Investigation of crop evapotranspiration and irrigation water requirement in the lower Amu Darya River Basin, Central Asia postprint

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Abstract

High water consumption and inefficient irrigation management in the agriculture sector of the middle and lower reaches of the Amu Darya River Basin (ADRB) have significantly influenced the gradual shrinking of the Aral Sea and its ecosystem. In this study, we investigated the crop water consumption in the growing seasons and the irrigation water requirement for different crop types in the lower ADRB during 2004–2017. We applied the FAO Penman–Monteith method to estimate reference evapotranspiration (ET0) based on daily climatic data collected from four meteorological stations. Crop evapotranspiration (ETc) of specific crop types was calculated by the crop coefficient. Then, we analyzed the net irrigation requirement (NIR) based on the effective precipitation with crop water requirements. The results indicated that the lowest monthly ET0 values in the lower ADRB were found in December (18.2 mm) and January (16.0 mm), and the highest monthly ET0 values were found in June and July, with similar values of 211.6 mm. The annual ETc reached to 887.2, 1002.1, and 492.0 mm for cotton, rice, and wheat, respectively. The average regional NIR ranged from 514.9 to 715.0 mm in the 10 Irrigation System Management Organizations (UISs) in the study area, while the total required irrigation volume for the whole region ranged from 4.2$\times 10^9 to 11.6\times$10^9 m^3 during 2004–2017. The percentages of NIR in SIW (surface irrigation water) ranged from 46.4% to 65.2% during the study period, with the exceptions of the drought years of 2008 and 2011, in which there was a significantly less runoff in the Amu Darya River. This study provides an overview for local water authorities to achieve optimal regional water allocation in the study area.

Full Text

Preamble

Investigation of Crop Evapotranspiration and Irrigation Water Requirement in the Lower Amu Darya River Basin, Central Asia

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Abstract: High water consumption and inefficient irrigation management in the agriculture sector of the middle and lower reaches of the Amu Darya River Basin (ADRB) have significantly influenced the gradual shrinking of the Aral Sea and its ecosystem. In this study, we investigated crop water consumption during growing seasons and the irrigation water requirement for different crop types in the lower ADRB from 2004 to 2017. We applied the FAO Penman-Monteith method to estimate reference evapotranspiration (ET_0) based on daily climatic data collected from four meteorological stations. Crop evapotranspiration (ETc) of specific crop types was calculated using crop coefficients. We then analyzed the net irrigation requirement (NIR) based on effective precipitation and crop water requirements. The results indicated that the lowest monthly ET_0 values in the lower ADRB occurred in December (18.2 mm) and January (16.0 mm), while the highest monthly ET_0 values occurred in June and July, with similar values of 211.6 mm. Annual ETc reached 887.2 mm, 1002.1 mm, and 492.0 mm for cotton, rice, and wheat, respectively. The average regional NIR ranged from 514.9 to 715.0 mm across the 10 Irrigation System Management Organizations (UISs) in the study area, while the total required irrigation volume for the entire region ranged from 4.2$×10^{9}$ to 11.6$×10^{9}$ m^3 during 2004–2017. The percentages of NIR in surface irrigation water (SIW) ranged from 46.4% to 65.2% during the study period, with the exceptions of the drought years 2008 and 2011, during which there was significantly less runoff in the Amu Darya River. This study provides an overview to assist local water authorities in achieving optimal regional water allocation in the study area.

Keywords: crop evapotranspiration; crop water requirement; net irrigation requirement; CROPWAT model; Amu Darya River; Aral Sea

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1 Introduction

Irrigation is a critical aspect of water resource management in inland river basins and essential for policy formulation in the agricultural sector. Water security in arid regions is extremely sensitive to climate change and increasing human activities [?, ?, ?, ?]. It is closely tied to knowledge of available water resources and the spatiotemporal variations of water demand from different users [?, ?, ?, ?]. The Amu Darya River (ADR) is vital to life in four Central Asian countries as it is the major source of water for domestic, agricultural, power generation, and industrial purposes [?, ?, ?]. Climate change in the headwater region and human activities in the lower reaches jointly impact water availability along the river [?, ?, ?, ?].

