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Optimizing irrigation efficiency improvements in the Aral Sea Basin

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ABSTRACT

Water scarcity driven by climate change, growing demand, and inefficient management of water and related infrastructure is a serious threat to livelihoods in the Aral Sea Basin (ASB) of Central Asia. In recent decades, downstream water shortages have become increasingly common and inflows into the Aral Sea have become very limited. Meanwhile, water losses are enormous both at conveyance and field levels because of outdated infrastructure and the dominance of highly inefficient basin and furrow irrigation methods. Intensification and modernization of irrigation systems, while requiring investment of scarce capital resources, could thus substantially reduce non-beneficial water consumption and help in coping with increasing water scarcity. This study applies a hydro-economic model that solves for the investment in improved irrigation efficiency across the various irrigation sites in the ASB that delivers the highest economic gains. Improvement of the efficiency of irrigation canals and implementation of field efficiency investments and practices, such as drip irrigation, and alternate dry or short furrow irrigation (for rice), would substantially improve economic outcomes. Conveyance efficiency investments are particularly worthwhile in downstream regions where sandy soils are common and return flows largely feed saline lakes in tail-end depressions. Meanwhile, field-level efficiency should be fully upgraded in all rice-producing regions through the use of drip and alternate wet and dry irrigation, as well as with drip irrigation in the cotton-producing Ferghana Valley of the Syr Darya Basin. The value of these improvements increases with reduced water availability. Implementation of an optimal set of investments could increase basinwide benefits by 20% (from US$ 3.2 to 3.8 billion) under normal water availability and by 40% (from US$ 2.5 to 3.5 billion) under dry conditions (80% of normal supply).

1. Introduction

Water scarcity is a major challenge facing populations in semi-arid and arid regions across the world [1]. In such water scarce regions, increasing the efficiency of water use is critical to economic development and food security [2]. Among water users, irrigated agriculture consumes more than 70% of all global water withdrawals [3]. Yet this activity is also typically extraordinarily inefficient: on average, only 40% of water delivered to the sector is used productively by crops [4]. Therefore, irrigated agriculture would seem to be a prime candidate for interventions aimed at reducing water demand and inducing water savings.

Measures to improve irrigation water use efficiency appear particularly essential in regions like the Aral Sea Basin (ASB) of Central Asia, which suffers from acute water scarcity. The basin's largely arid climate makes the use of irrigation for agricultural production a necessity, and 90% of total water consumption in the ASB is used for this purpose. The basin – covering the five Central Asian countries of Kazakhstan, Kyrgyzstan, Uzbekistan, Tajikistan, and Turkmenistan – also comprises one of the largest irrigated areas in the world, with more than 8.5 Mha of irrigated land (Fig. 1). Furthermore, the population of the region remains largely rural, and rural livelihoods depend heavily on farming and therefore also on water availability [5].

In the ASB, large-scale water diversions for irrigation began in the 1960s under the Soviet regime. The diversions were largely intended for the massive expansion of cotton cultivation and transformed the agricultural landscape of the region. At the same time, however, they also led to a dramatic reduction of inflows to and the consequent desiccation of the Aral Sea. The large-scale ecological changes that occurred in turn had catastrophic effects in downstream areas, increasing the risks of air- and water-borne illnesses, accelerating the degradation of ecosystems and

