Environ Earth Sci (2015) 73:5269–5279
DOI 10.1007/s12665-014-3773-9

ORIGINAL ARTICLE

Water allocation and water consumption of irrigation agriculture and natural vegetation in the Heihe River watershed, NW China

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Received: 9 May 2014 / Accepted: 3 October 2014 / Published online: 31 October 2014

Abstract To implement effective water resource management strategies, a sufficient data basis about the hydrologic situation must be available. An important parameter is the water consumption by the natural environment, e.g., evapotranspiration (ET). This study delivers actual evapotranspiration rates (ET_a) computed on the basis of Landsat TM/ETM+ and MODIS data. Vegetation mappings recorded during a field work campaign in 2012 allowed the correlation of ET rates to certain units of vegetation. The study site is located in the Heihe river basin, Northwest China, where the landscape is characterized by extending land under cultivation along the middle reaches and ecologically valuable Tugai vegetation further downwards. Due to the arid climate, all agriculture depends on irrigation with water taken from the Heihe River. As a result of a massive expansion of irrigated land in the last decades, an imbalance with regard to water allocation has developed. It is characterized by an overexploitation of the water resources in the middle reaches and a strong degeneration of the natural Tugai vegetation along the lower reaches due to water shortage. As a response, a water distribution plan has been adopted to define target amounts of water that shall reach the lower parts of the river. Total values of the ET_a over the whole vegetation period for corn, dates, orchards and grapes amount to 667.7, 762.2, 703.5 and 483.9 mm, respectively. For forest vegetation (ground coverage 80 %) and for shrub vegetation (80–100 % ground coverage), values of 496–530 mm and 177–233 mm were calculated, respectively. Areas with lower ground coverage show significantly lower ET_a values. Spatially, ET_a values decrease from the center towards the border of the oasis and from the middle towards the lower reaches. Agricultural land presents the largest water consumer. The total ET_a values over the vegetation period amount to 2.15 km^3 (middle reaches) and 0.28 km^3 (lower reaches), respectively. On this basis, a minimum discharge of 0.34 km^3 was calculated to maintain the natural vegetation downstream.

Keywords Evapotranspiration · Remote sensing · Water resource management · Tugai vegetation

Introduction

The worldwide water use and water consumption have increased during the near past mainly due to the expansion of agricultural land, which contributes to the current worldwide withdrawal of fresh water by 70 % (Siebert et al. 2010). Under limited water supply, especially in arid and semi-arid climatic conditions, increasing water consumption by agriculture exerts pressure on natural ecosystems and results in degradation of natural ecosystems (Wang et al. 2008a). In Central Asia, the region worldwide with the highest number of endorheic river basins, agriculture and the most productive and diverse natural ecosystems is located along those rivers. Then, we frequently find water competition between agriculture and natural

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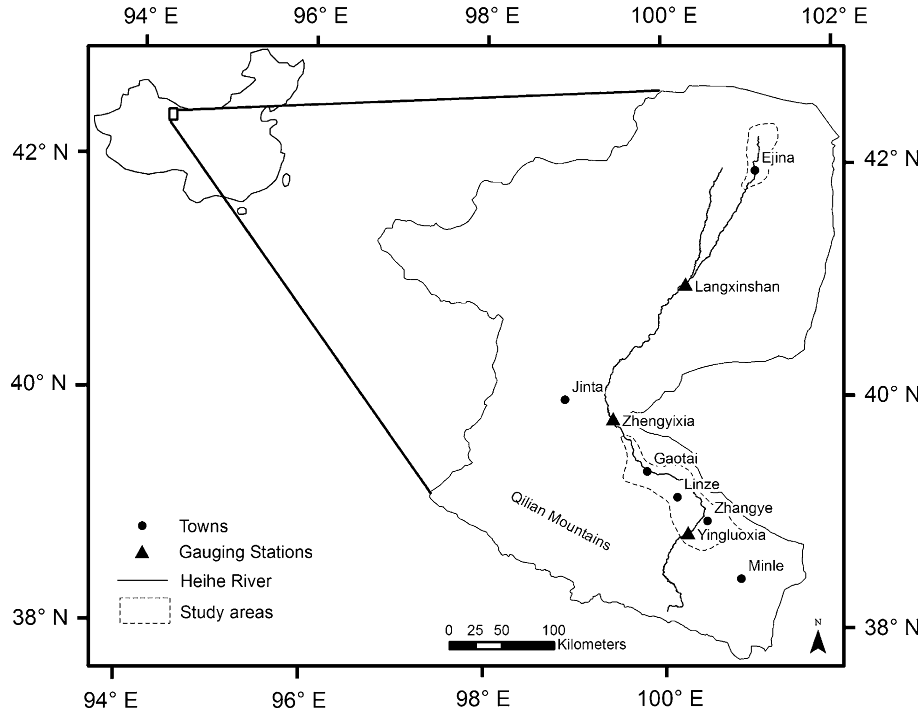

Fig. 1 Map of the Heihe river basin

ecosystems as well as water competition between upstream and downstream. Due to increasing water consumption upstream, agriculture downstream is often prone to water shortage, natural ecosystems are degraded, and terminal lakes vanished, e.g., the Aral Sea (Thompson 2008; Glantz 2005).