Calculations of water consumption for individual crop types are an important element of regional water balance analysis. These calculations are useful for regional water resource planning, improving irrigation system efficiency, and maintaining supply and balance in canal systems [?, ?, ?]. Regulating irrigation efficiency is an important policy process for agricultural development [?, ?]. Through improved water policy and management in arid regions, significant water savings could be achieved in irrigated agriculture [?, ?, ?].

The Amu Darya River Basin (ADRB) is an inland river basin in Central Asia [?, ?, ?] shared by Turkmenistan and Uzbekistan for agriculture [?, ?, ?]. During recent decades, a large increase in water used for irrigation, particularly for cotton production [?, ?, ?], has been a leading factor in the retreat of the Aral Sea and its ecological deterioration [?, ?, ?]. Although water misuse began in the mid-1920s when the Aral Sea Basin was under Soviet control [?, ?, ?], massive water withdrawal from irrigation canals such as the Karakum Canal [?, ?, ?, ?] has caused severe water scarcity in the downstream region [?, ?, ?]. In 1991, the state government launched a river channel renovation project to minimize damage to the natural water system [?, ?].

However, little research has examined irrigation water requirements and irrigation efficiency in the lower ADRB due to the lack of location-specific crop type information and irrigation scheduling for different crops [?, ?]. Irrigation efficiency is extremely low in the oasis located in the lower ADRB [?, ?, ?]. Improper use of irrigation water adversely affects crop yields in the lower ADRB [?, ?, ?].

Uzbekistan is considered one of the largest irrigation farming countries in Central Asia. Proper use of existing water and land resources can increase crop production and yields in the agriculture sector. Moreover, determining the water requirement for a particular crop can prevent large-scale water wastage beyond normal crop watering [?, ?, ?]. To minimize water shortages in Uzbekistan, including the lower ADRB [?, ?, ?], it is important to systematically irrigate crops based on their actual water demand [?, ?, ?]. Evapotranspiration is one of the best indicators for quantifying the impact of climate change and estimating water consumption of different crop types [?, ?, ?]. The FAO (Food and Agriculture Organization of the United Nations) CROPWAT model is a widely used method for calculating actual crop water use due to its practicability [?, ?, ?, ?].

Therefore, the objective of this study is to investigate the spatiotemporal changes of crop evapotranspiration (ETc) and water requirements for the main crop types cultivated within the irrigated area of the lower ADRB. The study estimated the ETc of cotton, winter wheat, rice, maize, alfalfa, various fruits and vegetables, melon, and potato (household-based) during the growing seasons from 2004 to 2017. The results will help improve irrigation efficiency, prevent water wastage, and ensure optimal regional water allocation in the study area.

2.1 Study Area

The study area comprises the lower reaches of the ADRB [Figure 1: see original paper], located in the Republic of Uzbekistan, Central Asia. The ADR is one of the major water sources in Uzbekistan and contributes the largest amount of water inflow to the Aral Sea. The main river sources of the ADR are the Vakhsh and Panj rivers (upstream) in the Republic of Tajikistan and Afghanistan. The ADR length is 2540 km from the Panj River, which is the main tributary of the ADR. Previously, the water management system was governed at a regional level in Uzbekistan. Since July 21, 2003, the previous administrative-territorial water management system was replaced with a basin principle of irrigation systems management [?, ?]. The Ministry of Agriculture and Water Resources divided the country into several large river basins, named Basin Management of Irrigation Systems (BUIS), with several Irrigation System Management Organizations (UISs) included in each BUIS. The main task of BUIS is allocating water to irrigation systems and main canals. UISs control water distribution in district canals and provide feedback to the main BUIS. The Water User' s Association (WUA) is responsible for water distribution to farmers, who are responsible for water demand and delivery regime to the WUAs according to crop type and area [?, ?]. The lower ADR BUIS (42°54 31.20 N, 59°12 44.24 E) in the lower ADRB is one of the largest basin management areas in Uzbekistan [Figure 1: see original paper]. Elevation in the study area decreases from southwest to northwest, ranging from 100 to 60 m above sea level.

