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ASSESSING WATER USE, ENERGY USE AND CARBON EMISSIONS IN LIFT-IRRIGATED AREAS: A CASE STUDY FROM KARSHI STEPPE IN UZBEKISTAN†

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ABSTRACT

The advantages of a nexus approach in addressing complex environmental challenges are becoming increasingly clear. In Central Asia, however, the nexus between water–food–energy has not received adequate attention, as the very few studies that have been conducted fell short of quantifying nexus trade-offs and benefits at a practical, small scale. This paper applies a quantitative accounting method to assess water and energy use intensity in irrigated areas of the Karshi Steppe of Central Asia that are supplied by pumping water uphill (lift-irrigated) from the underlying river. The results indicated that the potential water and energy savings as well as the greenhouse gas (GHG) emission reductions could be achieved by applying an optimal planning deficit irrigation schedule simulated using CROPWAT 8. Some 575 MCM (million cubic metres) of water and 259 GWh of electricity can be saved, while the CO_2 equivalent emissions can be reduced by almost 122 000 t. Achieving these savings requires a mix of technical and policy components. This paper describes an example of proper irrigation planning as a tool for water/energy savings and consequent reduction of CO_2 emissions. © 2019 John Wiley & Sons, Ltd.

KEY WORDS: water use; pump irrigation; energy use; irrigation scheduling; carbon emissions; Kashkadarya; Uzbekistan

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RÉSUMÉ

Les avantages d'une approche par lien pour résoudre des problèmes environnementaux complexes deviennent de plus en plus évidents. En Asie centrale, toutefois, le lien entre eau, nourriture et énergie n'a pas fait l'objet d'une attention suffisante, car les très rares études menées n'ont pas permis de quantifier les compromis et les avantages du lien à une petite échelle. Ce papier applique une méthode de comptabilité quantitative pour évaluer l'intensité d'utilisation de l'eau et de l'énergie dans les zones irriguées de la steppe de Karshi en Asie centrale alimentées par le pompage d'eau en amont (irrigué par élévation d'eau) à partir du fleuve sous-jacent. Les résultats ont indiqué que les économies potentielles d'eau et d'énergie ainsi que les réductions d'émissions de gaz à effet de serre (GES) pourraient être réalisées en appliquant un calendrier optimal d'irrigation déficitaire simulé avec CROPWAT 8. Quelque 575 MCM (millions de mètres cubes) d'eau et 259 GWh d'électricité peuvent être économisés, tandis que les émissions d'équivalent CO_2 peuvent être réduites de près de 122 000 t. La réalisation de ces économies nécessite un mélange de composants techniques et politiques. Ce papier décrit un exemple de planification appropriée de l'irrigation en tant qu'outil permettant d'économiser de l'eau/de l'énergie et, par conséquent, de réduire les émissions de CO_2.
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MOTS CLÉS: utilisation de l'eau; irrigation par pompage; utilisation d'énergie; calendrier d'irrigation; émission de dioxyde de carbone; Kashkadarya; Ouzbékistan

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INTRODUCTION

Population growth and expanding food demand are putting increasing pressure on the planet. The global population increased from approximately 3 billion people in the 1960s to 7.4 billion in 2015 and a higher proportion now live in urban areas than in rural areas (World Bank (WB), 2017). Social welfare is improving as the ratio of the global population living on less than US$1.90 a day has decreased by a third in less than a quarter of a century, from 35.3% in 1990 to 10.7% in 2013 (constant prices; WB, 2017). This is changing dietary preferences and leading to overconsumption (Food and Agriculture Organization of the United Nations (FAO), 2017). Notably, calories from animal sources in developing countries have more than doubled by the 1990s compared with the proportion in the 1960s (World Health Organization (WHO) and FAO, 2003).

Major challenges are still emerging. The global population is predicted to reach nearly 10 billion people by 2050 (United Nations, 2015), and to satisfy growing food demand requires agricultural production to be increased by 60% (World Water Assessment Programme (WWAP), 2015; FAO, 2017). Between now and 2040, the global primary energy demand is expected to increase between 9 and 43% according to the main energy scenarios developed by the International Energy Agency (IEA) (2016). In parallel, the pressure induced by climate change is expected to decrease water availability (Addams *et al.,* 2009; WB, 2016; FAO, 2017). Competition is expected to intensify for limited natural resources (i.e. water, land, animal life) to satisfy environmental needs, produce food and sustain economic growth.