Starting in the 1950s, new agricultural land was reclaimed all over China's drylands (Gruschke 1991). In the Heihe river basin in Gansu and Inner Mongolia (NW China), new land was reclaimed in Zhangye along the middle reaches of the Heihe River (Fig. 1) and to a smaller extent in the inland delta in Ejina (Wang et al. 2007; Ejina Qizhe 1998). Due to the arid climate along the Heihe River with annual precipitation of 170 mm in Zhangye and 60 mm in Ejina (http://www.tutiempo.net), all agriculture depends on irrigation with the river water being the only water source. The increased water consumption by agriculture along the middle reaches of the Heihe resulted in severe destruction of the natural ecosystems along the lower reaches of the Heihe and also impacted on land use there. The area of natural riparian vegetation in Ejina decreased from 6,440 km^2 in 1960 to 3,200 km^2 in 2010 (Jin et al. 2010). The terminal lake of the Heihe West Juyanhai has been dry since 1961 and most of the western branch of the Heihe in Ejina has been dry, too. The second terminal lake, East Juyanhai Lake, covered 35.5 km^2 in 1958, shrunk to 23.6 km^2 in 1980, and dried up in the beginning of the 1990s (Ejina Qizhe 1998). In 2002, it reappeared for a few months with an area of 12 km^2 (Wang et al. 2002).

The natural riparian vegetation in Ejina consists of a mosaic of Tugai forests, reed beds, and shrub vegetation. Tugai forests are the riparian forests of the deserts of Central Asia (Thevs et al. 2008a). These forests together with the reed beds are the most productive ecosystems of the deserts of Central Asia (Thevs 2012; Thevs et al. 2007) with most of the biodiversity concentrated there (Thevs 2007, 2008a). Besides that, the Ejina Oasis is of economic value as one of China's most important tourist attraction with respect to Tugai forests with almost 200,000 visitors per year.

Furthermore, the natural vegetation in Ejina plays an important role with regard to the prevention of sand storms originating in the deserts of NW China (Jiang and Liu 2010). An annual desertification rate of 5.6 % (Qi et al. 2004 quoted after Shan et al. 2008) has caused the expansion of sandy areas and thus supports the formation of sand storms (Wen et al. 2005; quoted after Guo et al. 2009).

In 2000, a water allocation plan was adopted by the Central Government of China, which shall ensure a guaranteed annual amount of water to be released into the lower reaches of the Heihe. The major objective of this water allocation plan was to restore the Tugai forests along the Heihe and part of the previous terminal lakes in Ejina. Compared to other river basins in China's drylands, the water allocation plan for the Heihe river basin was the earliest and it is imposed from the Central Government. The water allocation plan for the Tarim river basin in Xinjiang for example was only adopted by the Province

Government. So, we assume that among other water allocation plans in China's drylands, the governance structures enforcing the water allocation plan for the Heihe river basin are among the strongest and have the longest record of experiences. Therefore, for this study, the Heihe river basin was chosen.

This study aims at firstly showing the reality of the current water consumption in the Heihe river basin and secondly assessing, in how far the requirements of the water allocation plan are fulfilled. Therefore, the water consumption, i.e., evapotranspiration (ET_a), in the whole Heihe river basin downstream of the station Yingluoxia was mapped based on MODIS satellite images. Water balances were calculated for Zhangye and Ejina, as they are the main water consuming areas, and compared with the water allocation plan. In a second step, the water consumption was mapped for Zhangye and Ejina with Landsat satellite images, to determine the water consumption of the major crops in Zhangye and the natural vegetation in Ejina. This information was included to assess in how far water saving crops are planted or in how far water could be saved along the Heihe River.

ET_a can be determined with climate station data, i.e., by calculating reference ET and using crop coefficients (k_c) (Allen et al. 1998), as used by Jiao and Xu (2013) in the Heihe basin, or through the Bowen Ratio method (e.g., Malek and Bingham 1993), lysimeters (e.g., Howell et al. 1998 or Zheleznyh and Risbekov 1987), 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. Especially, lysimeters and eddy co-variance measurement devices require sophisticated installations.

In this study, ET_a of rather different natural ecosystems and crops needs to be assessed. There are crop coefficients (k_c) for most of the relevant crops as well as for wetlands (Allen et al. 1998). Thomas et al. (2006) and Hou et al. (2010) provided crop coefficients for *Populus euphratica* from Qira in Xinjiang, China, and Ejina in the Heihe river basin. These two sites with *P. euphratica* represent forests at the desert margin, but they cannot represent the full range of forests and other natural ecosystems. The crop coefficients (k_c) only can be applied for well-managed crops without water stress. Adjustments to sub-optimal conditions, which might be found in the study area, are possible, but require additional information (Allen et al. 1998), which is difficult to obtain in the quality needed.

To cover large, diverse, and remote areas, models have been developed to map ET_a on the basis of remote sensing data from satellites, either by applying relationships between vegetation indices and ET_a or using thermal infrared data (Kustas and Norman 1996). Among those two approaches, the latter approach is able to map ET_a of water-stressed vegetation and moist soils (Trezza et al. 2013). Frequently used models which use thermal infrared data are: surface energy balance algorithm (SEBAL) developed by Bastiaanssen (1995), Bastiaanssen et al. (1998, 2000, 2002, 2005), mapping evapotranspiration with internalized calibration (METRIC) after Allen et al. (2005), surface energy balance system (SEBS) according to Su (SEBAL, Advanced Training and Users Manual, 2002), simplified surface energy balance (SSEB) by Senay et al. (2007), 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).