The major portion of the study area is located in the Republic of Karakalpakstan (an autonomous republic within Uzbekistan) with six UISs (area of 1.89$×10^{4}$ km^{2}), while the remainder lies in the Khorezm region with four UISs (area of 0.46$×10^{4}$ km^{2}). The irrigated area is approximately

$0.75\times10^{6}-0.80\times10^{6}$ ha. The annual average air temperature is about 5.0°C–7.0°C, with maximum summer temperatures reaching 40.0°C. In winter, minimum temperatures decrease below -20.0°C. The number of sunny days in this region is 180–200 d/a. Annual precipitation ranges from 100 to 140 mm. Irrigated agriculture in the study area is the largest water consumer in Uzbekistan. Available water resources can be lower than 4.147×10^{9} m^3 in a dry year and higher than 11.581×10^{9} m^3 in a wet year. Agricultural water consumption largely depends on surface water, primarily from the ADR.

2.2 Data Sources

2.2.1 Meteorological Data

Meteorological data from 2004 to 2017 were obtained from the Kungrad, Chimbay, Nukus, and Urgench stations from the National Oceanic and Atmospheric Administration (https://gis.ncdc.noaa.gov/maps/ncei/cdo/daily), including daily average temperature, daily maximum temperature, daily minimum temperature, dew point temperature, average wind speed, average air pressure, and precipitation. Monthly precipitation and temperature data from the Center of Hydrometeorological Service of the Republic of Uzbekistan (Uzgidromet) were used for comparison and accuracy assessment of the downloaded climate data. Spatial distribution factors were processed using Thiessen' s Polygon [**?**, **?**].

To understand background information about this region, we analyzed annual average temperature and annual precipitation at the four meteorological stations (Chimbay, Kungrad, Nukus, and Urgench). During 2004–2017, annual average temperature ranged from 11.0°C to 14.5°C in the study area and showed decreasing trends at all four stations. The variations in annual average temperature were similar across stations, with minimum values in 2014 and maximum values in 2004 and 2016 [Figure 2: see original paper]. Average annual precipitation ranged from 80 to 180 mm during the study period and showed increasing trends at all stations. The Chimbay station had the highest annual precipitation, while the lowest values were recorded at the Urgench station [Figure 2: see original paper].

2.2.2 Planting Pattern and Crop Coefficient (Kc)

The main crop types in the lower ADRB included cotton, wheat, rice, maize, alfalfa, various fruits and vegetables, melon, potato (household-based), and feed crops (mainly sorghum). The area for each crop type as a percentage of the total area during 2004–2017 is shown in Figure 3 [Figure 3: see original paper]. Each irrigation area had its own variation within the cultivated area, with cotton, wheat, rice, and sorghum being the main crops. There were significant differences in planting patterns among the 10 UISs. For the four UISs in the northern part of the study area (Suenli, Kattagar-Bozatau, Kizketken-Kegeyli, and Kuanishjarma), sorghum was the most important crop type, accounting for more than 60% of the study area. For the six UISs in the southern part, cotton was the main crop type, occupying 40% of the total irrigated area of the lower ADR BUIS. The planting area of wheat was relatively small, accounting for 15% of the study area. Rice cultivation was mainly distributed in the Kattagar-Bozatau, Kuanishjarma, Koramazi-Kilichniyozboy, and Toshsoka UISs, with planting area percentages less than 10%. However, the rice planting area gradually increased from 2004 to 2017, particularly in the Kattagar-Bozatau, Kuanishjarma, and Toshsoka UISs, due to rising market prices.