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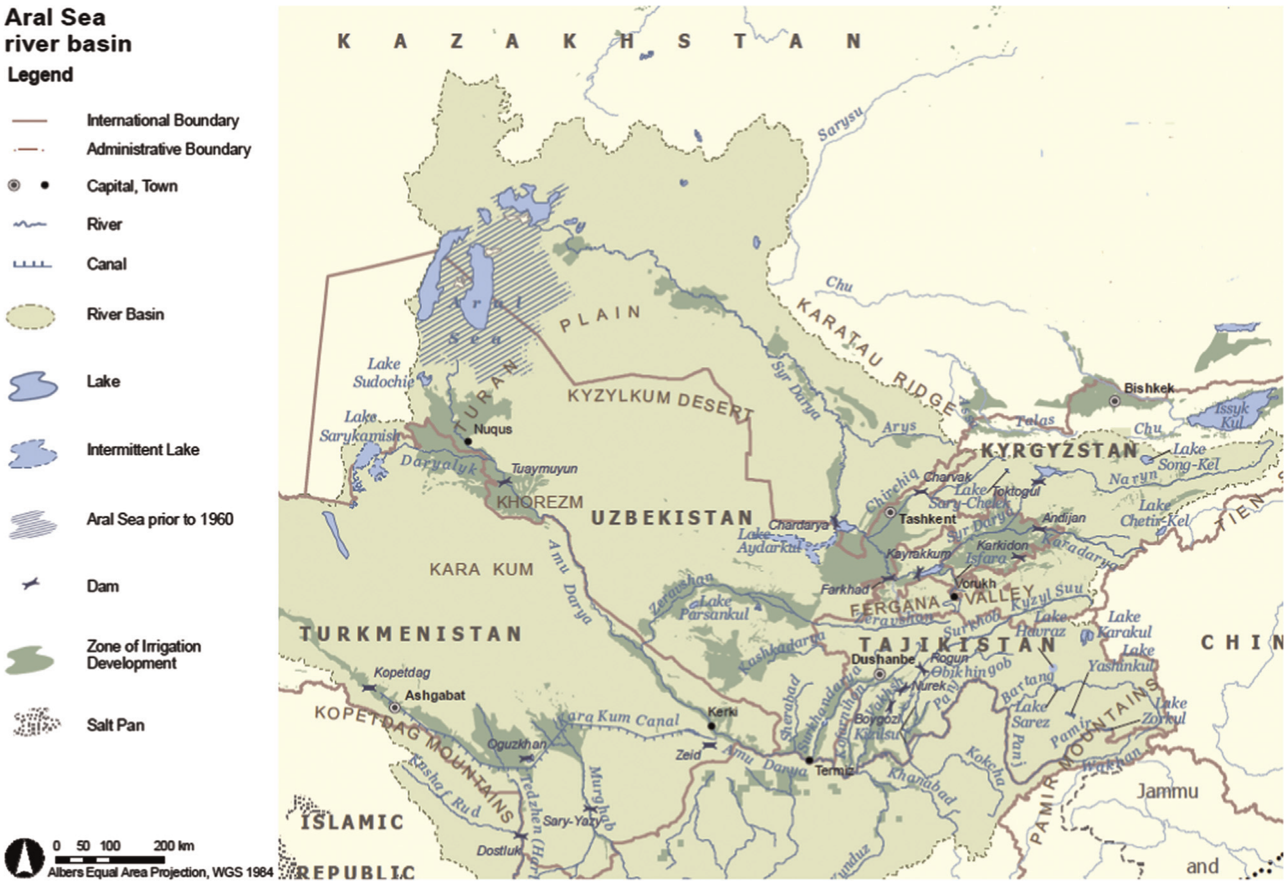

Fig. 1. Irrigated areas of the Aral Sea Basin. Source: FAO. AQUASTAT website, 2015. ⟨http://www.fao.org/nr/water/aquastat/basins/aral-sea/index.stm⟩ (accessed on 15.06.15).

agricultural lands, contributing to the collapse of fisheries and recreation, and to widespread unemployment [6]. Mitigating or even reversing the consequences of this ecological disaster would require the development of new transboundary policies that would increase downstream environmental flows.

Other changes in the geo-political landscape of the region make the rehabilitation of this ecosystem particularly difficult. These include the emergence of divergent interests among the five countries in the territory of the Aral Sea Basin that formed after the dissolution of the Soviet Union, climate change with outward signs of rising temperatures and aridity [7], growing populations, and upstream reservoir construction [8]. These dynamics continue to decrease and change the temporal pattern of downstream water availability, by increasing water demand throughout the basin, and by reducing water supply during critical periods, in the absence of a common and accepted agreement by the basin countries on how to manage resources sustainably for the future.