SEBAL was used by Yang et al. (2012) to map ET_a of the Hetao Irrigation District in Inner Mongolia, China, and found good agreements with data derived from climate stations. ET_a of irrigated agriculture was mapped by Conrad et al. (2007) for Khorezm, Uzbekistan, with the METRIC model using MODIS data. The results were in accordance with reference climate station ET_a values. Costa dos Santos et al. (2010) assessed daily ET_a for cotton in Brazil applying the SEBAL and S-SEBI models on Landsat satellite images. The ET_a of SEBAL and S-SEBI corresponded fairly well with each other and showed deviations of up to 7.1 and 16.1 %, respectively, compared with ET_a values calculated with the Bowen Ratio method.

Study area

The Heihe river basin, with an area of 120,000 km^2, is the second largest endorheic river basin in NW China (Li et al. 2012). The headwaters of the Heihe River are located in the Qilian Mountains south of the City of Zhangye. The river flows mainly through the provinces of Gansu (middle reaches) and Inner Mongolia (lower reaches) between 96°42′–102°00′E and 37°41′–42°42′N (Li et al. 2012).

The climate in the study area is arid and continental as shown in Table 1. In Zhangye, the mean annual temperature was 8.3 °C in 2011 and rainfall amounted to 86.35 mm. In Ejina, the mean annual temperature was 9.8 °C with 34.54 mm of rainfall. The climatic conditions

Table 1 Climate data of Zhangye and Ejina aggregated from 1973 to 2012 (http://www.tutiempo.net)

Climate station	Zhangye	Ejina
Position	38.93°N, 100.43°E	41.95°N, 101.61°E
Annual mean temperature (°C)	8	9.4
January mean temperature (°C)	−9	−10.7
July mean temperature (°C)	22.1	27.2
Annual precipitation (mm)	170	60

of 2011 were in the range of the long-term mean (http://www.tutiempo.net).

There are three gauging stations along the Heihe River (Fig. 1). At the gauging station Yingluoxia, the Heihe flows out of the Qilian Mountains into the oasis of Zhangye with its population of about 1.3 million people (Fig. 1). The oasis of Zhangye is the place where most water is consumed mainly for irrigated agriculture (Shan et al. 2008). Within the area of Zhangye, about thirty small rivers flow down from the Qilian Mountains, which now are diverted into irrigation, too. Only during spring or high flood events, some of these rivers reach the Heihe. Once the Heihe leaves Zhangye, it flows as a so-called losing stream through mainly gravel deserts northwards from Gansu into Inner Mongolia. Downstream of Zhangye, the Heihe passes the gauging station Zhengyixia (Fig. 1). About half way between Zhengyixia and the terminal lakes, the gauging station Langxinshan is located. There, the Heihe divides into two branches flowing into West and East Juyanhai Lake, respectively (Qi and Luo 2005) (Fig. 1). The runoff that passes the gauging station Langxinshan is the water which is available for Ejina with its population of 17,240 residents (Zhang et al. 2011).

The annual runoff at the gauging station Zhengyixia decreased from 1.19 km^3 in the 1950s over 0.942 km^3 in the 1980s to 0.475 km^3 between 1990 and 1995 (Feng and Cheng 1998). Thus, the Heihe River faced severe water shortage downstream of Zhengyixia. The terminal lake East Juyanhai Lake, which covered an area of 35.5 km^2 in 1958, shrunk to 23.6 km^2 in 1980, and dried up in the beginning of the 1990s (Ejina Qizhe 1998). In the course of decreasing runoff that reached Ejina County, soil salinisation increased in parts of the county (Qi and Cai 2007). Groundwater levels dropped from 0.5–1.3 m in the 1940s to 3–6 m in the 1990s (Guo et al. 2009). Even though, the runoff from the Qilian Mountains recorded at the gauging station Yingluoxia has not changed significantly for the past 50 years despite of global warming and shrinking glaciers in other mountains in China and Central Asia (Jiang and Liu 2010).

Due to the arid climate, all agriculture along the Heihe River depends on irrigation. The water supply to the agriculture in the middle reaches is mainly composed of surface water from the Heihe River and other smaller streams (70 %), and also groundwater (23 %) and effective precipitation (7 %) (Liu et al. 2010). Since the 1950s, the area under agriculture along the Heihe in Zhangye was enlarged from 82,600 ha in 1949 to 260,000 ha in 1995 (Feng and Chang 1998) and 253,300 ha in 2012 (Agriculture Administration Zhangye 2012). Before 2000, cotton and paddy rice were important crops in Zhangye. Now, corn has become the major crop in Zhangye. The corm production focuses on seed production, which is exported to other provinces of China. Peach and dates are found around the town Linze. Potatoes, rape, wheat, pear, and apricot are grown on higher elevations near the foot of the mountains. Cotton fields today are restricted to Gaotai and Jinta (Agriculture Administration Zhangye 2012). While agricultural land dominates along the middle reaches in Ejina, agriculture only covers 1 % of the distribution area of the riparian vegetation (Jin et al. 2010).