Due to elevated geography and local climatic conditions, the growing season started two or three weeks later in the northern regions (e.g., Khorezm and Karakalpakstan) compared with other regions in Uzbekistan [?, ?, ?]. Crop seeding and harvesting dates were collected from the Ministry of Agriculture and Water Resources. Kc values represent crop-specific characteristics that depend on crop type, growing stages, duration, climate, and location [?, ?]. Kc is a plant property used in estimating evapotranspiration [?, ?] and was obtained from the FAO database for each crop type during initial, development, mid-season, and late-season stages [?, ?]. Crop seasonal information in the study area is listed in Table 1 .

3.1 Reference Evapotranspiration (ET_0)

The FAO Penman–Monteith model is considered the universal standard for estimating ET_0 [?, ?, ?] and is widely used globally in the absence of measured data [?, ?, ?, ?]. Variables used for ET_0 calculation in this study included daily maximum and minimum temperature, humidity, hours of sunshine, and wind speed. ET_0 values were calculated using CROPWAT 8.0 software at daily time steps and adjusted to a monthly scale for analysis. The calculation formula is as follows:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where ET_0 is reference evapotranspiration (mm/d); R is net radiation at the crop surface (MJ/(m^2 · d)); G is soil heat flux density (MJ/(m^2 · d)), which equals zero; T is daily mean air temperature at 2 m height (°C); u_2 is wind speed at 2 m height (m/s); e is saturation vapor pressure (kPa); e is actual vapor pressure (kPa); e -e is saturation vapor pressure deficit (kPa); Δ is the slope of the vapor pressure curve (kPa/°C); and γ is the psychrometric constant (kPa/°C), considered as 0.0677 kPa/°C.

Allen et al. (1998) recommended the following equations to estimate net radiation:

$$R_n = R_{ns} - R_{nl}$$

$$R_{ns} = 0.77 \times SR$$

$$SR = 0.75 \times R_a$$

$$R_{nl} = \sigma \left[\frac{T_{max}^4 + T_{min}^4}{2} \right] (0.34 - 0.14\sqrt{e_a}) \left(1.35 \frac{SR}{SR_0} - 0.35 \right)$$

where R is net shortwave radiation (MJ/(m^2 · d)); R is net longwave radiation (MJ/(m^2 · d)); SR is incoming solar radiation (MJ/(m^2 · d)); R is extraterrestrial solar radiation (MJ/(m^2 · d)), depending on the Julian day number and station latitude, calculated as described by Allen et al. (1998) for each station; σ is the Stefan-Boltzmann constant (4.903$×10^{-9}$ MJ/(m^2 · d)); T and T are maximum and minimum temperature, respectively (°C); and SR_0 is clear-sky solar radiation (MJ/(m^2 · d)). The other parameters in Equation 1 were determined as follows:

$$\Delta = \frac{4098 \times e_s}{(T_{mean} + 237.3)^2}$$

where Δ is the slope of the vapor pressure curve (kPa/°C) and T is daily mean temperature (°C).

$$e_s = \frac{e_{max} + e_{min}}{2}$$

where e is saturation vapor pressure (kPa); e and e are saturation vapor pressures at maximum and minimum temperature, respectively (kPa).

$$e_a = 0.6108 \times \exp \left(\frac{17.27 \times T_{dew}}{T_{dew} + 237.3} \right)$$

where e is actual vapor pressure (kPa) and T is dew point temperature (°C).

