, Seydi, and Birata with ET_a values of 685, 823, and 935 mm, respectively (Table 7). The ET_c calculated for rice was 1,085 mm for 2009 and 1,198 mm for 2010 (Table 5).

The ET_a of reed-dominated Tugai vegetation is between 1,094 and 600 mm, while the ET_a of forest and shrub-dominated Tugai ranges from 967 to 308 mm. The ET_a values of the natural vegetation do not show any trend from upstream to downstream (Table 7).

Table 4 Areas of land-cover classes, i.e. land use and natural vegetation, in 2010 in Lebap Province, Turkmenistan, after classification of Landsat satellite images

Land cover	Area (ha)
Agriculture	345,340
Fallow land	48,250
Cotton	119,630
Wheat followed by corn (wheat-corn)	18,240
Wheat	145,520
Rice	330
Gardens	13,370
Riparian vegetation reed-dominated	39,540
Riparian vegetation forest and shrub-dominated	216,920

Table 5 ET_o and ET_a at the climate station Kabakly and ET_c of cotton, rice, and reed swamp based on the ET_o of Kabakly for 2009 and 2010

ET_o, ET_a, and ET_c, respectively (mm)	2009	2010
ET_o	926	979
ET_a climate station	711	694
ET_c reed swamp	1,077	1,125
ET_c cotton	869	925
ET_c rice	1,085	1,198

Table 6 ET_a of the vegetation seasons 2009 and 2010 of the riparian vegetation and cotton around Kabakly

Type of vegetation/ land cover	ET_a vegetation season 2009 (mm)	ET_a vegetation season 2010 (mm)
Tugai forest 1	948 ± 34 (15)	1,043 ± 67 (15)
Tugai forest 2	613 ± 140 (10)	842 ± 86 (10)
Tugai forest 3	907 ± 45 (5)	1,000 ± 63 (5)
Tugai forest 4	566 ± 69 (7)	910 ± 27 (7)
Tugai shrub	239 ± 42 (3)	259 ± 14 (3)
Reed	711 ± 204 (6)	882 ± 208 (6)
Cotton		528 ± 77 (29)

Mean ± standard deviation, in brackets number of pixels

Discussion

In 2010, wheat was grown on an area of 163,760 ha in Lebap Province, followed by cotton, which was planted on 119,630 ha (Table 3). This ratio between wheat and cotton is nearly the same as reported for the whole country (FAO 2013).

At the climate station Kabakly, the evapotranspiration mapped from Landsat is lower than the ET_a calculated from the climate station data. This deviation can be explained by the location of the climate station. The climate station had to be located next to a small group of *P. euphratica* trees. Therefore, the climate station represents

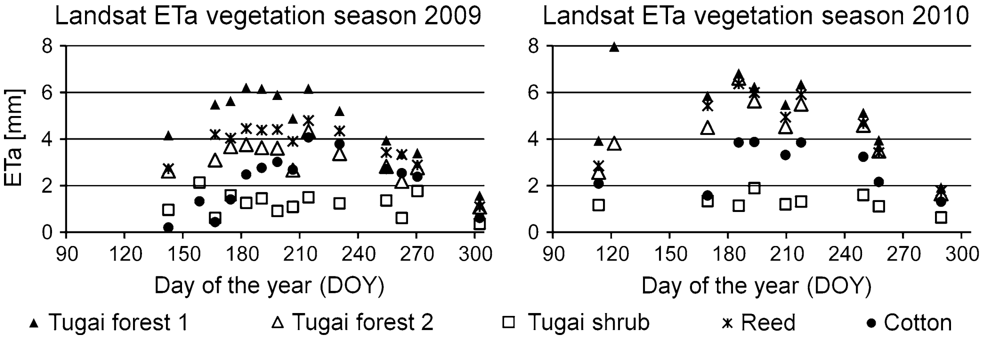

Fig. 3 Mean ET_a of Tuga forest 1, Tugai forest 2, Tugai shrub, reed, and cotton within the extent of the Quickbird satellite image during the vegetation seasons 2009 and 2010

Table 7 ET_a of cotton, wheat-corn, wheat, rice, gardens, reed-dominated Tugai, and forest-dominated Tugai for the vegetation season and planting season 2010 by county