In 2000, the "Integrated Water Resource Management Plan of the Heihe River Basin" was adopted (Guo et al. 2009), which includes water quotas for the middle and lower reaches of the Heihe River. This water allocation plan starts with an average runoff of 1.58 km^3/a at Yingluoxia. An amount of 0.95 km^3/a water must pass Zhengyixia to reach the lower section of the river (Wang et al. 2011b; Jiang and Liu 2010). The average annual discharge at Yingluoxia and Zhengyixia from 2000 to 2009 amounted to 1.747 and 0.995 km^3/a, respectively, so that the target amounts were accomplished (Environmental Protection Administration Zhangye 2012). According to Zhang et al. (2011) the average annual runoff was 0.53 km^3/a at Langxinshan from 2000 to 2008. This runoff at Langxinshan is equivalent to the amount of water that Ejina receives.

Though the annual amount of water which passes Zhengyixia fulfils the requirements of the water allocation plan, the runoff distribution within the years has been altered compared to natural conditions (Fig. 2).

Mongolia (lower reaches) between 96°42′–102°00′E and 37°41′–42°42′N (Li et al. 2012).

While the runoff at Yingluoxia peaks during August, at Zhengyixia, there are two runoff peaks: one in late summer/autumn and another one in winter/early spring. During summer, when the agriculture in Zhangye demands water for irrigation, water is consumed from the Heihe so that no water is left for the lower reaches. In autumn and winter/early spring, there is no demand for irrigation water so that water is released into the lower reaches.

Methods

In this paper, the actual evapotranspiration (ET_a) of the growing season 2011 of the Heihe river basin was mapped based on MODIS satellite images (MODIS-ET). In addition, ET_a of oasis Zhangye and Ejina was mapped with Landsat satellite images (Landsat-ET). The MODIS-ET was used to estimate the water consumption of agriculture and natural ecosystems of the whole Heihe river basin, while the Landsat-ET was used to assess the ET_a of the major crops and major natural ecosystems in Zhangye and Ejina, respectively. For both ET_a mapping procedures, the

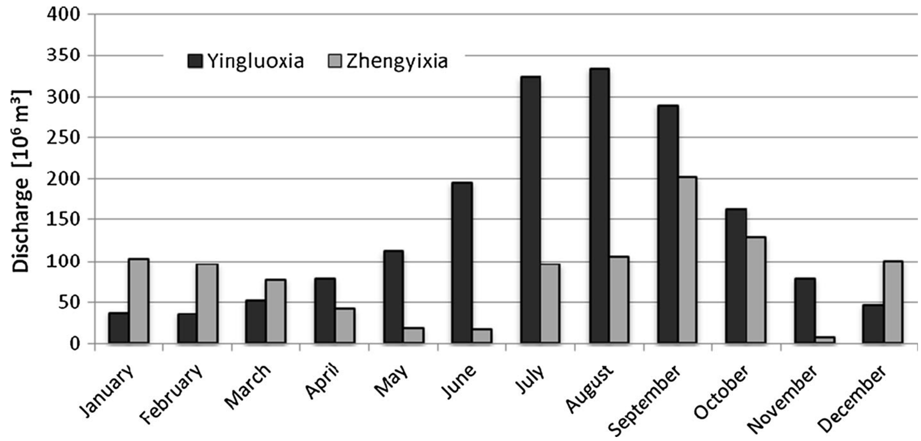

Fig. 2 Mean monthly discharge from 2000–2009 (Environmental Protection Administration Zhangye 2012)

S-SEBI approach was used (Roerink et al. 2000; Sobrino et al. 2005, 2007).

ET consumes energy and can be presented as a part of the land surface energy balance.

$$R_n - G - H - \lambda\mathrm{ET} = 0 \quad (1)$$

where R_n, G, H and λET refer to net solar radiation, soil heat flux, sensible heat flux, and latent heat flux [W/m^2], respectively (Allen et al. 1998). Evapotranspiration is expressed by the latent heat flux and can be computed by solving Eq. 1 for λET:

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

The simplified surface energy balance index (S-SEBI) applies the concept of the evaporative fraction ($\mathrm{ET_f}$) to solve the land surface energy balance (Roerink et al. 2000):

$$\mathrm{ET_f} = \lambda\mathrm{ET} / (\lambda\mathrm{ET} + H) = \lambda\mathrm{ET} / (R_n - G) \quad (3)$$

$G = 0$, when calculating daily values instead of instantaneous values (Allen et al. 1998). If energy values are converted into evapotranspiration values, Eq. 2 can be expressed as:

$$\mathrm{ET_a} = \mathrm{ET_f}\ \mathrm{ET_{pot}} \quad (4)$$

Source: Roerink et al. (2000) Here, the net radiation is expressed as potential evapotranspiration ($\mathrm{ET_{pot}}$) and latent heat flux as the actual evapotranspiration ($\mathrm{ET_a}$).

The $\mathrm{ET_{pot}}$ was computed according to Bastiaanssen (1995) on the basis of date, geographical position, transmissivity of the atmosphere, land surface temperature and albedo. The formulae were taken from the script of the GRASS GIS add-on "i.evapo.potrad" (GRASS GIS 2012). Since there was no transmissivity value available from climate stations, the value of 0.685 was adopted from a study in the Tarim basin, Xinjiang, China (Thevs et al. 2013).