These dynamics notwithstanding, there are reasons to believe that significant improvements in irrigation could be achieved in the basin. For one, irrigation technology in the region is dominated by inefficient methods (e.g. basin and furrow techniques), which have water application efficiencies of less than 50% [9, 10]. Second, irrigation canal infrastructures are outdated and poorly maintained and have conveyance efficiencies of less than 60% in many locations [6, 10].[1] While some return flows might be reused downstream, much of the ASB return flows from irrigation are either too saline and/or are diverted in drainage systems to salt lakes that cannot replenish the Sea [6, 10]. Third, many of the crops that are ubiquitous throughout the region are low in water productivity, such as cotton, wheat, and rice, even as water shortages increase in both magnitude and frequency [5, 9].

In light of these realities and challenges, improving the efficiency of water and land resources could help make more water available for downstream irrigation, ecosystems, and other uses in the ASB. The goal of this study is to identify the economically optimal allocation of technological investments in water application and conveyance efficiency across the irrigation sites, from a basin-wide perspective. To assess the potential water savings and economic benefits of these technologies, we apply an integrated hydro-economic model with a monthly time step to optimize the sum of irrigation, hydropower and ecosystem benefits, subject to constraints reflecting river flows and the complex structure of the hydrologic and agronomic systems of the ASB. The model determines the optimal spatial allocation of water, irrigated lands, and irrigation efficiency improvements within a basin-wide cooperation framework. A similar model architecture has previously been applied for analyses of water management options in the Mekong, Dong Nai and Maipo River Basins [11–13].

Previous modeling studies that considered changes in irrigation technology have mainly used three types of approaches: (a) a discrete approach that explicitly considers specific technologies – for example, drip and conventional irrigation – that have distinct water requirements and crop yields [14–16]; (b) a production function approach that implicitly considers irrigation technology through changes in water distribution uniformity [11, 17]; (c) a water savings-cost effectiveness approach that includes the cost per unit of saved water through irrigation efficiency improvements and implicitly considers irrigation technology through

[1] Water application efficiency is considered as the ratio of beneficial crop evapotranspiration to total water delivered to the field. Conveyance efficiency is calculated as the ratio of irrigation water withdrawal from a river or other water supply node to water actually delivered to the farm gate. Overall irrigation efficiency is thus the product of water application and conveyance efficiency.

assumptions about the share of water intake delivered to the farm gate (conveyance efficiency) or the share of applied water that is beneficially used by crops (for water application efficiency)[2] [18]. The model used in this paper follows the third approach.

Several studies have previously considered the technical and economic aspects of water use efficiency improvements in the ASB. Some of these studies provide estimates of the technical water saving potential of different conservation technologies including drip irrigation, surge flow, and laser guided land leveling at the field level [19–21], at a national scale (e.g., for drip irrigation in Uzbekistan [22]), and at the basin scale (e.g., for drip irrigation, alternative furrow, and surge flow irrigation techniques in cotton production) [23]. Bekchanov et al. [10] further estimated the costs, benefits, and investment requirements of a range of water conservation measures including drip irrigation, laser guided land leveling, alternate dry furrow, and surge flow. Researchers of the ZEF/UNESCO Uzbekistan Project[3] [15, 24] analyzed the economic and production effects of adopting drip irrigation, laser guided land leveling, and other options of improving water use efficiency using farm-level and regional agricultural production models and curves relating the average costs of water use efficiency improvement options with their water saving potential [25]. A hydro-economic analysis by Cai et al. [18] is the only prior study from the region that analyzed the economic and water use effects of water saving technologies in the Syr Darya Basin using a basin-wide water management model.

The current study includes several modeling improvements over the previous work, such as increased disaggregation of users and crops, consideration of more recent data, and analysis of both the Amu and Syr Darya sub-basins. Including the two sub-basins of the ASB is especially helpful for better understanding the net effects of interventions to improve irrigation efficiency on flows into the Aral Sea. Additionally, an integrated hydro-economic model that has a theoretically consistent water balance model from river to field has been used for assessing the value of irrigation efficiency improvements for water, food and environmental security. Moreover, we analyze a relevant policy case that among other things indicates the spatial distribution of benefits of efficiency improvements, their sensitivity to costs, and the tradeoffs in allocating water savings to environmental flows versus additional irrigation intensification and expansion.

