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Water Consumption of Agriculture and Natural Ecosystems along the Ili River in China and Kazakhstan

Niels Thevs [1,2,*], Sabir Nurtazin [3], Volker Beckmann [2], Ruslan Salmyrzauli [3] and Altyn Khalil [2]

1. Central Asia Office, World Agroforestry Center, Bishkek 720001, Kyrgyzstan
2. Institute of Botanik and Landscape Ecology, University of Greifswald, Greifswald 17489, Germany; Volker.beckmann@uni-greifswald.de (V.B.); altyn.khalil@gmail.com (A.K.)
3. Biological Faculty, Kazakh National University, Almaty 050040, Kazakhstan; nurtazin.sabir@gmail.com (S.N.); ruslaan.200587@gmail.com (R.S.)

* Correspondence: N.Thevs@cgiar.org; Tel.: +996-771-771-993

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Abstract: The Ili River is a transboundary river shared by China, upstream, and Kazakhstan, downstream. The Ili is the main water supplier to Lake Balkhash, the largest lake in Central Asia after desiccation of the Aral Sea. Agreements over water allocation have not been concluded between China and Kazakhstan. This paper investigated water consumption of agriculture and riparian ecosystems in the Ili river basin, to provide information for further debate on water allocation, through the Simplified Surface Energy Balance Index (S-SEBI) approach using Moderate Resolution Imaging Spectroradiometer (MODIS) satellite images. The overall water consumption in the Ili river basin was 14.3 km^3/a in 2000, 17.2 km^3/a in 2005, and 15 km^3/a in 2014. In 2000, China and Kazakhstan consumed 38% and 62% of the water, respectively. By 2014, the relative share of China's water consumption increased to 43%. In China, 80% of the water consumption is due to agriculture. High runoff during the past 10 years enabled increasing water consumption in China and sufficient water supply to agriculture and riparian ecosystems in Kazakhstan. When runoff of the Ili River decreases, as expected for most rivers in Central Asia, then irrigation efficiency has to be further increased in China, and irrigation systems in Kazakhstan have to be restored and modernized in order to reduce water consumption and protect Lake Balkhash and the riparian ecosystems.

Keywords: transboundary river; upstream-downstream conflict; remote sensing; evapotranspiration; MODIS; wetland; Central Asia; Lake Balkhash

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1. Introduction

Central Asia, which extends from the Caspian Sea into Mongolia, is largely dominated by drylands and mountains [1]. Furthermore, Central Asia is the region with the worldwide highest number of endorheic or closed river basins, i.e., rivers that do not drain into the sea, but instead drain into an end-lake or inland delta [2]. The most well-known end-lake was the Aral Sea [3]. The desiccation of the Aral Sea mostly due to irrigation water withdrawals is known as one of the worst man-made environmental disasters, and scientists have warned that the "Aral Sea Syndrome" could repeat in other parts of the world [4]. The major rivers in Central Asia have in common that they are transboundary rivers, along which there is an upstream-downstream conflict over water and competition for water between water users, like irrigated agriculture and natural ecosystems [5].

Following the desiccation of the Aral Sea, Lake Balkhash has become the largest lake of Central Asia with an area of 17,000 km^2 [6]. The Ili River delivers 70%–80% of the annual inflow into Lake

Balkhash. The Ili Delta, in total 8000 km^2 large, is the largest natural delta and wetland complex of Central Asia; it permanently receives water and, thus, still remains in a rather undisturbed stage [7–10]. In a dryland region like Central Asia, such inland deltas are of crucial importance, as they provide a wide range of ecosystem services, like fodder, raw material, fish, carbon storage, good water quality, tourism, and identity [10]. Furthermore, those inland deltas are a hotspot of biodiversity, as shown by the list of Ramsar Sites of Central Asia, for e.g., [9].

Therefore, on one hand, the Ili River is of crucial significance to sustain the runoff needed to maintain natural riparian ecosystems, like the Ili Delta, and Lake Balkhash as well as provide water for irrigated agriculture [11]. On the other hand, the Ili River is a transboundary river shared by Kazakhstan, downstream, and China, upstream (Figure 1). The Ili River's two source rivers, i.e., Künez and Tekes, have their headwaters in the Tianshan Mountains in Xinjiang, China. The largest tributary to the Ili River, the Kash River, originates from China, too. Thus, about two thirds of the Ili runoff are generated in Xinjiang, China.