The $\mathrm{ET_f}$ is the part of the $\mathrm{ET_{pot}}$ which is realized as the $\mathrm{ET_a}$. $\mathrm{ET_f}$ is calculated on the basis of so-called anchor pixels, the cold and hot pixels (Roerink et al. 2000; Sobrino et al. 2005, 2007; Bastiaansen et al. 2007; Senay et al. 2007). Cold pixels are such pixels in which $\mathrm{ET_a} \approx \mathrm{ET_{pot}}$ and $\mathrm{ET_f} \approx 1$. The land surface temperature (LST) is low, because the available energy is used for evapotranspiration. In contrast, in hot pixels, $\mathrm{ET_a} = 0$ and $\mathrm{ET_f} = 0$, too. Here, the land surface temperature is high, because all available energy is converted into the sensible heat flux. Technically, cold pixels cover well-watered vegetation without water stress for the plants during the study period (SEBAL, Advanced Training and Users Manual 2002). Hot pixels are areas without vegetation coverage that are not sealed like streets or roofs. In the S-SEBI approach, a linear relationship between the land surface temperature (LST) and $\mathrm{ET_f}$ is assumed. Thus, $\mathrm{ET_f}$ is calculated as:

$$\mathrm{ET_f} = (T_\mathrm{h} - T_\mathrm{x}) / (T_\mathrm{h} - T_\mathrm{c}) \quad (5)$$

whereby T_h, T_c, and T_x refer to the LST at the hot pixels, cold pixels and the pixel, for which the $\mathrm{ET_f}$ is calculated, respectively (Roerink et al. 2000; Sobrino et al. 2005; 2007).

In this study, cold pixels were chosen from wetlands with dense reed vegetation and small parts of open waters, which were present during the whole growing season. Wetlands in which open waters fell dry during the growing season were excluded, to ensure that the vegetation never suffered water stress. Such wetlands only were available in Zhangye and around the East Juyanhai Lake. Due to this large distance between those wetlands, it was not possible to map the whole river basin with Landsat, because Landsat scenes along the Heihe River between Zhangye and Ejina do not include such wetlands. Therefore, the whole river basin's $\mathrm{ET_a}$ was mapped with MODIS, because the whole river basin is covered by the range of one MODIS scene.

Hot pixels were selected from sandy areas, adjacent to dense vegetation but far enough to avoid boundary effects on the LST. It was not possible to choose fallow agricultural land for hot pixels as suggested in SEBAL, Advanced Training and Users Manual (2002), since no agricultural field actually has the size of a MODIS pixel (1 × 1 km). Hot and cold pixels for Landsat were selected within the reference pixels chosen for MODIS.

Following this approach, MODIS-ET and Landsat-ET maps were produced. For the MODIS-ET maps, MODIS 8-day lands surface temperature (MOD11A2) and 16-day albedo (MCD43A3) were used, which yielded daily ET_a maps every 8 days. The ET_a values in between were linearly interpolated. For the Landsat-ET maps, all available Landsat 5 and 7 images were used, if the cloud coverage was less than 25 %. On the Landsat images, which were included into this study, clouds were digitized manually and those areas were excluded from the ET mapping. Missing values due to clouds were also linearly interpolated. Daily ET_a values were summed up to total values over the whole growing season.

The growing season was defined from May 1st to September 30th for the natural ecosystems. This time period was adopted from other studies that focused on the ET_a of natural vegetation in the Heihe river basin (Hou et al. 2010; Si et al. 2005). However, corn as the major crop is planted in April and harvested in the middle of September (Zhao et al. 2010). Planting times for other crops are not known. Thus, to include all kinds of agricultural land, an extended vegetation period of April 1st to October 31st was assumed for cultivated land. This time period was also taken for the large-scale analysis over the whole basin. To retrieve ET_a values from irrigated agriculture and natural vegetation, vegetation and land-use records were taken (Braun-Blanquet 1964) during May and June 2011 in Zhangye and Ejina.

Results

The spatial distribution of the daily ET_a (MODIS-ET) is illustrated in Fig. 3 taking May 15th and August 1st as examples. In Ejina, the East Juyanhai Lake shows high ET_a in spring (top left in Fig. 3) and summer (top right in Fig. 3), i.e., throughout the whole growing season. In August (top right in Fig. 3), the Tugai forests have daily ET_a of 4–5 mm, while their daily ET_a in spring is less than 2 mm (top left in Fig. 3). In Zhangye, the ET map from August (bottom right in Fig. 3) reflects clearly the irrigated agriculture with daily ET_a of up to 7 mm. The spots, which show high daily ET_a values in May, are lakes and wetlands. In both areas, the ET_a rates decline towards the border of the oasis and with increasing distance to the river as water source.

The MODIS-ET_a sums for the whole growing season 2011 yielded a total water consumption of 2.11 km^3 in Zhangye and 0.28 km^3 in Ejina.

The ET_a values (Landsat) for the whole growing season of the major crops and vegetation units are listed in Tables 2 and 3, respectively. The Landsat-ET summed up over the whole growing season of *Zyzyphus jujuba*, corn, and orchards, i.e., 762, 668, and 704 mm, respectively, do not differ significantly. The corresponding Landsat-ET of grapes, 484 mm, is significantly lower than of the three formers. Further crops were not differentiated, because the fields were too small to find fields which could accommodate one whole Landsat pixel of 60 m × 60 m.