County	Cotton	Wheat-corn	Wheat	Rice	Gardens	Reed Tugai	Forest Tugai
Koytendag	658	744	294		607	918	730
Magdanly			216				
Dovleti	617	793	266		596		
Great Turkmenbashi	597	757	278		607	733	625
Atamyrat	624	870	297		615	1,094	630
Khalach	620	863	318		595	771	308
Khogzhambaz	595	846	281		595	834	841
Garabekevyul	530	745	274		508	771	705
Sayat	530	677	307		512	600	663
Sakar	546	738	329		538	827	707
Farap	526	709	314		555	832	602
Serdarabad	542	756	350		566	980	639
Garaschilik	565	829	328		556	828	809
Galkynysh-S	575	876	327		535	739	735
Seidi	485	567	286	823	416	803	805
Galkynysh-N	566	565	156	685	423	962	875
Birata	542	533	262	935	431	1,063	967

The vegetation season has been defined to last from 1st of April (DOY 91) to 31st of October (DOY 304) 2010. For wheat-corn the season was defined as 15th of September (DOY 258) to 31st of October (DOY 304) 2009 and 1st of April (DOY 91) to 31st of October (DOY 304) 2010, while for wheat the season was defined as 15th of September (DOY 258) 2009 to 31st of October (DOY 304) 2009 and 1st of April (DOY 91) to 15th of June (DOY 166) 2010. Empty cells in the Table are due to the land cover in the different counties, e.g. rice is only planted in Seydi, Galkynysh-N, and Birata

these trees, while the corresponding Landsat pixel includes a certain area bare of vegetation. Therefore, the ET_a of this whole Landsat pixel is reduced. Additionally, the oasis effect might also contribute to this deviation. Oasis effect means that heat advection from nearby desert areas enhances evapotranspiration without decreasing the land surface temperature as recorded by the Landsat satellite.

The evapotranspiration mapped for the Tugai forests adjacent to the Amu Darya in this study, i.e. 907–1,043 mm (Table 6), is nearly as high as the ET_a of Tugai forests investigated in Khorezm, Uzbekistan, by Khamzina et al. (2009), i.e. 1,030–1,250 mm, and is in the same range as Tugai forests mapped along the Tarim River in Xinjiang by Thevs et al. (2013), i.e. 798–1,115 mm. The ET_a of reed found in this study (Table 6) of 711 and 882 mm is lower than Tugai forests and also lower than ET_a of permanently watered wetlands along the Tarim River, i.e. 1,687–1,790 mm (Thevs et al. 2013). This can be explained as the reed stands considered in this study are small so that the Landsat pixels partly cover adjacent fields or other vegetation with lower ET_a. The ET_a of shrub vegetation found in this study, i.e. 238 and 259 mm (Table 6), is slightly higher than the ET_a of *Tamarix* stands investigated by Thomas et al. (2006), which ranged from 92 to 180 mm. This difference can be explained by the different geographical settings between the sites. The shrub vegetation considered in Table 4 is about 1.5 km away from the main course of the Amu Darya. During flood season, submerged areas are only 500 m away from these shrub sites. In contrast, the *Tamarix* stands investigated by Thomas et al. (2006) are much further away from the next river, and that river very rarely carries floods in the vicinity of these *Tamarix* stands.

The ET_a of cotton is in the same range as the norms for water consumption from Soviet times are 550–600 mm (Nechaeva and Nikolayev 1962) and as reported by Mukhamedjanov and Mukhamedjanov (2014). But, ET_a of cotton of this study is low compared to ET_c of cotton, i.e. 869 and 926 mm in 2009 and 2010, respectively (Table 5), the actual evapotranspiration of 807 mm measured with a lysimeter near Tashkent (Zhelesnyh and Risbekov 1987), or the ET_a of cotton of 1,100 mm, mapped from MODIS satellite images, along the Tarim River in Xinjiang, China (Thevs et al. 2013). Xinjiang attains very high cotton yields, i.e. up to 2 t lint cotton per ha (Xinjiang Statistics Bureau 2012), being equivalent to 6 t seed cotton per ha (unpublished data from farm interviews), while the seed cotton yield in Turkmenistan only is 1.7 t/ha (Kim 2012). Therefore, the low ET_a of cotton in Lebap partly might go along with water-stressed plants or fields on which the crop is partly lost, both resulting in low yields. The cotton yields from the lysimeter experiment (ET_a of 807 mm) near Tashkent were up to 3.1 t/ha seed cotton (Zhelesnyh and Risbekov 1987). As the crop coefficients from Allen et al. (1998) have been developed for well-watered and well-managed crops, the ET_c here is higher than the ET_a. Furthermore, the low ET_a of cotton partly might be also explained, because it is underestimated during spring time. At the beginning of the vegetation season, i.e. April and May, the daily ET_a of cotton was near to zero or even negative. Such ET_a values apparently are too low and reduce the ET_a summed up for the whole vegetation period.