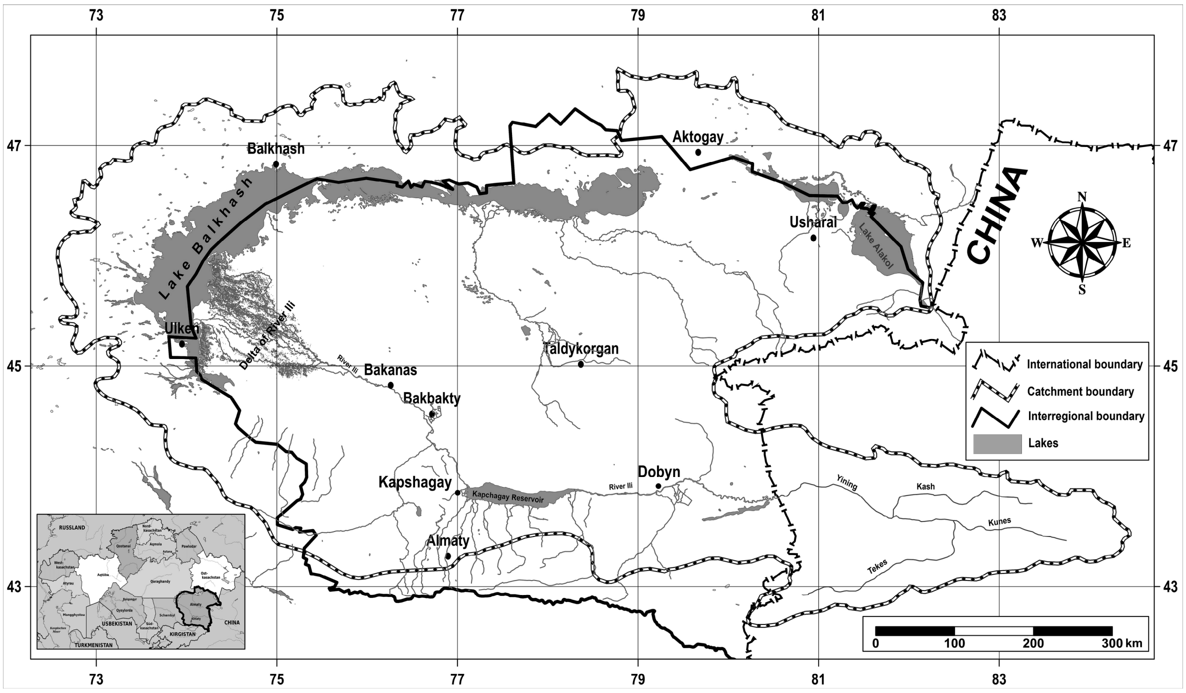

Figure 1. Map of the Ili river basin and Lake Balkhash [12].

Currently, most of the agricultural land along the Ili River is located in China. The second largest area of agricultural land is located between Almaty and the Kapchagay Reservoir along a number of rivers that were tributaries to the Ili River before agricultural land was reclaimed. Most of the natural riparian ecosystems along the Ili River are located in Kazakhstan, either Tugai forests along the Ili River between the border with China and the Kapchagay Reservoir or the vast wetlands of the Ili Delta. The Ili Delta, being the largest and in terms of biodiversity most significant natural riparian ecosystem along the Ili River [9,12,13], is located in a downstream position.

Along the Ili River, there is water competition and an upstream-downstream conflict over water between countries (China and Kazakhstan) and water users, i.e., agriculture versus natural riparian ecosystems. This competition most likely will be aggravated in the course of climate change and melting glaciers due to reduced river discharge [11]. Already, this competition has been leading to debates and statements that each of the conflicting parties or water users consumes too much water of the Ili River [12,14].

From 1998 to 2001, Kazakhstan and China had consultations over transboundary rivers shared by the two countries. In 2001, an agreement on the partnership with respect to utilization and protection of those transboundary rivers was signed between the two governments [15]. Under this agreement, the Kazakh-Chinese Joint Commission on the utilization and protection of transboundary rivers was established. The Commission has held annual meetings since 2003, during which, issues of water quality and natural disasters along the Ili River and other transboundary rivers were discussed. However, the issue of water allocation between China and Kazakhstan has not been negotiated and resolved [12,15,16].

This paper aims at contributing to the information needed to come to agreements over allocation of water against the background of competition over water. This paper investigated the water consumption of agriculture and riparian ecosystems in the Ili river basin, both in the Chinese and Kazakh parts, in order to provide data for further debate on water allocation.

The term water consumption is used as the water that leaves the river basin studied through evapotranspiration. The evapotranspiration was assessed through maps of the actual evapotranspiration (ET_a) derived from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data for the years 2000, 2005, 2009, 2010, and 2014.

2. Materials and Methods

2.1. Study Region

This study analyzed the water consumption of the major water consumers, agriculture and natural riparian ecosystems, in the Ili river basin. The Ili river basin is part of the Ili Balkhash Basin, which is shown in Figure 1. In total, about two thirds of the Ili runoff is generated in Xinjiang, China [7,8,17]. There, the two source rivers, Künez and Tekes, and the major tributary, the Kash River, originate in the Tianshan Mountains in Xinjiang, China. The Ili River delivers 70%–80% of the annual inflow into Lake Balkhash. The remaining 20%–30% stem from the four rivers: Karatal, Aksu, Lepsi, and Ayaköz [7].

The part of the Ili river basin in China corresponds with the Ili Autonomous Kazakh Prefecture (herein after: Ili Prefecture). This prefecture covers an area of 56,300 km^2 and is home to a population of 4.74 million people [18]. In 2004, the total area sown with grains (corn and wheat), oil seeds, cotton, and sugar beet being the major crops was 702,100 ha [19,20]. By 2014, the sown area increased to 1,322,700 ha. The areas planted with corn, cotton, and rice were substantially increased compared to 2004 and also 2010, e.g., corn increased from 183,420 ha in 2010 to 342,040 ha in 2014 and rice from 121,300 ha in 2010 to 194,100 ha in 2014 [18]. Irrigation demand has increased from 50–300 mm in 1989 to 400–600 mm in 2010 in most irrigated areas along the Ili River in the Ili Prefecture [21]. The Ili river basin in China is considered to offer the most favorable conditions for agriculture in Xinjiang [19]. Therefore, the Ili Prefecture was indicated as a key-region for further agricultural development in the 1990s [19].

In Kazakhstan, the Ili river basin harbors most of Kazakhstan's irrigated area, which amounts to 447,500 ha of irrigated fields, 41,400 ha of pasture land, and 11,900 ha of hay meadows. The major crop is wheat. Other important crops are corn, sugar beets, tobacco, fruits, vegetables, and rice [22]. In the Ili Delta, located at Lake Balkhash, the major land use is animal herding with *Phragmites australis* (common reed) being the major fodder plant [23,24]. The Kazakh part of the Ili Balkhash Basin is home to 3.3 million people, which is one fifth of the total population of Kazakhstan. The large majority of that population lives in the Ili river basin, which includes the City of Almaty with its population of about 1.5 million people [22,25].

The climate is continental and semi-arid to arid throughout the Ili river basin. Temperature and annual precipitation are shown in Table 1. The precipitation increases towards the mountains, as indicated by the fairly high precipitation of Almaty.