3.2 Crop Water Requirement (CWR)

CWR is the amount of water equal to that lost from a crop due to evapotranspiration and equals the total actual evapotranspiration in a crop field during the growing season [?, ?]. Estimation of CWR is derived from ETc, calculated by Equation 9:

$$ET_c = K_c \times ET_0$$

where ETc is crop evapotranspiration (mm); Kc is the crop coefficient at a specific growth stage (dimensionless); and ET_0 is reference evapotranspiration (mm). Due to differences in planting patterns among irrigation regions, CWR varies by UIS [?, ?, ?]. Accordingly, we calculated regional crop water requirement (CWR g) in different UISs using Equation 10:

$$CWR_{reg} = \sum_{i=1}^{n} \frac{ET_{c,i} \times A_i}{A}$$

where CWR g is the average crop water requirement for each UIS (mm); i is a specific crop type (i = 1, 2, 3, ···, 10), such as cotton, wheat, rice, maize, alfalfa, melon, vegetables, potato, and sorghum; ET , is crop evapotranspiration (mm) for crop type i; A is the planting area of crop type i (m^2); and A is the total crop area in the UIS (m^2).

3.3 Effective Precipitation (Peff) and Net Irrigation Requirement (NIR)

Effective precipitation is the fraction of total precipitation from rainfall and snowmelt that is available for crop use and can be stored in soil [?, ?]. In this study, the following equations were used to calculate Peff [?, ?, ?]:

$$P_{eff} = \begin{cases} \frac{125 \times P - 2.5}{125} & \text{if } P \leq 250 \text{ mm} \\ 0.1 \times P + 125 & \text{if } P > 250 \text{ mm} \end{cases}$$

where Peff is effective precipitation (mm), used in the CROPWAT model to calculate monthly precipitation values, and P is monthly precipitation (mm).

NIR (mm) is the water quantity required for crop growth, or the amount of water necessary to reach field capacity. It represents the difference between CWR and Peff [?, ?]. NIR for each crop type is calculated by:

$$NIR = CWR - P_{eff}$$

To compare with actual irrigation volumes for each UIS, we calculated regional net irrigation requirement (NIR g, mm) and regional irrigation water demand (IWD g, m^3) as follows:

$$NIR_{reg} = CWR_{reg} - P_{eff}$$

$$IWD_{reg} = NIR_{reg} \times A$$

where NIR g is the regional net irrigation requirement for each UIS (mm); Peff is the average effective precipitation within the UIS; and A is the total crop area (m^2) in the UIS.

4.1 Estimation of ET_0

ET_0 values were calculated at a daily scale and adjusted to monthly data. Maximum ET_0 values occurred in summer months (211.6 mm in June and July), while minimum values occurred in winter months (18.2 mm in December and 16.0 mm in January) [Figure 4: see original paper]. Annual ET_0 ranged from 1110.0 to 1193.0 mm/a at Chimbay, 1137.0 to 1256.0 mm/a at Kungrad, 1147.0 to 1224.0 mm/a at Urgench, and 1126.0 to 1224.0 mm/a at Nukus meteorological stations. Both the highest monthly ET_0 and highest average annual ET_0 were observed at the Kungrad station.

4.2 Estimation of CWR in the Lower ADRB

CWR values for different crop types during 2004–2017 were calculated separately for each UIS. As shown in Figure 5 [Figure 5: see original paper], cotton, rice, alfalfa, and fruit crop fields had the highest water consumption, with average CWR values during the growing season of 887.2 mm, 1002.1 mm, 991.4 mm, and 883.6 mm, respectively. The average CWR for wheat fields was 492.0 mm, the lowest value in the study area. Average CWR values for maize, vegetables, melon, potato, and sorghum were 674.9 mm, 619.1 mm, 640.2 mm, 588.5 mm, and 665.0 mm, respectively.

To evaluate the accuracy of ETc estimation for different crop types in the lower ADRB, we compared estimated ETc values for cotton, wheat, rice, other grain (sorghum), alfalfa, vegetables, and potato with previous studies [**?**, **?**, **?**, **?**], with results shown in Table 2 . The results showed reasonable ranges, although our estimated ETc values for cotton and alfalfa were higher than those reported by Bobojonov (2008) and Schieder (2011), and similar to results from Liu et al. (2020). Estimated ETc values for wheat, rice, sorghum, and vegetables fell between the results of the three previous studies, while estimated ETc for potato was the lowest among previous calculations. These differences can be attributed to global change factors prevalent at the regional scale, such as decreases in temperature, soil moisture, and Kc changes [?, ?, ?, ?]. Additionally, uncertainty from meteorological input data cannot be ruled out. Previous studies were conducted in different time periods, and new climatic conditions may produce different ETc in this long, continuous time series.