The use of natural resources is interrelated and interdependent and is commonly referred to as a nexus. Increasingly, the utility of applying a nexus approach that accounts for trade-offs and strengthening synergies across natural resources is receiving wide global recognition (Addams *et al.,* 2009; Overseas Development Institute (ODI) *et al.,* 2012; Asian Development Bank (ADB), 2013; FAO, 2014; Metzger *et al.,* 2016; WB, 2016). The nexus concept is advantageous in capturing and addressing complex and interrelated resource systems between different areas of concern such as water, food, energy and even land, soil, minerals, ecosystems (FAO, 2014), climate and the environment (WB, 2016). Regardless of the scope of the nexus choice, the nexus framework clarifies interlinked challenges and opportunities that are absent in the isolated management of resources. However, quantifying the nexus trade-offs between different sectoral areas to date has been limited.

Among the various world regions, Central Asia has the most pressing water and energy challenges. The region is infamously known for the Aral Sea catastrophe where a large inland lake almost disappeared as a result of mismanaged irrigated agriculture. Despite the poor legacy, agriculture remains an important economic activity in the region and is mostly irrigated because of the arid climate. Full control irrigation (surface, sprinkler and drip irrigation) is applied in over 90% of the region's irrigated area (FAO, 2013), but water use is inefficient because of the deteriorating infrastructure (Rakhmatullaev and Abdullaev, 2014). Two large regional transboundary rivers feeding into the Aral Sea experience high (Amudarya River basin) and extremely high (Syrdarya River basin) water stress (Gassert *et al.,* 2013). Water stress has been defined as the average exposure to five indicators (baseline water stress, inter-annual and seasonal variability, drought severity and flood occurrence) weighted by gridded water withdrawals (Gassert *et al.,* 2013). Additionally, Central Asian countries are among the most energy-intensive. Uzbekistan, for example, is the most energy-intensive country on the planet while Turkmenistan and Kazakhstan are among the top 11 (Stuggins *et al.,* 2013).

The nexus between water, food and energy in the region is exceptionally complex. Extensive lift-irrigated schemes where water is lifted by large pumps uphill from the underlying river contribute greatly to that complexity. In the Amudarya River, water is normally lifted 130 m or higher using seven pumping stations. Some 1.84 million ha in the region falls under pumped irrigation (Rakhmatullaev and Abdullaev, 2014). The three most intensive users of lift irrigation are Turkmenistan, Uzbekistan and Tajikistan where 16, 27 and 40% of the total irrigated area are pump-lifted, respectively. Irrigation is responsible for 10, 11 and 20% of the total electricity use in Turkmenistan, Tajikistan and Uzbekistan, respectively (Rakhmatullaev and Abdullaev, 2014).

The few studies that have focused to date on nexus issues in the region have been limited to description or advocacy of the concept without application (Granit *et al.,* 2012; Abdullaev and Rakhmatullaev, 2016) or have treated the nexus space narrowly as water for agriculture versus water for energy (Jalilov *et al*., 2015, 2016). Region-specific studies focusing on quantification of the wider water–energy–food nexus are lacking. Needless to say, nexus analysis at smaller, sub-basin scales in Central Asia or studies quantifying the nexus in specific schemes such as in lift-irrigated areas are non-existent.

To fill this gap, this paper applies an integrative nexus approach to assess water and energy use intensity and associated greenhouse gas emissions (GHG) focusing on lift-irrigated agriculture at a sub-basin scale, using the Karshi Steppe of Uzbekistan as a case study, and was carried out within the framework of a project financed by the United States Agency for International Development (USAID).

MATERIALS AND METHODS

Study area

The study area is situated within the Amu Darya River basin in Central Asia. Administratively the Karshi Steppe is part of Kashkadarya Province, which contains 13 districts and the provincial capital of Karshi (Figure 1). With a population of about 3 million, the province's area is about 28 600 km^2 with irrigated farmlands covering some 514 000 ha. Approximately 60% of the population are rural and their livelihoods depend on irrigated agriculture. Some 21 000 farmers are currently active in the province (Djumaboev *et al.,* 2017).

Grain cultivation and gardening were practised by the locals long before the Soviet occupation (1924–1991) (Khodjaev and Avazov, 2011). The Ministry of Land Reclamation and Water Resources promoted more effective use of machinery, expanded irrigated areas, created and improved existing irrigation systems between the late 1920s and early 1930s (Tolstov, 1962). As a result, the area of irrigated land in Kashkadarya increased more than eight times between 1915 and 2010, reaching 514 000 ha in 2010 (Khodjaev and Avazov, 2011). This expansion was achieved through ambitious hydraulic programmes, which involved building irrigation canals, dams, pumping stations; the most notable of these programmes is the large-scale Karshi Steppe Reclamation Programme (Khodjaev and Avazov, 2011).

After gaining independence in 1991, Uzbekistan started transitioning from a Soviet-style command state towards a market-oriented economy (Bobojonov, 2008). In this process, state and collective farms have been transformed into private farm holdings of various types and this process was accelerated after 2003 (Spoor, 2007). Uzbekistan achieved self-sufficiency in grain production and became one of the world's largest cotton producers (Müller, 2006).