Table 1. Climatic features of Bayanbulak, Yining City, Almaty, and Bakanas (www.weatherbase.com).

Climatic Feature	Bayanbulak	Yining	Almaty	Bakanas
Elevation (m above sea level)	2459	669	846	395
Annual average temperature (°C)	−4	8	10	9.5
January average temperature (°C)	−25	−8	−4.7	−7.1
July average temperature (°C)	10	21	23.8	25.2
Annual precipitation (mm)	267	260	570	240.2
Average wind speed during growing season (April–October) (m/s)		2 *	1.1	2.7

Note: * Wind speed was only available from climate station Panfilov, about 70 km from Yining.

The headwaters of the Ili River, like the other major rivers of Central Asia, are fed by snow, glacier melt, and rainfall in the mountains. The long-term average runoff in the Ili river basin was 22.87 km^3/a, with 17.04.km^3/a generated in China and 5.83 km^3/a in Kazakhstan [7].

During the 1960s, about 15 km^3/a were drained into Balkhash Lake, with about 12 km^3/a coming from the Ili and 3 km^3/a from the four minor rivers [7,8]. In 1970, the Kapchagay Reservoir on the Ili River (Figure 1) in today's Kazakhstan was filled and the area under irrigation was increased. Thus, after 1970, the runoff of the Ili and the other rivers of the Ili Basin reaching Balkhash Lake shrunk to 12.2 km^3/a–12.9 km^3/a [26,27]. In 1983, Balkhash Lake reached a water level of 341 meters above sea level (m a.s.l.), which was 2 m lower than in the 1960s. The lake area shrunk to 16,000 km^2. 1988 was a positive turning point for the Ili River and Balkhash Lake, as the Kapchagay Reservoir was not further filled and 1988 was an extremely wet year [28]. By 2000, the water level rose to 342 m a.s.l. [29] and 342.85 m a.s.l. in 2012 [30]. During the past ten years, the annual average runoff of the Ili River, as measured at Dobyn at the Chinese-Kazakh border, was 493 m^3/s, while it was only 432 m^3/s for the period 1929 to 2006 (Figure 2).

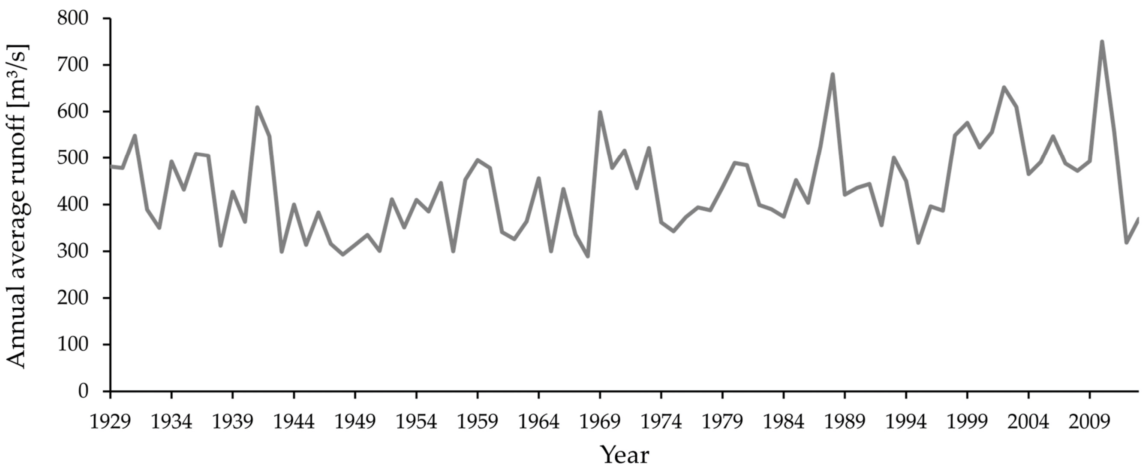

Figure 2. Annual average runoff of the Ili River at hydrostation in Dobyn (m^3/s) [30].

From 1984 to 2000, the annual water withdrawal dropped form 4.18 km^3 to 2.31 km^3 in the Kazakh part of the Ili river basin, while the water withdrawal in the Chinese part increased from 1.4 km^3 to 4.0 km^3 [22,31].

Most of the agricultural land along the Ili River in China as well as in Kazakhstan depends on irrigation from the river due to the low precipitation. The natural riparian ecosystems receive their water either through flood events or from the groundwater. The natural riparian ecosystems consist of reed beds, riparian forests (Tugai), halophytic meadows, desert meadows, and shrub vegetation, according to the Russian vegetation classification [9,32]. Reed beds are periodically or permanently submerged; they are mostly species-poor vegetation dominated by *Phragmites australis* and *Typha angustifolia*. The riparian forests, also called Tugai forests in the Russian and partly in the international literature [32,33], are composed of *Salix soongorica*, *S. wilhelmsiana*, *S. caspica*, *S. cinerea*, *S. serrulatifolia*, *S. alba*, *Populus pruinosa*, *P. euphratica* (syn. *P. diversifolia*), and *Elaeagnus oxycarpa*. Halophytic meadows are formed on sites which are not or seldom submerged, with groundwater levels of 1.5–2.5 m below the surface [32]. Desert Meadows are distributed on terraces along active river branches or on previous old flood plains with groundwater levels deeper than 2.5 m below the surface. The most widespread species are *Alhagi pseudalhagi*, *Tamarix ramosissima*, and *Halimodendron halodendron*. The shrub vegetation splits into *Tamarix* areas, *Haloxylon aphyllum* dominated areas, and shrub communities dominated by halophytes, e.g., *Halostachys caspica* or *Halocnemum strobilaceum* [26]. Reed beds and Tugai forests are by far the most productive riparian ecosystems [10,32,34,35] and the most water consuming ones [36,37].