Figure 6 [Figure 6: see original paper] shows CWR g in the 10 UISs. Results indicated that CWR g values in the four UISs in the northern part of the study area were lower than those in the six UISs in the southern part. The lowest CWR g was 599 mm in the Kizketken-Kegeyli UIS (observed in 2004), while the highest was 780 mm in the Pakhtaarna-Nayman UIS (observed in 2016). CWR g in a given area depended on both climate conditions and crop planting patterns. The most important factor influencing CWR g was temperature change, which is basic input data for evapotranspiration calculations. In the four UISs with lower CWR g values in the northern part, lower temperatures were observed at the Chimbay and Kungrad meteorological stations, while higher temperatures at the Nukus and Urgench stations corresponded to higher CWR g values in the six southern UISs. Moreover, low water-consuming crops such as sorghum and wheat were the main crop types in the four northern UISs, accounting on average for 71.1%, 70.6%, 69.7%, and 69.2% of total crop area in Suenli, Kattagar-Bozatau, Kizketken-Kegeyli, and Kuanishjarma UISs, respectively, during 2004–2017. For the six southern UISs, particularly Koramazi-Kilichniyozboy and Shovot-Kulovot, the area percentages of cotton and rice were relatively higher than in other UISs, resulting in the largest CWR g values in these two UISs.

4.3 Estimation of Peff and NIR

The key factor in irrigated agriculture is proper water allocation [?, ?]. Because Uzbekistan' s Ministry of Agriculture and Water Resources determines water supplies to each crop at the beginning of every year, improper use of specified water may lead to negative consequences such as water shortages in downstream zones. Figure 7 [Figure 7: see original paper] shows variations in CWR, Peff, and NIR at the BUIS scale. NIR values differed substantially among crop types, and NIR variation was highly related to changes in CWR and Peff. Rice had the largest water requirement, while wheat had the smallest. For most crops (except wheat), the highest estimated CWR values occurred in 2014, and the lowest in 2004. Due to differences in growth periods for main crop types, even under the same or similar climatic conditions, Peff varied considerably among crops. The highest Peff was estimated for fruits and alfalfa because of high precipitation received throughout the year, while the lowest Peff was estimated for rice. Higher Peff values were observed in 2007 and 2016.

Lower Peff indicates that supplementary irrigation is needed to meet daily CWR.

Therefore, rice was the crop type with the highest irrigation water requirement, with NIR values ranging from 901.4 to 1046.0 mm during 2004-2017. However, the lowest NIR occurred in 2007 due to higher Peff that year. The lowest NIR values occurred in wheat fields, ranging from 347.3 to 433.7 mm. Figure 8 [Figure 8: see original paper] shows NIR g and IWD g calculations for the 10 UISs. Results indicated that estimated NIR g for various crops was similar across different UISs due to similar climatic conditions in the study area. However, IWD g differed considerably due to variations in crop planting structure and total area among UISs. NIR g values were 514.9 mm and 715.0 mm in the Kizkegen-Kegeyli (2004) and Koramazi-Kilichniyozboy UISs (2017), respectively. The highest IWD g range in the Suenli UIS depended on crop area, varying from 1010.0$×10^{6}$ to 1200.0$×10^{6}$ m^3. The lowest IWD g ranged from 228.0$×10^{6}$ to 255.0$×10^{6}$ m^3 in the Koramazi-Kilichniyozboy UIS and from 260.0$×10^{6}$ to 302.0$×10^{6}$ m^3 in the Kattagar-Bozatau UIS, reflecting lower irrigation use in these areas.