Agricultural Reform Acts have helped to create water users' associations (WUAs) in the region after 2000. WUAs are responsible for supplying water allocated by government agencies to farmers in an equitable manner. However, issues related to equity and reliability of water supply exist within WUAs which prevents water management improvements at plot level. These issues in combination with salinity and waterlogging lead to significant crop yield reductions.

Water use and challenges

Kashkadarya Province experiences frequent water shortages. The climate in Karshi Steppe can be characterized as a cool semi-arid (steppe) that corresponds to the BSk class (BS-Arid Steppe climate), which, according to the climate classification system of Köppen-Geiger (Peel *et al.,* 2007), is continental with long, dry, hot summers and relatively mild winters. The temperature ranges between −2 °C in winter and to over 30 °C in summer (Sadikov *et al.,* 1979). The area experiences a substantial annual deficit caused by higher average annual potential evapotranspiration that exceeds 1240 mm, while average annual precipitation is much lower, about 245 mm (Khodjaev and Avazov, 2011).

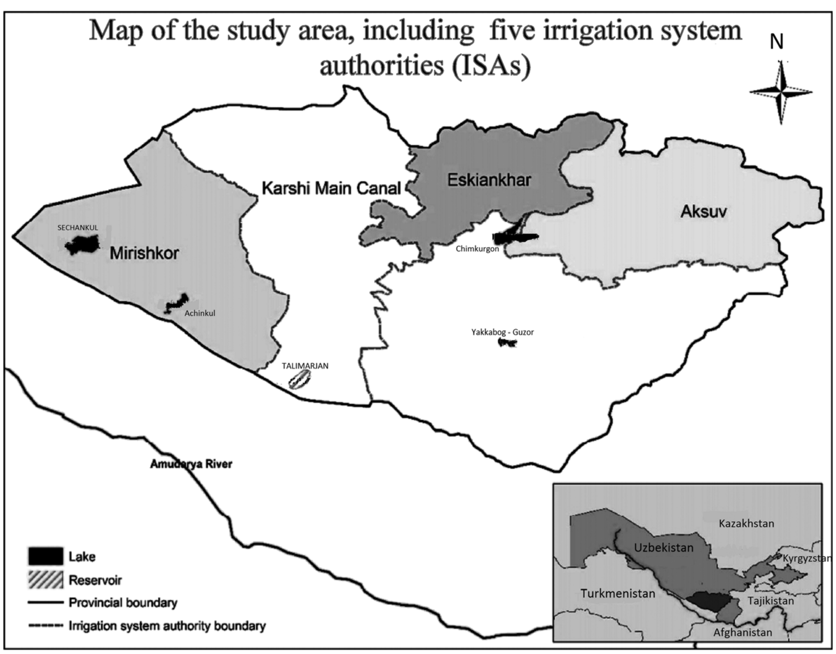

Figure 1. Map of the study area, including five irrigation system authorities (ISAs)

The main agricultural challenge in Kashkadarya Province is soil salinization. Almost half of the irrigated land (about 45%) is salinized. Groundwater can be found at a depth of 2–3 m on average and is also considerably salinized (International Water Management Institute (IWMI), 2016). Intense evapotranspiration and the capillary rise of groundwater have led to salt accumulation in the upper 1 m of soil. A widely practised method of combating salinization is through leaching, in which large water volumes are applied to a field. In irrigated areas of the province, the most prevailing soil types are sierozems, although occurrences of solonetzs and solonchaks have increased (Edlinger *et al.,* 2012).

Surface and subsurface drainage systems were widely implemented as control measures for the anticipated rise of the groundwater table in the 1960s when the Karshi Steppe Reclamation Programme was designed. However, such systems are ageing and most of them are no longer effective as a result of erosion and sedimentation. As a consequence, in many parts of the province the groundwater table has risen, negatively impacting crop yields. Many farmers in the province identify soil salinity and waterlogging as major hardships (Ministry of Agriculture and Water Resources (MAWR), 2001), with little access to agricultural machinery being identified as the next most serious challenge according to farmers.

Lift irrigation in the case study area

The Karshi Steppe was selected for three main reasons. First, the lift irrigation scheme in the Karshi Steppe is the largest in Uzbekistan and uses around 4.5–5 km^3 of water within a hydrological year. Second, 80% of the total irrigated area or 404 000 ha out of 505 000 ha in Kashkadarya Province is pump irrigated (Bucknall *et al.,* 2003). Lastly, there are data available to perform analyses.