The Landsat-ET of the natural vegetation increases with the total coverage. The Tugai forests show higher ET values than the shrub vegetation for corresponding total coverages. Thus, corresponding to the total coverage, the ET_a of the natural vegetation decreases with increasing distance from the river courses (Fig. 2). Forests and shrub vegetation with the highest total coverage (70 % and more) have ET_a values of 530 and 393 mm, respectively (Table 3), which are lower ET_a values than found for corn, orchards, and *Z. jujuba* (Table 2).

Landsat-ET_a and MODIS-ET_a are very similar for agriculture and natural vegetation as shown in Fig. 4.

Discussion

ET_a maps and ET_a of crops and natural ecosystems

Several studies have shown that MODIS and Landsat produce similar results with respect to ET_a mapping (Allen et al. 2008; Compaoré et al. 2007; Hong et al. 2005). The models used for calculation of ET_a in these publications (Metric, SEBAL) also applied the concept of hot and cold pixels.

The computed mean ET_a of 667.7 for corn (Table 2) as the main crop is within the range of other studies covering the Heihe basin and surrounding landscapes (Table 4). Only Ding et al. (2013) reported a significantly lower ET_a for 2008. For 2009, Ding et al. (2013) reported an ET_a which is in the range of the standard deviation of the ET_a mapped in this study (Table 2). Ding et al. (2013) trace this difference back to lower radiation energy, LAI, soil relative extractable water and canopy conductance in 2008 compared to 2009. Howell et al. (1998) published the evapotranspiration of irrigated corn measured with a lysimeter in Texas as 741 to 841 mm over the growing season. A major reason for the difference to the ET_a of corn in this study is the different irrigation. While the lysimeter of Howell et al. (1998) was irrigated with a sprinkler, in Zhangye corn is

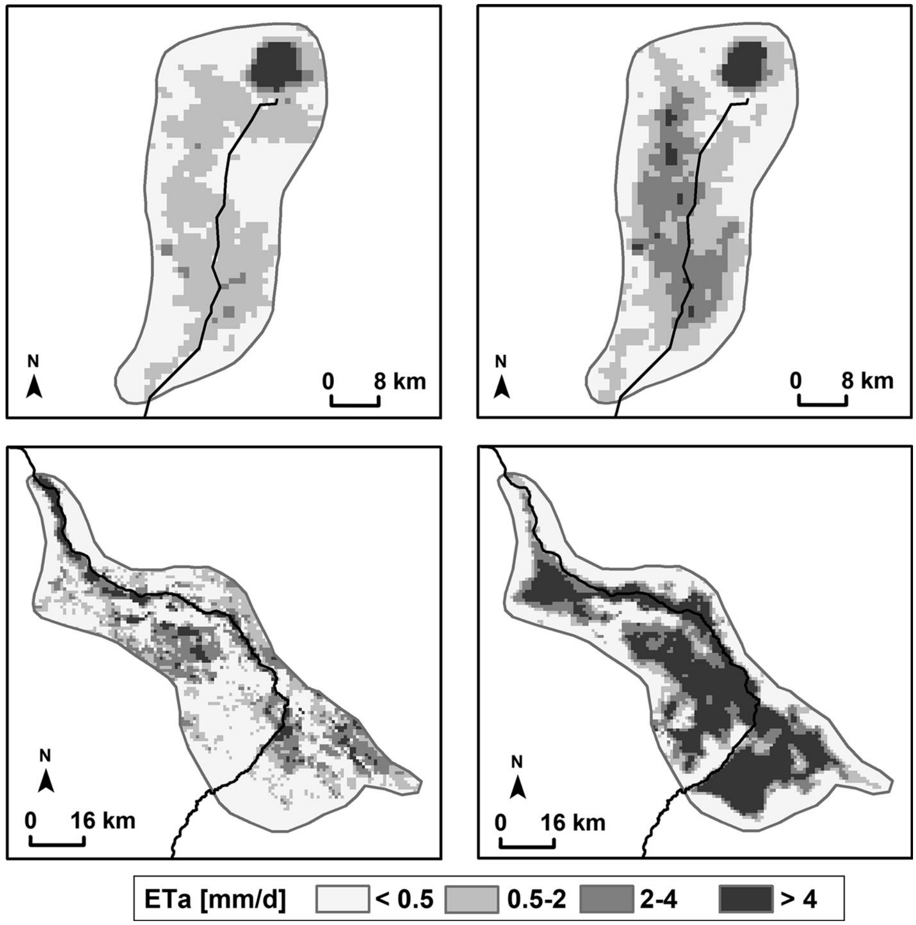

Fig. 3 Spatial distribution of the ET_a on 15.05.2011 and 01.08.2011 in Ejina (images *top left* and *top right*, respectively) and on 01.05.2011 and. 01.08.2011 in Zhangye (images *bottom left* and *bottom right*, respectively)

Table 2 ET_a values of irrigated agricultural in Zhangye for the whole growing season 2011