2.2. Eavpotranspiration Mapping of Major Water Consumers

Actual evapotranspiration (ET_a) of the growing seasons 2000, 2005, 2009, 2010, and 2014 was mapped based on MODIS satellite images for agricultural land and riparian ecosystems in the Ili river basin. The Simplified Surface Energy Balance Index (S-SEBI) approach was used to make the ET_a maps [38–40].

ET_a can be determined point-wise through climate station data and interpolated to cover larger areas, for e.g., by calculating a reference evapotranspiration (ET) and applying crop coefficients from land use maps [41]. As such, interpolation is difficult over areas with sparsely distributed climate stations and/or lacking land use maps. Algorithms, e.g., Surface Energy Balance Algorithm (SEBAL) [42,43], Mapping EvapoTranspiration at high Resolution with Internalized Calibration (METRIC) [44], Surface Energy Balance Systrem (SEBS) [45], and Simplified Surface Energy Balance Index (S-SEBI) [38–40], have been developed in order to map ET_a on the basis of satellite images, Landsat, Moderate-resolution Imaging Spectroradiometer (MODIS), or Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), as reviewed by [46–48]. All these approaches require so-called anchor pixels in non water-limited vegetation and areas with no evapotranspiration. Most approaches need climate data from the location of the anchor pixels in the non water-limited vegetation. As such, climate station data are not available so the S-SEBI approach was chosen.

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

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

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 [35]. Evapotranspiration is expressed by the latent heat flux and can be computed by solving Equation (1) for λET:

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

The Simplified Surface Energy Balance Index (S-SEBI) applies the concept of the evaporative fraction (ET_f) in order to solve the land surface energy balance [32]:

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

G = 0, when daily values are calculated instead of instantaneous values [40]. If energy values are converted into evapotranspiration values, Equation (2) can be expressed as [38]:

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

In Equation (4), the net radiation is expressed as potential evapotranspiration (ET_{pot}) and latent heat flux as the actual evapotranspiration (ET_a).

ET_{pot} was computed after [36] 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 7 2012). Since there were no transmissivity values available from climate stations, the value of 0.685 was adopted from a study in the Tarim Basin, Xinjiang, China [36].

ET_f is the part of ET_{pot} which is realized as evapotranspiration, i.e., as ET_a. ET_f is calculated based on anchor pixels, the so-called cold and hot pixels [38–40,42,43]. Cold pixels are those pixels where $ET_a \approx ET_{pot}$ and $ET_f \approx 1$. The land surface temperature (LST) is low, because the available energy is used for evapotranspiration. In contrast, in hot pixels, $ET_a = 0$ and $ET_f = 0$. In hot pixels, the land surface temperature is high, because all available energy is converted into sensible heat flux. Technically, cold pixels cover well-watered vegetation without water stress for the plants during the study period [49]. Hot pixels are areas without vegetation coverage, but are not sealed like streets or roofs, and do not heat up due to other reasons like dark soil or locally high temperatures in dune valleys. In the S-SEBI approach, a linear relationship between the land surface temperature (LST) and ET_f is assumed. Thus, ET_f is calculated as follows:

$$ET_f = (T_h - T_x)/(T_h - T_c) \quad (5)$$

T_h, T_c, and T_x refer to the LST at the hot pixels, cold pixels, and the pixel, for which ET_f is calculated, respectively [38–40].

As LST decreases with elevation, this linear relationship can only be assumed for areas with small elevation differences. Therefore, the study area was split into three subregions and ET_a maps were produced for each of those subregions. The subregions were (1) the Ili River downstream of Kapchagay with the rice areas around Bakbakty, Bakanas and the Ili Delta, (2) all areas between an elevation of 450 m and 700 m a.s.l., and (3) all areas between 700 m and 900 m a.s.l. Above 900 m a.s.l. no areas were available to select cold and hot pixels.

Cold pixels were chosen from wetlands with dense reed vegetation and small areas of open waters which were present during the whole growing season. Hot pixels were selected from sandy areas adjacent to either agricultural land or riparian ecosystems, but far enough to avoid boundary effects of the LST. Fallow agricultural land was not chosen for hot pixels, as suggested in [39], because no agricultural field actually had the size of a MODIS pixel (1 × 1 km). ET_a maps were produced every 8 days with MODIS 8-day lands surface temperature (MOD11A2) and 16-day albedo (MCD43A3) as input data. Missing ET_a data, for e.g., areas covered by clouds in one of the 8-day ET_a maps, were filled with the average of the preceding and following ET_a maps. ET_a maps were summed over the whole growing season to generate ET_a maps for the whole growing season. The growing season was defined from 1 April to 30 September.

ET_a maps were produced for the MODIS scene path 23 row 4 (scene center at 45.0° N 77.8° E), which covers most of the Ili river basin (Figure 3). Agricultural Land outside the ET_a maps, due to its location outside the MODIS scene map or due to its elevation above 900 m a.s.l., was included into the calculation of overall water consumption by applying the average ET_a of all agricultural land from inside the ET_a maps. The coverage of the MODIS scene path 23 row 4, greyish background in Figure 3, and the agricultural land outside the ET_a maps are shown in Figure 3.

Agricultural land area was taken from [39], who had digitized agricultural land manually from Landsat satellite images (Table 2).

The areas of dense reed vegetation, submerged and non-submerged, of the Ili Delta were taken from [8]. The area of riparian vegetation in the Ili river basin upstream of the Ili Delta was mapped out through a threshold of the Normalized Differential Vegetation Index (NDVI) of the MODIS images. That threshold was the average NDVI—standard deviation of NDVI of the dense reed vegetation of the Ili Delta.

Table 2. Agricultural land (ha) in the Ili river basin from 1970s to 2013 [50].