A cascade of seven pumping stations supplies about 75% of the agriculture water in the province from the Amudarya River. Water is mainly lifted 130 m or more from the underlying Amudarya River to be discharged into the Talimarjan reservoir. The pumping stations have an estimated conveyance capacity of about 175–195 $m^3\ s^{-1}$ (Khodjaev and Avazov, 2011). The Kashkadarya River and a number of small rivers supply some 20% of agricultural water in the province, while the Zarafshan River supplies some 5% of agricultural water through the Eskiankhar canal.[1]

The major agricultural crops grown in the province are wheat, cotton, fruits and vegetables, and fodder crops. This study focuses on cotton and wheat because they are the primary crops grown in the area in terms of using agricultural land: 59% of the agricultural land in 2016 was allocated to them (31% cotton and 28% wheat), whereas land allocation for all other categories such as orchards, fodder crops, vegetables and other crops (Figure 2) in the area is much less (Amu-Kashkadarya BISA for 2016). According to data from Mirishkor District, cotton on average consumes 6500–7000 $m^3\ ha^{-1}$ of water during the growing season whereas wheat consumes 4500–5000 $m^3\ ha^{-1}$ of water.[1] The growing season corresponds to the period between April and September when irrigation takes place. Light irrigation and various maintenance including water infrastructure maintenance take place during the non-growing season.

The economic analysis conducted by Bucknall *et al.* (2003) suggests that current price projections make nearly all pump-irrigated lands in Uzbekistan profitable for farming. However, even a small reduction in the price of crops grown in Kashkadarya, e.g. by 10%, would make pump irrigation unprofitable. Farmers would then have to adjust their practices by improving water efficiency or growing other profitable crops such as vegetables, fruits and cotton (Bucknall *et al.,* 2003).

Assessing water and energy use in irrigated agriculture

We applied a two-step nexus approach to determine the reduction in quantity of water and its associated energy use in the Karshi Steppe. Specifically, first, the crop water requirement was computed for improved water management in the study area. Second, the energy requirements and CO_2-equivalent GHG emissions from the energy used to pump enough water to match the calculated crop water requirement in the Karshi Steppe were calculated. The calculated crop water requirement and associated energy use and CO_2-equivalent GHG emissions were then compared with the current, actual water applied in the Karshi Steppe to reveal potential water and associated energy savings as well as the CO_2-equivalent GHG emission reductions through improved irrigation.

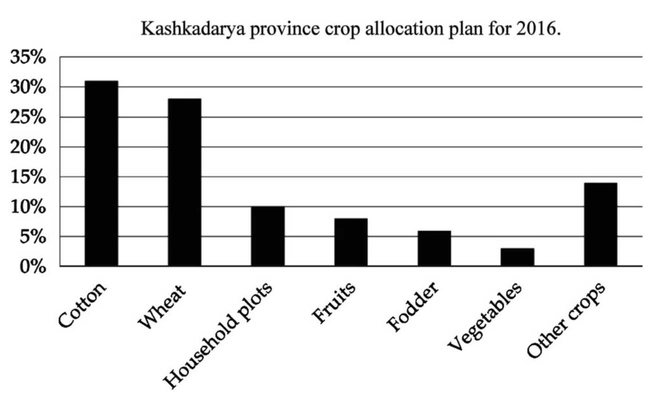

Figure 2. Kashkadarya province crop allocation plan for 2016

Crop water requirement (CWR) calculation

Amu-Kashkadarya BISA national database reports that 103 000 ha of lift-irrigated area in the province were under wheat cultivation and 120 000 ha under cotton cultivation in 2012–2013 and 2013–2014. A soil water balance model CROPWAT 8 was used to calculate the volumetric irrigation demand for these crops (FAO, 2009). The input data for the model were obtained from two field trials that were carried out at the experimental station of the Kashkadarya Research Institute of Grain Breeding and Seed Production of Cereal Crops (KRI) in Kovchin village (38°48′23.6″ N, 65°34′47.0″ E) and Kojar village (38°48′51.6″ N, 65°34′51.7″ E) during 2012–2013 and 2013–2014.

Daily climate data (relative humidity, sunshine, minimum and maximum temperature, wind speed, radiation and precipitation) were obtained from Karshi State Weather Station for 2012–2013 and 2013–2014. Recorded average minimum and maximum temperatures during the field site experiments were 2.9 °C in January and 38.3 °C in July respectively, while 15.9 °C was recorded as the average annual air temperature. Precipitation occurred mainly during the cold months between October and March when the average yearly amount equalled 244 mm (Figure 3).

In mid-October 2012 an automatic meteorological station was established in the area of the KRI, about 15 km from the experimental sites in Karshi City. As shown in Figure 3, initial measurements show that maximum air temperature in November–December 2012 and May–June 2013 was close to the long-term data, while in January–March 2013 the temperature was higher by 1.7–3.3 °C and in April 2013 was lower by 1.8 °C. However, the maximum air temperature in November 2013, January, March and May 2014 was higher by 0.8–3.3 °C and in December 2013, in February and April 2014 was lower by 1.2–5.3 °C than the long-term period. The coldest month during the study period was February 2014. Precipitation in February 2014 was less by 61% compared to the annual means. So, a deficit of precipitation and lack of soil moisture in the winter crop root zone especially in the spring months were compensated for by irrigation applied at the experimental site.