Similar to cotton, the low ET_a of wheat and rice might be explained by water stressed plants corresponding with low yields. Wheat and rice yields in 2010 were 3.53 and 2.42 t/ha, respectively. The former is high compared to the average of whole Central Asia, i.e. 1.31 t/ha, but lower than neighbouring Uzbekistan, i.e. 4.59 t/ha (FAOSTAT 2013), where wheat is grown under irrigation, too. The latter is well below world's average, i.e. 4.33 t/ha (FAOSTAT 2013).

The different ET_a of cotton and wheat-corn from upstream towards downstream (Table 7) is explained through a slightly better water supply to irrigation upstream compared to downstream rather than climatic variability within the study area, because the two climate data from the stations Turkmenabad and Kabakly follow very similar trends (Fig. 2).

The gap between the ET_a of cotton mapped in this study and the crop water requirement of 1,025 mm per season (Chapagain et al. 2006) can be explained mainly through water losses along the irrigations channels and water, which is diverted onto the fields, in order to leach salts out of the soil and prepare the soil for planting. High water losses from irrigation channels are reported from Khorezm, Uzbekistan and a crop water requirement, which is threefold as much as the evapotranspiration of cotton, was reported by Tischbein et al. (2012).

Conclusions

From this study, it is concluded that there is a large gap between the amount of water taken up from the Amu Darya and the water really used by the irrigated crops. This low water use efficiency might be due to water losses from channels and high amounts of water needed for soil preparation, i.e. leaching of salts. This situation is similar to Khorezm, Uzbekistan, which lies just downstream of Lebap at the Amu Darya (Tischbein et al. 2012). Water seepage from the net of irrigation channels results in rising groundwater levels, or even water logging, and enhanced soil salinization. Water logging and soil salinization are major factors, which impact on the agricultural sector in Turkmenistan (O'Hara 1997). Most likely, this situation has not changed much until today, as it is reflected by the gap between ET_a of cotton and other crops and the crop water requirement. A great improvement would be to line channels so that seepage from the channels is avoided. Thus, more water would be directed to the field plots, where it is needed, so that higher yields could be attained with the same amount of water diverted from the Amu Darya. Such improvement is very urgent under presumably increasing water supply uncertainties to Turkmenistan as a downstream country under climate change and a still weak governance of transboundary water resources in Central Asia (Janusz-Pawletta 2014).

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References

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration—guidelines for computing crop water requirements. FAO Irrigation and drainage paper 56. FAO, Rome

Allen RG, Tasumi M, Morse A, Trezza R (2005) A Landsat-based energy balance and evapotranspiration model in Western US water rights regulation and planning. Irrig Drain Syst 19:251–268

Bakhtiyarov RI (2006) Utilization of the water resources of the Amu-Darya Basin for development of the productive forces of Central Asian republics. Power Tech Eng 7:1159–1164

Bastiaanssen WGM (1995) Regionalization of surface flux densities and moisture indicators in composite terrain. Ph.D. Thesis, Wageningen University, Wageningen

Bastiaanssen WGM, Ahmad M, Yuan CM (2002) Satellite surveillance of evaporative depletion across the Indus Basin. Water Resour Res 38:1273–1282

Bastiaanssen WGM, Noordman EJM, Pelgrum H, Davids G, Thoreson BP, Allen RG (2005) SEBAL model with remotely sensed data to improve water resources management under actual field conditions. J Irrig Drain Eng 131:85–93

Chapagain AK, Hoekstra AY, Savenje HHG, Gautam R (2006) The water footprint of cotton consumption: an assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries. Ecol Econ 60:186–203

Chen Y, Li W, Xu C, Ye Z, Chen Y (2014) Desert riparian vegetation and groundwater in the lower reaches of the Tarim River Basin. Environ Earth Sci. doi:10.1007/s12665-013-3002-y

Cleverly JR, Dahm CN, Thibault JR, Gilroy DJ, Allred Coonrod JE (2002) Seasonal estimates of actual evapo-transpiration from *Tamarix ramosissima* stands using three-dimensional eddy covariance. J Arid Environ 52:181–197

D'Urso G (2010) Current status and perspectives for the estimation of crop water requirements from earth observation. Ital J Agron 5:107–120