Country	1970s	1990s	2001	2013
Kazakhstan	1,242,170	1,093,362	613,317	492,958 *
China	572,294	630,928	808,551	940,276
Total	1,814,464	1,724,290	1,421,868	1,433,234

Note: * Part of the fields in Kazakhstan are planted only if there is enough water available. This figure only reflects 2013.

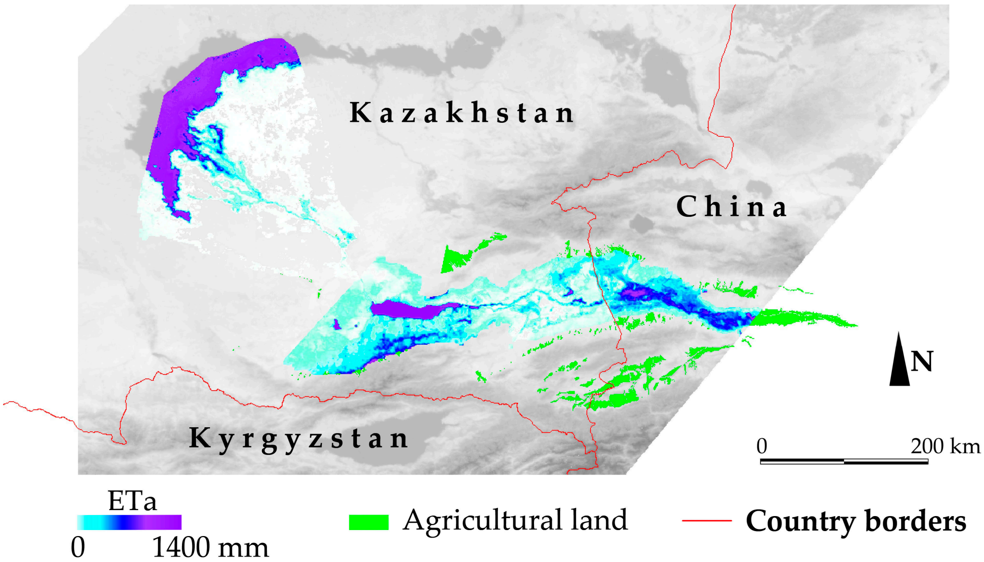

Figure 3. Map of actual evapotranspiration (ET_a) in 2014. In this map, ET_a of open waters has not been corrected to 1000 mm during the growing season. The greyish background is the land surface temperature (LST) image from 5 August 2014 of the Moderate Resolution Imaging Spectroradiometer (MODIS) scene path 23 row 4.

Major water bodies were digitized manually. Their evaporation was assumed as 1000 mm over the growing season [7,8].

Monthly reference evapotranspiration (ET_o) and crop evapotranspiration (ET_c) of cotton, wheat, rice, and reed were calculated after [41] for the climate stations Panfilov, Almaty, and Bakanas (www.weatherbase.com), in order to have a validation of the ET_a maps. As Yining lacked wind data, nearby Panfilov was chosen.

3. Results

Within the mapped area of agriculture, riparian ecosystems, in particular the wetlands of the Ili Delta and Kapchagay Reservoir, realized the highest evapotranspiration and, thus, water consumption, as shown in Figure 3.

The overall water consumption in the Ili river basin attributed to agriculture, riparian vegetation, and major water bodies started with 14.3 km^3/a in 2000, jumped to 17.2 km^3/a in 2005, and gradually decreased afterwards. The one exception to that trend was in 2010 where there was a slight increase compared to 2009 and 2014. The water consumption in 2014 was the lowest since 2005 (Table 3). In total, agriculture is the biggest water consumer, followed by riparian vegetation.

Table 3. Water consumption (km^3/a) of 2000, 2005, 2006, 2010, and 2014 for agriculture, riparian vegetation, and major water bodies along the Ili River in China and Kazakhstan.

Subarea	2000	2005	2009	2010	2014
China					
Agriculture	4.5	5.3	5.3	5.0	5.6
Riparian vegetation	0.9	0.9	1.0	0.9	0.8
Major water bodies	0.0	0.1	0.1	0.1	0.1
Water consumption China	5.4	6.3	6.4	6.0	6.5
Kazakhstan					
Agriculture	2.0	2.7	2.8	2.6	2.3
Riparian vegetation	5.6	6.6	5.3	6.2	4.6
Reed beds Ili Delta	2.13	2.36	1.91	2.42	1.82
Major water bodies (except for Balkhash Lake)	1.4	1.7	1.6	1.6	1.6
Water consumption Kazakhstan	9.0	10.9	9.7	10.4	8.5
Total water consumption	14.3	17.2	16.1	16.4	15.0

Divided by countries, the ratio of water consumption was 38% in the Chinese part of the Ili river basin and 62% in the Kazakh part in 2000. This ratio changed to 43% versus 57% in 2014. This went along with a rather steady increase of water consumption in the Chinese part of the Ili river basin from 5.4 km^3/a in 2000 to 6.5 km^3/a in 2014. This increase of water consumption in the Chinese part of the Ili river basin, including the slight decrease in 2010, was mainly due to the increasing water consumption of agriculture, which accounted for more than 80% of the water consumption in the Chinese part of the Ili river basin, as listed in Table 3.

The water consumption of the Kazakh part of the Ili river basin swung between 10.9 km^3/a in 2005 and 8.5 km^3/a in 2014. The most substantial decrease was observed from 2010 at 10.4 km^3/a to 2014 with 8.5 km^3/a. In the Kazakh part of the Ili river basin, riparian vegetation was the biggest water consumer, which accounted for more than half of the water consumption, followed by agriculture, and major water bodies. Among the water bodies, Kapchagay Reservoir evaporates the most, which made it a significant water consumer in the Kazak part of the Ili river basin. The water consumption of the riparian vegetation as well as the reed beds in the Ili Delta followed the trend of the overall water consumption in the Kazak part of the Ili river basin (Table 3) and decreased from 5.6 km^3/a in 2000 to 4.6 km^3/a in 2014.