Daily crop water needs (I) were calculated by the following equation:

$$I_i = \mathrm{ETc}_i - P_i + \mathrm{RO}_i - \delta w_i - G_i \tag{1}$$

where ETci is the crop evapotranspiration in day i (mm) (in CROPWAT 8 water balances were estimated in daily base);[2] P_i is precipitation (mm); RO is surface runoff (mm); δw is soil moisture content in the root zone (mm); and G is the water capillary rise (mm). The empirical formula from the USDA Soil Conversation Service was used to estimate the fraction of effective rainfall (P_{eff}) that is available for each crop type (USDA, 1967). Water intercepted by plants or lost as runoff was excluded.

$$P_{\mathrm{eff}} = \left(\frac{P_i}{125}\right) \times (125 - 0.2 \times P_i), \quad \text{for } P_i \leq 250\ (\mathrm{mm}) \tag{2}$$

$$P_{\mathrm{eff}} = 125 + 0.1 \times P_i, \quad \text{for } P_i \leq 250\ (\mathrm{mm}) \tag{3}$$

Previous empirical methods for estimating capillary rise in Central Asia did not take into account root peculiarities

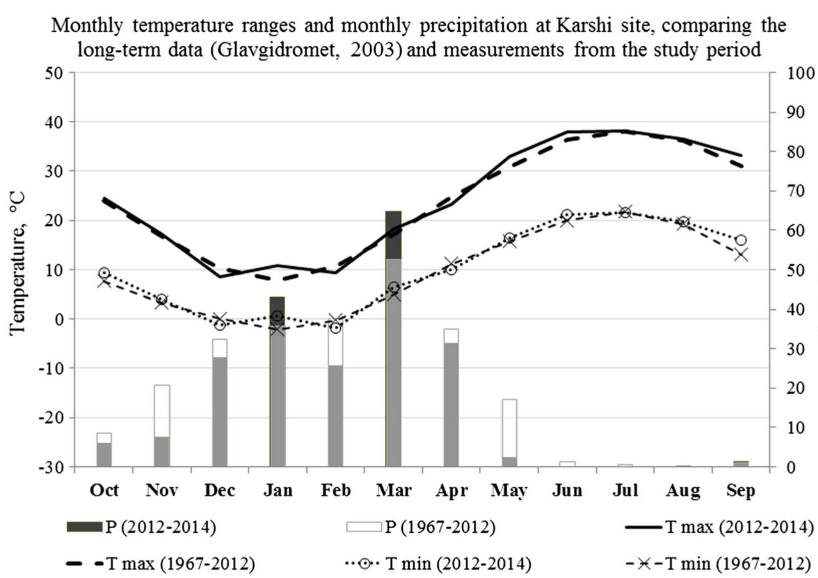

Figure 3. Monthly temperature ranges and monthly precipitation at Karshi site, comparing the long-term data (Glavgidromet, 2003) and measurement from the study period. [Colour figure can be viewed at wileyonlinelibrary.com]

and crop development stages. Such considerations were recognized later by other scientists such as Harchenko (1975), Dukhovny, (1984), Harchenko-Laktaev-Horst (discussed in WUFMAS, 1999, 2000), Horst (2001) and Uzgipromeliovodkhoz (Khasankhanova, 1999). In our work, we used the equation that is most suitable for the local conditions. Specifically, we used national crop coefficients developed by Uzgipromeliovodkhoz that are based on available lysimetric and experimental data obtained from various regional research institutes and organizations (Khasankhanova, 1999) to estimate the potential water from groundwater with the knowledge that in Karshi, the shallow water table (2–3 m) is found in around 40% of the area.

Crop evapotranspiration (ETc) refers to water lost to the atmosphere from the soil as evaporation and from plants during transpiration. The ETc is calculated using by the crop coefficient approach (K_c) specified by Allen *et al.* (1998):

$$\mathrm{ET_c} = K_\mathrm{c} \text{ x } \mathrm{ET_0} \tag{4}$$

where K_c is a crop coefficient that is affected by the plant growth stages and crop characteristics and ET_0 is reference evapotranspiration. The daily ETc and precipitation data for Kashkadarya Province for 2012–2013 and 2013–2014 were utilized to calculate the CWR.