FAO (2013) Irrigation in Central Asia in figures. FAO water report 39. FAO, Rome. http://www.fao.org/docrep/018/i3289e/i3289e.pdf. Accessed 25 June 2013

FAOSTAT (2013) http://faostat3.fao.org/home/index.html#HOME. Accessed 30 June 2013

Feike T, Mamitimin Y, Li L, Abdusalih N, Doluschitz R (2014) Development of agricultural land and water use and its driving forces in the Aksu-Tarim Basin, P.R. China. Environ Earth Sci. doi:10.1007/s12665-014-3108-x

Fiorentino C, Ventrella D, Giglio L, Di Giacomo E, Lopez R (2010) Land use cover mapping of water melon and cereals in Southern Italy. Ital J Agron 5:185–192

Glantz MH (1999) Creeping environmental problems and sustainable development of the Aral Sea Basin. Cambridge University Press, Cambridge

Gowda PH, Chavez JL, Colaizzi PD, Evett SR, Howell TA, Tolk JA (2007) Remote sensing based energy balance algorithms for mapping ET: current status and future challenges. Am Soc Agric Biol Eng 50:1639–1644

Gowda PH, Chavez JL, Colaizzi PD, Evett SR, Howell TA, Tolk JA (2008) ET mapping for agricultural water management: present status and challenges. Irrig Sci 26:223–237

Gries D, Zeng F, Foetzki A, Arndt SK, Bruelheide H, Thomas FM, Zhang XM, Runge M (2003) Growth and water relation of *Tamarix ramosissima* and *Populus euphratica* on Taklamakan desert dunes in relation to depth to a permanent water table. Plant Cell Environ 26:725–736

Groll M, Opp C, Kulmatov R, Ikramova M, Normatov I (2014) Water quality, potential conflicts and solutions—an upstream-downstream analysis of the transnational Zarafshan River (Tajikistan, Uzbekistan). Environ Earth Sci. doi:10.1007/s12665-013-2988-5

Hou P, Beeton RJS, Carter RW, Dong XG, Li X (2007) Response to environmental flows in the lower Tarim River, Xinjiang, China: ground water. J Environ Manag 83:371–382

Kalma JD, McVicar TR, McCabe MF (2008) Estimating land surface evaporation: a review of methods using remotely sensed surface temperature data. Surv Geophys 29:421–469

Khamzina A, Sommer R, Lamers JPA, Vlek PLGH (2009) Transpiration and early growth of tree plantations established on degraded cropland over shallow saline groundwater table in northwest Uzbekistan. Agric For Meteorol 149:1865–1874

Kim V (2012) Water footprint for cotton in Turkmenistan. Master thesis, University of Greifswald

Lioubimtseva E (2014) A multi-scale assessment of human vulnerability to climate change in the Aral Sea Basin. Environ Earth Sci. doi:10.1007/s12665-014-3104-1

Malek E, Bingham GE (1993) Comparison of the Bowen ratio-energy balance and the water balance methods for the measurement of evapotranspiration. J Hydrol 146:209–220

Minderlein S, Menzel L (2013) Evapotranspiration and energy balance dynamics of a semi arid mountainous steppe and shrubland site in northern Mongolia. Environ Earth Sci

Ministry of Nature Protection of Turkmenistan (2002) Biodiver-sity strategy and action plan for Turkmenistan. Ministry of Nature Protection of Turkmenistan, Ashgabad

Nechaeva NT, Nikolaev WN (1962) pojasnitelnnyj tekst k karte pastbish ravninnoj Turkmenii. Turkmenskij Nauchno-Issledovatelskij Institut Zhivotnovodstva I veterinarii, Ashgabat

O'Hara SL (1997) Irrigation and land degradation: implications for agriculture in Turkmenistan, Central Asia. J Arid Environ 37:165–179

Ogar NP (2003) Vegetation of river valleys. In: Rachkovskaya EI, Volkova EA, Khramtsov VN (eds) Botanical geography of Kazakhstan and Middle Asia (Desert region). Komarov Botanical Institute of Russian Academy of Sciences, Saint Petersburg, pp 313–339

Ovezberdyyeva A (2009) Sustainable water management in Turkmenistan: challenges and solutions. Master thesis, University of Greifswald

Palmer MA, Reidy Liermann CA, Nilsson C, Flörke M, Alcamo J, Lake PS, Bond N (2008) Climate change and the world's river basins: anticipating management options. Front Ecol Environ 6:81–89