The evapotranspiration of agriculture and riparian vegetation given in mm over the growing season (Table 4) showed similar trends over time as the water consumption given in Table 3.

Table 4. Actual evapotranspiration (ET_a) (mm) over the growing seasons of 2000, 2005, 2006, 2010, and 2014 for agriculture and riparian vegetation along the Ili River in China and Kazakhstan.

Subarea	2000	2005	2009	2010	2014
China					
Agriculture	475	541.9	548	513.8	573.9
Riparian vegetation	557.5	592.1	567.4	557.9	572.6
Kazakhstan					
Agriculture	351	475.6	484.8	447.1	405.2
Riparian vegetation	492.8	616.1	525.6	608.2	546.7
Riparian vegetation outside Ili Delta	338	464.8	426.9	427.4	428.3
Reed within the land cover classes Submerged dense reed and grazed reed	612.7	671	543.2	687.3	517.4
Submerged dense reed					815.2
Grazed reed					415.9

The monthly evapotranspiration of agriculture, averaged over all growing seasons studied, peaked in July in the Chinese part of the Ili river basin at 130.6 mm, while in the Kazakh part it peaked in June with 90.5 mm (Figure 4).

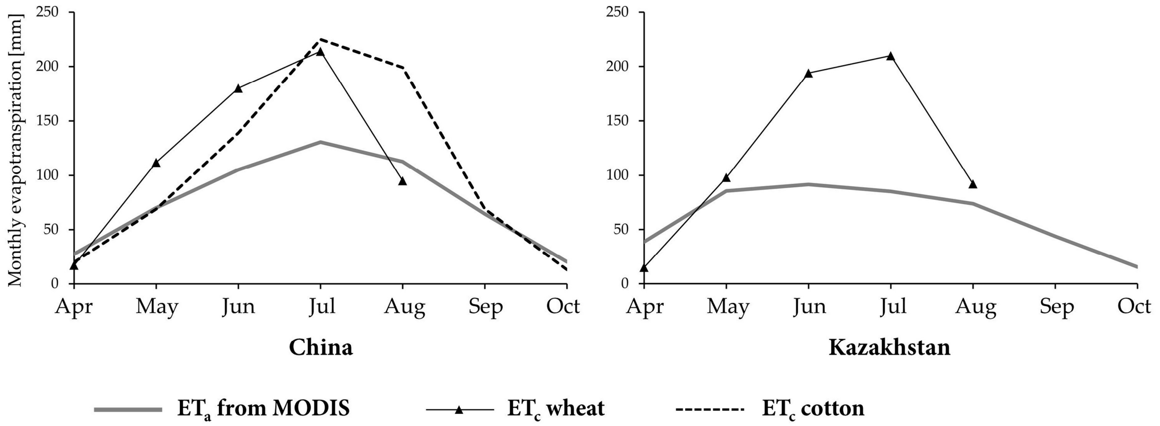

Figure 4. Monthly actual evapotranspiration, ET_a, from MODIS (average from 2000, 2005, 2009, 2010, and 2014) for agricultural land along the Ili River in China and Kazakhstan, and monthly ET_c for wheat and cotton.

ET_c as computed from the climate station data (Table 5) was higher than the values from the ET_a maps, which are shown in Table 4. The differences between ET_c (Table 5) and ET_a map (Table 4) are smallest for reed and submerged dense reed, respectively. ET_o and ET_c of wheat was highest in Bakanas (1079 mm and 727 mm, respectively) and lowest at Station Almaty (908 mm and 609 mm, respectively).

Table 5. Reference evapotranspiration (ET_o) and crop evapotranspiration (ET_c) according to [35] based on monthly climate data from stations Panfilov, Almaty, and Bakanas.

ET_o/crop	Panfilov	Almaty	Bakanas
ET_o	950	908	1079
ET_c of:			
Cotton	765		
Wheat (spring wheat)	621	609	727
Rice	865		1006
Reed (standing water)			1115
Reed (moist soil)			1082

Also, the monthly ET_c substantially exceeded the monthly evapotranspiration, as shown in the ET_a maps, during most months of the growing season (Figure 4). In July, monthly ET_c doubled ET_a from the ET_a maps (Figure 4). Only during early spring and autumn was the monthly ET_c slightly lower than ET_a maps. The monthly evapotranspiration from the ET_a maps of agriculture, averaged over all growing seasons studied, peaked in July in the Chinese part of the Ili river basin with 130.6 mm, while in the Kazakh part, it peaked in June with 90.5 mm (Figure 4).

When looking at larger areas of rice paddies, ET_a maps show values which are in the range of the computed ET_c of the climate station Panfilov (as shown in Figure 5 for an example from the Ili Prefecture). Also, the fields in the bottom line of pixels in Figure 5 show ET_a values between the ET_c of wheat and cotton of the climate station Panfilov (Table 5).