The CWR was determined using the following equation (FAO, 2005):

$$\mathrm{CWR}_i = \sum_{t=0}^{T}(K_{ci}\times \mathrm{ET_0} - P_\mathrm{eff}) \text{ mm} \tag{5}$$

where K_{ci} is the crop coefficient of the specified crop *i* at the growth stage *t* and where *T* is the final growth stage. ET_0 = reference crop evapotranspiration (mm day^{-1}) and is defined as

$$\mathrm{ET_0} = \frac{0.408\times\Delta(R_\mathrm{n} - G) + \gamma\times\frac{900}{T+273}\times U_2(e_\mathrm{s} - e_\mathrm{a})}{\Delta + \gamma\,(1 + 0.34\times U_2)} \text{ mm day}^{-1} \tag{6}$$

where *G* is the soil heat flux density [MJ m^{-2} day^{-1}], R_n is the net radiation [MJ m^{-2} day^{-1}], *T* is daily mean air temperature at a height of 2 m [°C], U_2 is the wind speed at a height of 2 m [m s^{-1}], e_a is the actual vapour pressure [kPa], e_s is the saturation vapour pressure (kPa], [$e_s - e_a$] is the deficit saturation vapour pressure [kPa], Δ is the slope of the vapour pressure curve [kPa $°C^{-1}$], and γ is a psychrometric constant [kPa $°C^{-1}$].

The annual gross crop water needs (mm) were first calculated for each crop type for 2012–2013, then the crop water needs were averaged and combined utilizing the land use data (ha) to produce an estimate of the net water demand in irrigation (m^3) in an average year for the Karshi region. However, not all applied irrigation water can be used as there are losses that can be caused by runoff, evaporation or non-uniform application that depends on irrigation method. The theoretical efficiency of surface irrigation, for example, is low and reaches around 60% (Brouwer *et al.,* 1989). A more efficient method would be a sprinkler system that reaches around 80% efficiency, but a well-designed drip irrigation system's efficiency can be even higher and can exceed 90% (Brouwer *et al*., 1989). An efficiency of 60–65% is assumed for the furrow irrigation method that is used in approximately 95% of the area in the Karshi region (Laktaev, 1978).

Since actual cotton yields (2.2–2.5 t ha^{-1}) were much lower than the potential yield for cotton for other regions (4–4.5 t ha^{-1}), and the reduction in crop yield was caused by a shortage of soil water, a simple, linear crop-water production function introduced in the FAO Irrigation and Drainage paper No33 (Doorenbos and Kassam, 1979) was used to estimate actual evapotranspiration ETa corresponded to the actual yields Ya:

$$\left(1 - \frac{Y_\mathrm{a}}{Y_\mathrm{p}}\right) = K\mathrm{y}\left(1 - \frac{\mathrm{ET_a}}{\mathrm{ET_p}}\right) \tag{7}$$

where Y_p is potential and Y_a actual yield, ET_p is the potential and ET_a the actual cumulative evapotranspiration. K_y is a crop yield response factor that represents the effect of reduced evapotranspiration on yield losses. This was used in optimal model-based deficit irrigation scheduling using the CROPWAT 8 computer program.

Energy use and CO_2 emissions

CO_2 emissions are linked to burning energy to produce electricity supplied to pumps. In this study, electric energy was used to operate pumps that lift water from the Amudarya River. Generally, 2.73 kWh of electricity are required to lift 1000 m^3 water to a height of 1 m at 100% efficiency that ignores friction losses (Nelson and Robertson, 2008). Adapting the work of Qureshi (Qureshi, 2014), specific electric energy consumption can be expressed as

$$E_\mathrm{c} = \frac{2.73\times D\times V}{\mathrm{OPE}\times(1 - T1)\times 1000}, \text{kWh} \tag{8}$$

where E_c is consumed electricity (kWh), *V* the water volume (m^3), *D* the lifting height (m), OPE stands for the overall pumping plant efficiency (%), and T1 distribution and transmission losses. In Uzbekistan, electric pumps are assumed to have an average OPE of 80% (personal communication with Stanislav Rudnev).[3] Average distribution and transmission losses of electricity in Uzbekistan are 20% (Kochnakyan *et al*., 2013). The lifting height in Kashkadarya varies and can be separated into four groups: 0 up to 50 m, from 50 up to 100 m, from 100 up to 150 m and from 150 up to 200 m (Bucknall *et al.,* 2003). According to the WB (Bucknall *et al.,* 2003) out of 404 000 ha of lift-irrigated area in Kashkadarya, water for 80 000 ha or 19.8% is pumped up to 50 m, for 320 000 ha or 79.2% pumped between 100 and 150 m, for 4000 ha or less than

Table I. Total water pumped, in MCM (million cubic metres) for cotton and wheat in Kashkadarya by assumed lifting zones

	Water use in lift irrigation areas in Karshi Steppe				
Crop	Total water use	0 to <50 m	50 to <100 m	100 to <150 m	150 to 200 m
Wheat	1040	205	0 (0)	822	10
Cotton	918	181	0 (0)	725	9
Total	1960	387	0 (0)	1550	19

1% is pumped between 150 and 200 m, with no water being pumped between 50 and 100 m. In this study we assumed that the proportion of irrigated area for cotton and wheat corresponds to a similar breakdown and assumed the midpoint as the lifting height (i.e. 25, 75, 125 and 175 m) (Table I).