Rakhmatullaev S, Huneau F, Kazbekov J, Le Coustumer P, Jumanov J, El Oifi B, Motelica-Heino M, Hrkal Z (2010) Groundwater resources use and management in the Amu Darya River Basin (Central Asia). Environ Earth Sci 59:1183–1193

Rakhmatullaev S, Huneau F, Celle-Jeanton H, Le Coustumer P, Motelica-Heino H, Bakiev M (2013) Water reservoirs, irrigation and sedimentation in Central Asia: a first-cut assessment for Uzbekistan. Environ Earth Sci 68:985–998

Rapajov M (2002) National environmental action plan. Ministry of Nature Protection, Ashgabat

Reddy JM, Muhammedjanov S, Jumaboev K, Eshmuratov D (2012) Analysis of cotton water productivity in Fergana Valley of Central Asia. Agric Sci 3:822–834

Roerink GJ, Su B, Menenti M (2000) S-SEBI A simple remote sensing algorithm to estimate the surface energy balance. Phys Chem Earth (B) 25:147–157

Sammis TW (1981) Yield of alfalfa and cotton as influenced by irrigation. Agron J 73:323–329

Senay GB, Budde M, Verdin JP, Melesse AM (2007) A coupled remote sensing and simplified surface energy balance approach to estimate actual evapotranspiration from irrigated fields. Sensors 7:979–1000

Sobrino JA, Gómez M, Jiménez-Muñoz JC, Olioso A, Chehbouni G (2005) A simple algorithm to estimate evapotranspiration from DAIS data: application to the DAISEX campaigns original research article. J Hydrol 315:117–125

Sobrino JA, Gómez M, Jiménez-Muñoz JC, Olioso A (2007) Application of a simple algorithm to estimate daily evapotranspiration from NOAA–AVHRR images for the Iberian Peninsula. Remote Sens Environ 110:139–148

Stanchin I, Lerman Z (2003) Agrarian reforms in Turkmenistan. The Hebrew University of Jerusalem, the Center for Agriculture Economic Research, the Department of Agricultural Economic and Management, Jerusalem

Stanchin I, Lerman Z (2005) Water in Turkmenistan. The Hebrew University of Jerusalem, the Center for Agriculture Economic Research, the Department of Agricultural Economic and Management, Jerusalem

Su Z (2002) The surface energy balance system (SEBS) for estimation of turbulent heat fluxes. Hydrol Earth Syst Sci 6:85–99

Thevs N, Zerbe S, Peper J, Succow M (2008) Vegetation and vegetation dynamics in the Tarim River floodplain of continental-arid Xinjiang, NW China. Phytocoenologia 38:65–84

Thevs N, Buras A, Zerbe S, Kühnel E, Abdusalih N, Ovezberdyyeva A (2012) Structure and wood biomass of near-natural floodplain forests along the Central Asian rivers Tarim and Amu Darya. Forestry 81:193–202

Thevs N, Rouzi A, Kubal C, Abdusalih N (2013) Water consumption of agriculture and natural ecosystems along the Tarim River, China. Geo-Öko 34:50–76

Thomas FM, Foetzki A, Arndt SK, Bruelheide H, Gries D, Zeng FJ, Zhang XM, Runge M (2006) Water use by perennial plants in the transition zone between river oasis and desert in NW China. Basic Appl Ecol 7:253–267

Tischbein B, Awan UK, Abdullaev I, Bobojonov I, Conrad C, Jabborov H, Forkutsa I, Inrakhimov M, Poluasheva G (2012) Water management in Khorezm: current situation and options for improvement (hydrological perspective). In: Martius C, Rudenko I, Lamers JPA, Vlek PLG (eds) Cotton water salts and soums. Springer, Heidelberg, pp 69–92

Treshkin SY (2001) The Tugai forests of floodplain of the Amudarya River: ecology, dynamics and their conservation. In: Breckle SW, Veste M, Wucherer W (eds) Sustainable land use in deserts. Springer, Heidelberg, pp 95–102

Xinjiang Statistics Bureau (2012) Xinjiang Statistical Yearbook of 2011. China Statistics Press, Beijing

Zheleznyh V, Risbekov YU (1987) Analysis of experimental investigations on lizimeters comparatively with data on cotton field. http://www.cawater-info.net/bk/water_land_resources_use/english/iptrid/uz_34.pdf. Accessed 28 Aug 2013