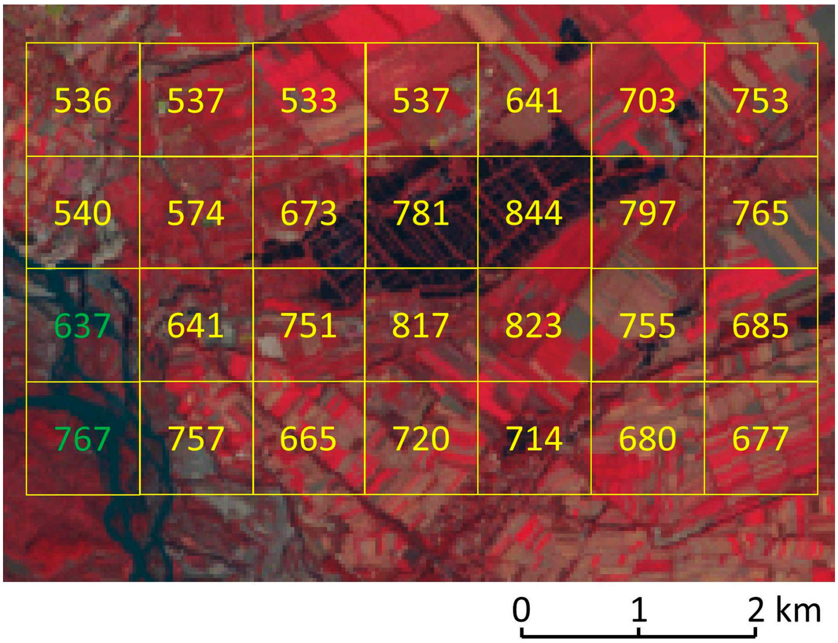

Figure 5. ET_a of a representative area of agricultural land in the Ili Prefecture over the growing season of 2014. Yellow boxes show pixels of the ET_a map. Yellow numbers: ET_a (mm) within the given pixel. These pixels belong to agricultural land as used in this study. Green numbers: ET_a (mm) within the given pixel. These pixels belong to riparian vegetation. Background: Landsat image (LC8, path 147, row 30) from 9 September 2013.

The ET_a values of a representative wetland as shown in Figure 6 are in the range of the ET_c given for reed in Table 5. ET_a is lower, between 803 mm and 848 mm, in the pixels that include a substantial amount of other vegetation than reed, which appears whitish in the background Landsat image.

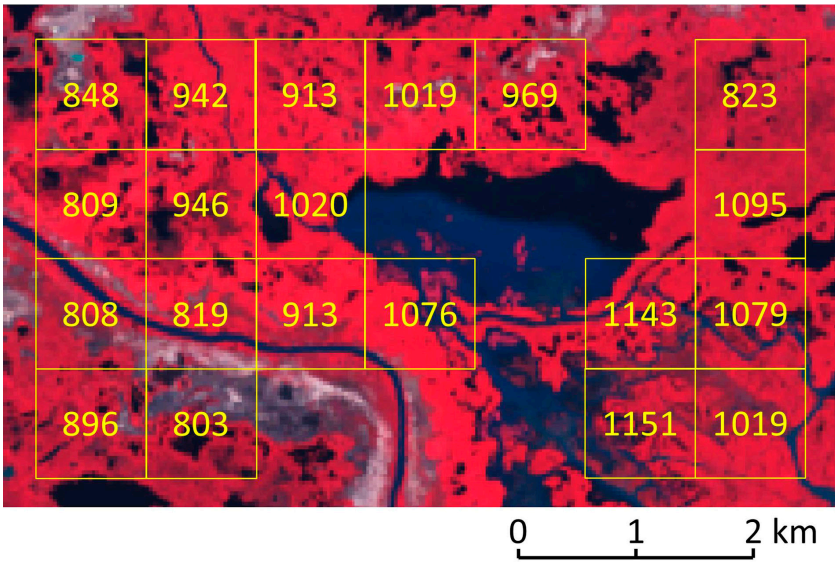

Figure 6. ET_a of a representative wetland area in the Ili Delta over growing season 2014. Yellow boxes show pixels of the ET_a map. Yellow numbers: ET_a (mm) within the given pixel. These pixels belong to submerged dense reed. Background: The areas not covered by pixels are either open waters or vegetation other than reed. Landsat image (LC8, path 151, row 28) from 19 August 2013.

4. Discussion

The evapotranspiration of agricultural land in the Ili river basin was in the range of other studies from Central Asia, for e.g., from the upper Ili river basin in China [17], Turkmenistan [51], and the Tarim Basin in Xinjiang [36]. However, the evapotranspiration found in this study was slightly lower than evapotranspiration for corn (668 mm) mapped with S-SEBI for Zhangye in Northwest China by [37]. This difference can be explained; corn in the Ili river basin is a crop, among others like wheat, which consumes less water. Zhangye is the major corn seed producer of China. Corn seed there is grown under drip irrigation and managed very carefully with regard to fertilizer and pests in order to avoid crop losses [37]. Such crop losses would reduce the evapotranspiration mapped from the satellite images. The evapotranspiration of the riparian vegetation (Table 3) in the Ili river basin was in the range of evapotranspiration of riparian ecosystems with 30% to 50% total vegetation coverage from the Tarim River [36]. Due to the large pixel size, pixels of riparian vegetation might contain areas that are not well vegetated or areas of low producing and low water consuming riparian vegetation. Only the evapotranspiration of submerged dense reed from the Ili Delta (Table 4) showed similar values as dense riparian vegetation (total coverage of 70% and more) from the Tarim River [36] and reed beds from the Amu Darya [51].

The huge differences between ET_a maps and computed ET_c also can be explained partly by the pixel size of MODIS; part of the MODIS pixels, which are assigned to either reed, riparian vegetation, or agricultural land, cover other vegetation with less evapotranspiration, as shown in Figure 6 as an example. Furthermore, the Penman-Monteith approach [41] follows the assumption that crops are well managed and never water stressed. This assumption does not hold true for larger parts of fields in the Kazakh part of the Ili river basin [22].