The CO_2 equivalent emission per unit of electricity was obtained from Edenhofer *et al*. (2011). In Uzbekistan, 88% of electricity generation is based on natural gas (Kochnakyan *et al*., 2013). An associated GHG emission from natural gas-based electricity generation can span from 290 to 930 g of CO_2-equivalent per kWh (Edenhofer *et al.,* 2011). In this study, the 50th percentile value, that is 469 g CO_2-equivalent/kWh, was used (Edenhofer *et al.,* 2011). The energy used to pump water for wheat and cotton irrigation in Kashkadarya was multiplied by 469 g CO_2-equivalent/kWh to obtain the GHG emissions.

RESULTS

The results suggest that the water used for lift irrigation in Kashkadarya can be reduced significantly by applying improved irrigation that does not affect crops yields. Water for wheat irrigation can be reduced from the current 1040 to 605 MCM, yielding a total saving of 435 MCM (Table II). Analogously, water for cotton irrigation can be reduced from the current 918 to 778 MCM, which translates into savings of 140 MCM of water. Total water savings from improving wheat and cotton irrigation in Kashkadarya can be almost 575 MCM which can be left in the source rivers or pumped to irrigate additional crops.

An important aspect of sustainable crop production in Central Asia is to improve the efficiency of irrigation water management. At present, Central Asian farmers, including those in Uzbekistan, employ a traditional irrigation method from the Soviet era that is based on dividing irrigated areas into nine hydro-module zones (HMZs). The principle of the HMZ method is that crop-specific irrigation recommendations for each HMZ are based on the depth of the groundwater table and the soil characteristics (e.g. soil texture, thickness of soil layers) (Uzbek Academy of Agricultural Sciences, 1992). However, such recommendations have not accounted for fluctuations in the groundwater table and changes in cultivars in the post-Soviet period.

Modernizing and improving canals and other hydraulic structures are at the centre of most state-funded efforts. For instance, the Ministry of Finance of Uzbekistan recently announced an initiative to establish a Melioration Fund that aims to rehabilitate aged, on-farm drainage systems to improve productivity and combat salinization. Such efforts are certainly required to improve water management at the national scale, but they have to be simultaneously matched by efforts aimed at improving irrigation water management at the small scale (e.g. fields and farms). This can be done by adopting water-saving technologies at small scale, such as drip irrigation, ET-based irrigation scheduling, and crop-monitoring sensors such as ET meters, irrometers and soil moisture monitoring TDR sensors for assessing the vigour of crops.

Farmers cannot usually plan irrigation schedules in advance because of water supply uncertainties. Instead, water availability or access to it (including groundwater) and crop water needs drive farmers' decisions on the timing of irrigation. In the past, many researchers have attempted to identify optimal irrigation schedules for various crops grown in the water-scarce Aral Sea basin. Based on field experiments, Mukhamedjanov *et al*. (2016) demonstrated that improving irrigation management by using techniques such as ET-

Table II. Comparison of water and energy consumption savings between current and simulated (improved) irrigation practices obtained from the Cropwat 8 model (2012–2014)

Crop	Total pumped area (ha)	Irrigation application (mm)		Total water use (MCM)		Total water saving (MCM)	Electricity consumption (GWh)		Total energy saving (GWh)
		Current	Improved irrigation practices	Current	Improved irrigation practices		Current	Improved irrigation practices	
Wheat	103 000	1 010	587	1 040	605	435	469	273	196
Cotton	120 000	765	648	918	778	140	414	351	63
Total	223 000	N/A	N/A	1 960	1 380	575	883	624	259

Note: current water use estimates are obtained from the Amu-Kashkadarya Irrigation System Basin national database.

Table III. The optimal irrigation depths and water use for wheat and cotton for 2012–2013 and 2013–2014 (mm) (Irrigation norms calculated using the CROPWAT model. Total pumped area taken from BISA data)

Crop	2012–2013 (mm)		2013–2014 (mm)		Average optimum irrigation rate (mm)	Total pumped area (ha)	Improved water use (MCM)
	Sandy loam	Silt loam	Sandy loam	Silt loam			
Wheat	469	535	708	636	587	103 000	605
Cotton	663	607	684	639	648	120 000	778

based irrigation scheduling can achieve a 30% reduction in irrigation requirements. They concluded that cotton crops achieve optimal yields by an irrigation application of 400–480 mm. To simulate optimal irrigation schedules for cotton and wheat, CROPWAT model simulations were utilized in this study. Our results suggest that an irrigation application reduction in the range of 45–55% of the total crop ET is feasible without affecting soil salinization and compromising yields. We conclude that in Kashkadarya Province, the optimal irrigation application for cotton and wheat would be 590–650 mm (Table III).