Crop	*n*	ET_a mean (mm)	Standard deviation	Sign. $\alpha < 0.05$
Zyzyphus jujuba	7	762	61	a
Corn	560	668	134	a
Orchards	16	704	43	a
Grape	15	484	26	b

n indicates the number of pixels queried from the Landsat-ET_a map. The letters in the last column indicate significant differences between ET_a mean of the different crops at $\alpha < 0.05$

Table 3 ET_a values of natural vegetation in Ejina for the whole growing season 2011

Vegetation type	Total coverage (%)	*n*	ET_a mean (mm)	Standard deviation	Sign. $\alpha < 0.05$
Shrub	≤10	40	21	55	f
Shrub	>10 and ≤50	58	115	25	e
Shrub	>50 and ≤70	37	233	27	d
Shrub	>70	49	393	83	c
Forest	≤20	14	102	10	e
Forest	>20 and ≤50	25	223	32	d
Forest	>50 and ≤70	29	356	31	c
Forest	>70	20	530	43	b

n indicates the number of pixels queried from the Landsat-ET_a map. The letters in the last column indicate significant differences between ET_a mean of the different crops at $\alpha < 0.05$

grown under drip irrigation coupled with plastic mulch. Thereby, the plastic mulch reduces evaporation from the soil surface, especially, when the corn is still in its initial stage. Thevs et al. (2014) reported ET_a values of wheat–corn rotations from Turkmenistan of 533 to 876 mm over the growing season. The higher ET_a compared to this study is mainly due to the ET_a of two crops compared to only corn in this study.

The Landsat-ET_a of *Z. jujuba*, corn, and orchards do not show a significant difference, while the ET_a of grapes is significantly lower (Table 2). The reason might be the lower vegetation coverage in grape plantations, where wine shrubs are planted in rows with space of about 1 m in between. These gaps lower the overall vegetation coverage of a field. Intercropping of date palm with fruits, vegetables

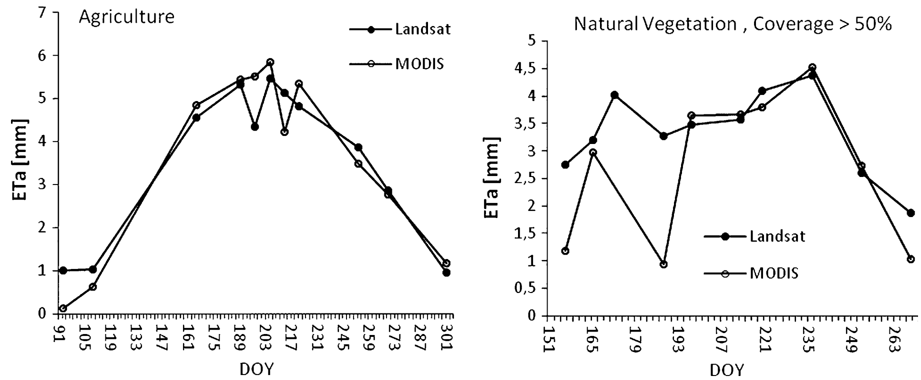

Fig. 4 Daily MODIS-ET_a and Landsat-ET_a for agriculture in Zhangye (*left*) and natural vegetation in Ejina (*right*)

Table 4 ET_a summed up over the growing season for corn over the vegetation period in the Heihe basin and neighboring regions

ET_a (mm)	Growing season	Study area	Method	Source
668	01.04–31.10. 2011	Zhangye	Based on S-SEBI	This study
591	March–Oct. 2007	Pingchuan (near Zhangye, Gansu)	Penman–Monteith	Liu et al. (2010)
777.8	21.04–15.09. 2007	Pingchuan (near Zhangye, Gansu)	Bowen Ratio	Zhao et al. (2010)
693.1	21.04–15.09. 2007	Pingchuan (near Zhangye, Gansu)	Penman–Monteith	Zhao et al. (2010)
618.3	21.04–15.09. 2007	Pingchuan (near Zhangye, Gansu)	Penman–Monteith	Zhao et al. (2010)
615.7	21.04–15.09. 2007	Pingchuan (near Zhangye, Gansu)	Soil water balance	Zhao et al. (2010)
560.3	21.04–15.09. 2007	Pingchuan (near Zhangye, Gansu)	Priestley–Taylor	Zhao et al. (2010)
552.1	21.04–15.09. 2007	Pingchuan (near Zhangye, Gansu)	Hargreaves	Zhao et al. (2010)
503.1	02.05.–25.09. 2008	Shiyanghe Experimental Station for Water Saving, Gansu	Priestley–Taylor	Ding et al. (2013)
562.4	21.04.–28.09.2009	Shiyanghe Experimental Station for Water Saving, Gansu	Priestley–Taylor	Ding et al. (2013)

and pasture is common in traditional areas of date production (Carr 2012), which increase the total vegetation coverage. On corn fields and orchards, vegetation coverage was generally high.

The ET_a of a *P. euphratica* forest with a canopy coverage of 80 % in Ejina determined by Hou et al. (2010) with the Bowen Ratio method amounts to 446.96 mm and, thus, is in the range of the values calculated in this study. The Landsat-ET_a of *P. euphratica* with a total coverage of 70 % and more in this study is 530.2 mm (Table 3). The daily ET_a values of *P. euphratica* reported by Jia et al. (2012) on 12.09.2003 in Ejina (0.12–5.41 mm; mean 2.27 mm) comprise the range of data of this study on 09.09.2011 (0.53–3.02 mm). The high ET_a was found close to the river, i.e., on a site with high groundwater level, while the low ET_a values were found on sites further away from the river.