The increase of water consumption by agriculture in the Ili Prefecture (Table 3) is in line with the increase in the area under agriculture and the increase of evapotranspiration given in Table 4. The increasing evapotranspiration can be explained by a shift from wheat and oil seeds to rice and corn in the Ili Prefecture. Rice and corn are more water consuming than oil seeds and wheat [41]. In the Kazakh part of the Ili river basin, wheat is dominating with more winter wheat than in the Ili Prefecture. Winter wheat is harvested earlier in summer than corn or rice so that its peak water demand is earlier, too. This is reflected by the monthly evapotranspiration shown in Figure 4, as the peak for Kazakhstan is earlier and lower than in the Ili Prefecture. The dominance of wheat also explains the lower evapotranspiration in the Kazakh part of the Ili river basin compared to the Ili Prefecture. The water consumption of agriculture in the Kazakh part of the Ili river basin does not follow such a clear trend like in the Ili Prefecture, because part of the land is planted according to availability of water in autumn and spring. This applies for agricultural land around Almaty with its rather high precipitation (Table 1). There, a considerable part of agriculture relies mainly on rain and only occasionally use additional irrigation. As a significant part of the irrigation systems are still not working, farmers count on rain and decide to crop or not based on the weather conditions.

The water consumption of the riparian vegetation follows roughly the runoff of the Ili River as shown in Figure 2 [30]. The water consumption of the riparian ecosystems increased from 2000 to 2005 as the runoff at the beginning of the 2000s was higher than during end of the 1990s. From 2004 to 2009, the runoff decreased, which is reflected in a lower water consumption of the riparian ecosystems in 2009 compared to 2005. The extremely high runoff in 2010 corresponds with the increase of the water consumption of riparian ecosystems in 2010, but this increase in water consumption was not as extreme as at the peak of runoff, which can be seen in Figure 2. After 2010, the runoff dropped to levels similar to end of the 1990s. This is reflected in the low water consumption in 2014. The riparian ecosystems have a delayed reaction of the runoff. During a period of low runoff, part of the riparian ecosystem degrades due to water shortage. The remaining area of that riparian ecosystem will consume less water. During a following period with high runoff, the riparian ecosystems expand again, which needs some time, so that the resulting increase of water consumption takes place 2–3 years after the increase of runoff. In addition to the low runoffs before 2014, increased water consumption of agriculture upstream in the Ili Prefecture is another reason contributing to the shrinking water consumption of riparian ecosystems along the Ili River in Kazakhstan. Only agriculture upstream in the Ili Prefecture showed a significant upward trend.

If the long term average annual runoff of the Ili river basin of 22.87 km^3/a [7] is considered, then a runoff between 5.7 km^3/a and 8.5 km^3/a could drain into Lake Balkhash under the water consumption listed in Table 3. Even considering that this runoff is only 70% to 80% of the water that eventually reaches Lake Balkhash, because the four minor rivers drain the remaining water into the lake, these 5.7 km^3/a to 8.5 km^3/a are well below the runoff that drained into Lake Balkhash in the 1960s and still below the runoff into Lake Balkhash during the 1970s, when the Kapchagay Reservoir was filled. Irrigation efficiency over NW China increased from 0.42 in 2000 to 0.48 in 2010 [21]. For the Kazakh part of the Ili river basin, a canal efficiency of 0.59 was reported [31], which will result in an overall irrigation efficiency lower than that in China. So, through restoration of canals and modernization of irrigation systems towards drip or sprinkler irrigation, the water consumption of agriculture in the Kazakh part of the Ili river basin could be reduced substantially. In China, since it already has attained a higher irrigation efficiency, there is less space for improvement per area, but due to the larger total area of agriculture, further improvements in the field of irrigation efficiency could still reduce water consumption substantially. If both countries reduced their water consumption attributed to agriculture by 1 km^3/a, at least a runoff into Lake Balkhash as high as that seen during the 1970s, when the Kapchagay Reservoir was filled, could be attained under the average runoff of the Ili river basin as considered above.

Nevertheless, the water level of Lake Balkhash has risen since the 1980s. The increase of the water level of Lake Balkhash, while water consumption takes place that presumably does not allow runoff levels like in the 1960s, can be explained by the high runoff from the headwaters of the Ili River, as shown in Figure 2. Such high runoff during the recent past is explained by accelerated glacier melt in the course of climate change [11]. So far, the high runoff in the near past has enabled increasing water consumption in the Ili Prefecture, while maintaining large areas of riparian ecosystems downstream. However, 2014 showed a situation of low runoff measured at Dobyn, while water consumption upstream in the Ili Prefecture still increased, but riparian ecosystems in Kazakhstan, especially the Ili Delta, realized less water consumption. This reduction in water consumption of the riparian ecosystems was coupled with a reduction in productivity of those ecosystems, as witnessed during field observations in, for e.g., [24]. In the context of the upstream-downstream situation along the Ili River, the increase of agricultural water consumption in the Ili Prefecture has taken place at the cost of water consumption of the riparian ecosystems along the Ili River downstream in Kazakhstan.

The computed ET_o and ET_c (Table 5) showed the highest values for Bakanas, which can be explained as Bakanas has the highest temperatures in the summer and the highest wind speed (Table 2) during the growing season. Therefore, agriculture in Bakanas will be less water efficient than in the other major agriculture areas along the Ili River, assuming similar yield levels and irrigation infrastructure.

In the course of climate change, it is expected that the runoff of most rivers in Central Asia will decrease substantially within this century. When the runoff of the Ili River decreases as expected for most rivers in the region of Central Asia, then water consumption upstream in the Ili Prefecture and in Kazakhstan has to be reduced substantially, in order to protect Lake Balkhash and the Ili Delta in their current area and status. In Kazakhstan, restoration of irrigation infrastructure and a shift to drip or sprinkler irrigation needs to take place in order to contribute to the protect ion of Lake Balkhash and the Ili Delta. In China, irrigation needs to be improved further. Due to the larger agricultural area in China, further improvements in irrigation efficiency—to a level that Kazakhstan also needs to attain—will have a substantial effect to reduce water consumption and, thus, also contribute to the protection of Lake Balkhash and the Ili Delta. All over the Ili river basin, high water consuming crops like rice, corn, and cotton should be reduced in area or at least not expanded, and crops that consume less water, like wheat or flax, should not be reduced in area.

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