Irrigation efficiency in the province is low, owing to the low efficiency of the widely practised furrow irrigation method that has an attainable efficiency of 75% (Laktaev, 1978). Therefore, switching to more efficient irrigation methods such as sprinkler and drip irrigation systems can bring additional water savings. However, even greater efficiency can be achieved by further use of optimized irrigation schedules in combination with advanced management options such as application rate control and farm levelling. We propose to retain the present furrow irrigation method but introduce improved irrigation planning by using crop-modelling tools (CROPWAT 8) which can eliminate unspecified 'issues' related to supply to WUAs, which would then enable better water management and scheduling at the crop level. This type of improvement in irrigation management is considered to be the most cost-effective and the most feasible option in comparison with introducing sprinkler or drip irrigation which are costly.

Under current irrigation methods, GHG emissions from pump operations for wheat and cotton irrigation in Kashkadarya Province exceed 400 000 t of CO_2-equivalents (Table IV). However, the potential for reductions is enormous. By switching to improved irrigation, GHG emissions from pump irrigation for wheat and cotton can be reduced by 30% in Kashkadarya Province. The energy use reductions and thus the potential GHG emission reductions are particularly reasonable for wheat irrigation. Some 40% of GHG emissions can be eliminated by applying improved irrigation in the wheat fields.

Table IV. The GHG emissions from lift irrigation and potential for emission reductions through optimal irrigation

Crop	Current emissions	Emissions under optimal irrigation	Potential for emission reductions[a]	
	(kt)	(kt)	(kt)	(%)
Wheat	220	128	92	41.9
Cotton	194	164	30	15.3
Total	414	292	122	29.4

[a]Emission reductions achieved by reducing energy use for lift irrigation through applying optimal irrigation and ignoring pump efficiency improvements.

This analysis shows that many benefits can be obtained by adopting improved irrigation practices in the lift-irrigated areas of Central Asia. Saving water, and reducing energy use and CO_2 emissions are beneficial for farmers and the environment. But adopting improved irrigation practices involves reversing farmers' thinking from increasing irrigation supplies (e.g. 'maximize crop production') to reducing irrigation supplies (e.g. 'optimize crop production'). This transformation in farmers' thinking could be triggered by revising energy pricing. For example, limiting or eliminating subsidies for electricity and water can help show the real monetary savings to farmers who can then experience the direct link between their actions and their finances.

CONCLUSIONS

The area under lift-irrigated agriculture has been increasing over the last few decades and has become very valuable for agricultural production in many Central Asian states. More than half of the total available water for summer crops throughout Kashkadarya Province is supplied through pump lifting. These pump-irrigated areas consume large quantities of energy and are responsible for large GHG emissions in

Uzbekistan. Extraction of 1960 MCM of pumped water in Karshi, for the main crops such as cotton and wheat, consumes over 880 GWh of energy. The GHG emissions from this energy use are 414 000 t yr^{-1} of CO_2 equivalent emissions. The results of this study demonstrate that using improved irrigation practices can save up to 575 MCM of irrigation water. This will then reduce the energy demand and the GHG emissions by around 30%. Thus, improving irrigation management can bring a multitude of benefits such as reducing water stress, energy consumption and GHG emissions. To put things into perspective, saving 259 GWh of electricity through improved irrigation practices will reduce 122 000 t yr^{-1} of CO_2 equivalent emissions which equals eliminating emissions from over 25 000 cars for 1 year.[4]

The results of this work reveal two key messages. First, lift irrigation in Kashkadarya is responsible for large water and energy use as well as GHG emissions. Second, and related, the potential for water and energy use reductions is enormous, which also translates into significant GHG emission reductions. Therefore, it is essential to develop advanced on-farm water management practices concurrently with eliminating energy subsidies in agriculture to increase water productivity, reduce energy demand and protect the environment in Central Asia.

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AUTHOR CONTRIBUTIONS

Kakhramon Djumaboev designed the methodology. Kakhramon Djumaboev, Tulkun Yuldashev, and Bunyod Holmatov wrote the paper. Zafar Gafurov collected weather data and prepared the study area map.

ENDNOTES

1. Personal communication with Amu-Kashkadarya Basin Irrigation System Authority (BISA) official in 2016.
2. I = 1, 2, 3,….n, where 1 = the first day of the simulation period and n = the number of days in the crop season.
3. Stanislav Rudnev, UzGIP specialist, collected OPE data from Kashkadarya BISA, Karshi Main Canal Management Department to write a report on the cost of replacing old pump stations responsible for lifting water from the Amudarya River to Karshi Steppe.
4. Assuming that a typical vehicle in 1 year emits about 4.7 t of CO_2 (United States Environmental Protection Agency (USEPA), 2016).

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