The Landsat-ET_a of *Tamarix ramosissima*, 393 mm for *T. ramosissima* stands with a total coverage of 70 % and more, is in line with the results of two studies by Si et al. (2005) and Liu et al. (2010) located in Zhangye and Ejina, respectively, who reported an ET_a for the growing season of 248.2 and 416.6 mm. Three years of eddy co-variance observations were carried out in a Tamarisk stand in the lower Tarim river by Yuan et al. (2014). There, ET_a values of 509.3 and 499.8 mm in 2012 and 2013, respectively, were recorded over the vegetation period.

Calculating water balances for the Heihe middle and lower reaches

Water balances were calculated after Wu et al. (2013), to estimate how much the water quotas were met or exceeded:

$$P - \mathrm{ET} - O + I = \Delta \mathrm{gw} + \Delta s \quad (6)$$

with P being precipitation, ET referring to total evapotranspiration, O being basin outflow, I being inflow in the basin, and Δgw and Δs referring to change in groundwater and soil moisture storage. A negative term $\Delta \mathrm{gw} + \Delta s$ would indicate that the water quota was exceeded and groundwater and soil moisture were depleted, to meet the water consumption of irrigation and natural vegetation.

The basin inflow for the middle reaches consists of the runoff at Yingluoxia, 1.747 km^3 in 2000–2009 (Environmental Protection Administration Zhangye 2012), 0.63 km^3 of water carried by smaller streams, which flow from the Qilian Mountains towards the Heihe within

Zhangye, as shown in Fig. 1 (Jin et al. 2009), and 0.175–0.42 km^3 of groundwater flowing from the Qilian Mountains (Gansu Provincial Bureau of Water Resources (GPBWR) 2003). Water outflow of the oasis of Zhangye is represented by the mean annual flow rate of the Heihe at Zhengyixia of 0.995 km^3 in 2000–2009 (Environmental Protection Administration Zhangye 2012). Annual precipitation over the study area was 0.39 km^3 in 2011 (http://www.tutiempo.net/en). ET is 2.11 km^3 for the middle reaches of the Heihe. The term $\Delta gw + \Delta s$ thus becomes -0.163 to 0.1 km^3 for 2011. Thus, the water consumption in Zhangye matches the water allocation plan and does not exceed the water quota given.

While the water quota for the middle reaches was not exceeded, the runoff at the station Langxinshan was 0.53 km^3 in 2000–2008 (Zhang et al. 2011). This runoff is equivalent to the inflow for the above equation. As the Heihe river basin is endorheic, there is no outflow from the lower reaches. Precipitation was 0.017 km^3 in 2011 (http://www.tutiempo.net). ET for 2011 was determined with 0.28 km^3. Thus, $\Delta gw + \Delta s$ for the lower reaches (Ejina) for 2011 was 0.267 km^3. Guo et al. (2011) and Zhao et al. (2007) state that there is a transfer loss of 30 %, due to evaporation and leakage, from Langxinshan to the center of Ejina. If this 30 % transfer losses was included into the calculation for the lower reaches, than $\Delta gw + \Delta s$ still would be 0.108 km^3/a. Thereby, the precipitation in Ejina and Zhangye in 2011 was below the long-term average. Thus, it can be concluded that the water allocation plan with respect to the lower reaches of the Heihe River is fulfilled.

Conclusions

In this study, the ET_a of agriculture and natural ecosystems was assessed through the remote sensing-based S-SEBI approach, to evaluate in how far water requirements for the lower reaches of the Heihe River are met, as fixed in the water allocation plan of the Heihe basin. Thereby, this study reflects the year 2011. The water allocation plan with respect to the lower reaches of the Heihe River was fulfilled in this year, even though the annual precipitation was below the long-term average (http://www.tutiempo.net).

A study by Jiang and Liu (2010) shows the positive effect of the implementation of the water distribution plan with regard to regeneration of vegetation, increasing of biodiversity, and decreasing of groundwater lowering. In contrast, Guo et al. (2009) claimed that positive changes, however, occurred only on a small scale and the overall structures and functions of the degraded ecosystem could not yet be recovered.

The water currently reaches the downstream river stretch during winter and spring. During those seasons, the groundwater layers are refilled and sustain the water supply for the natural vegetation for the following summer (Xiao et al. 2014). But, recruitment from seed germination, especially of the only forest-building tree species, *P. euphratica*, is not possible under the current water allocation, because the germination and establishment need summer floods (Thevs et al. 2008b; Xiao et al. 2014). Therefore, it would be essential to temporally adjust flooding events to the germination period of *P. euphratica* (Guo et al. 2009) and enable summer flood pulses at least every few years (Xiao et al. 2014), to sustainably protect the whole range of natural ecosystems along the downstream of the Heihe River.

Acknowledgments We thank the Kurt-Eberhard-Bode-Foundation within the Stifterverband für die Deutsche Wissenschaft for funding this research within the Research Project Sustainable water management and wetland restoration in settlements of continental-arid Central Asia. Furthermore, we thank the German Academic Exchange Service (DAAD) for funding the field work stay of Henrike Hochmuth in China.

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