4.4 Analysis of Irrigation Water Utilization in the Lower ADRB

Generally, the ratio of irrigation water requirement to actual irrigation water can express irrigation efficiency. Here, actual irrigation water volume included water from surface and groundwater sources [**?**, **?**]. However, only actual irrigation volume from surface water (surface irrigation water, SIW, m^3) was obtained during the study period. As shown in Figure 9 [Figure 9: see original paper], surface water supplied to irrigation areas in the lower ADRB was closely related to ADR inflow (i.e., at the Tuyamuyun-out hydrological station). Actual SIW allocated to the study area ranged from 4.2$×10^{9}$ to 11.6$×10^{9}$ m^3 during 2004-2017. The highest SIW values occurred in 2005 and 2010, which were typical wet years, while the lowest SIW occurred in 2008. To analyze SIW utilization degree in the study area, we calculated the percentage of IWD (sum of IWD g in the 10 UISs, m^3) in SIW. Percentages ranged from 46.4% to 65.2%, indicating that a significant amount of surface water distributed in the lower ADRB was wasted. However, in the drought years of 2008 and 2011, inflow from the ADR decreased sharply, and the percentage of IWD in SIW rose to 97.3% and 98.6%, respectively, requiring more groundwater extraction to supplement irrigation water shortages [**?**, **?**]. In this region, flood irrigation in sandy soils has low efficiency due to high water wastage. Another major problem is that some regions reuse irrigation return water, which naturally increases field salinity [**?**, **?**]. Therefore, it is necessary to develop optimal water allocation patterns according to real irrigation demand in each UIS (i.e., IWD g), which would provide scientific references for water allocation at crop field or regional scales. Water-saving technologies should be applied to improve irrigation water efficiency.

According to our results, high water-consuming crops including cotton, alfalfa, and rice consumed over 40% of irrigation water in the lower ADRB at the BUIS scale. Conrad et al. (2016) indicated that winter crops have potential for saving river water due to wheat' s lowest ratio of IWD to CWR. However, Uzbekistan's economy highly depends on cotton production, leaving little chance for widespread wheat promotion. Over the past few decades, overuse and waste of surface water resources have indirectly affected the Aral Sea and the region' s ecological environment, requiring greater consideration of ecological benefits in irrigation water allocation and water resources planning in the lower ADRB.

5 Conclusions

In this study, reference evapotranspiration (ET_0), crop evapotranspiration (ETc), and crop water requirement (CWR) in the lower Amu Darya River Basin (ADRB) during 2004–2017 were estimated using the FAO Penman-Monteith method, and net irrigation requirement (NIR) was analyzed. Average ETc (representing CWR) values for cotton, rice, and wheat were 887.2 mm, 1002.1 mm, and 492.0 mm, respectively. Regional CWR values across the 10 UISs ranged from 598.7 to 779.9 mm, and regional NIR ranged from 514.9 to 715.0 mm during the vegetation period each year. More than 40% of irrigation water was consumed by cotton, alfalfa, and rice, which had high NIR values. The annual volume of surface water allocated to the lower ADRB varied from 4.2×10^{9} to 11.6×10^{9} m^3. However, at least 46.4%-65.2% of this water was wasted in irrigation processes. The main reason for irrigation water loss is the long-standing prevalence of flood irrigation. Additionally, natural water losses from canals (evaporation and infiltration) are often severe. Excessive irrigation not only wastes water resources in arid inland regions but also results in fertilizer loss, soil salinization, and waterlogging.

Both CWR and NIR results at crop field and regional scales can serve as scientific references for irrigation water allocation and optimization among UISs in the lower ADRB. Existing irrigation procedures have significant potential for revision through water-saving approaches and innovative technologies such as drip irrigation. In most irrigation areas of China' s Xinjiang Uygur Autonomous Region, drip irrigation and other water-saving modes have been widely implemented, significantly improving water resource irrigation efficiency. These approaches will help improve irrigation water efficiency in the lower ADRB, Uzbekistan, thereby assisting in alleviating severe water policy tensions through sustainable management of water consumption among agrarian communities in the study area.

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