The next section describes the hydro-economic model that comprises irrigation, hydropower production, and environmental benefit functions, hydrological and water flow relationships along the river and to the fields in the ASB, and the linkages between surface water, groundwater and return flows. It also discusses the data used in the model, calibration procedures and scenario assessments considered in this study. In Section 3, we compare the modeling outcomes across scenarios and consider the economic value of irrigation technology improvements. The final section summarizes findings of the modeling simulations and offers additional concluding remarks.

2. Basin-wide water management model

2.1. Modeling framework

2.1.1. Objective function

The objective function of the hydro-economic model maximizes the sum of irrigation benefits (IB_r) across the irrigation sites (r), energy production benefits (HP_s) by hydropower production plants (s), and environmental benefit (EB):[4]

$$\pi = \sum_r IB_r + \sum_s HP_s + \omega \cdot EB, \tag{1}$$

where π corresponds to the total benefits from these three respective components (in US$ million); and ω is a weight assigned to the environmental benefit. Given the lack of monetized estimates of the value of flows into the Aral Sea, this weight is included to allow testing of the sensitivity of the model to these values. In considering the optimal water allocation for the basin, the model treats production at all sites included in each of the irrigation and hydropower sets equally; in other words there is no prioritization of upstream vs. downstream sites, and there are no specific country demands that must be satisfied. This does not apply to municipal and industrial water demands, however, which are imposed as constraints that must be satisfied prior and independently of the hydropower and irrigation objectives.

2.1.2. Environmental flow benefits

Due to lack of data indicating temporal variation in the value of inflows into the Aral Sea and deltaic zones (EB), environmental flow benefits are considered to be a linear function of the annual environmental flow (the sum of monthly flows [EF_t]):

$$EB = b0 + b1 \sum_t EF_t \tag{2}$$

where $b0$ and $b1$ are parameters of the environmental benefit function and EF_t is the monthly environmental flow from the Amu Darya (the node link "A5 → THE ARAL SEA") and Syr Darya (the node link "S4 → THE ARAL SEA") into the Aral Sea.[5] A piecewise linear relationship between annual environmental flows and benefits was approximately estimated based on values for a subset of environmental benefits as they relate to observed levels of flows into the Aral Sea [26]. Specifically, these include rough estimates of benefits from sustainable wetlands, fishery, sea navigation, resort activities, and improved rural livelihoods [27]. Because of data limitations many other important environmental benefits related to microclimate regulation, stable groundwater levels, and cultural and intrinsic values are not considered.

2.1.3. Hydropower production benefits

Benefits from hydroelectricity production are estimated as:

$$HP_s = \sum_t epr_t \, EP_{s,t} \tag{3}$$

where epr_t is price per unit of hydroelectricity output and $EP_{s,t}$ is the amount of hydropower produced by power station (s) in a particular month (t).

2.1.3.1. Hydropower generation. Hydropower production from

[2] Note that the choice of irrigation technology is implicitly reflected in the extent of savings – for instance, a field application efficiency of 90–95% would require implementation of drip irrigation for crops, or of transplanting for rice. Lower water application efficiency of 60–70% for cotton can be interpreted as utilization of low cost techniques such as alternate dry furrow or short furrows [10].

[3] ⟨http://www.zef.de/proposal_khorezm.0.html⟩

[4] Endogenous decision variables and groups of sets are written with upper case letters while model parameters (exogenous variables) and sets (identifiers) are presented with lower case letters.

[5] For more details on estimating the coefficients of environmental benefit function, see Bekchanov [23], section 4.4.6. We note here that there are limited data on the value of environmental flows in this system, particularly in the context of understanding the long-term sustainability of benefits from the Aral Sea ecosystem.

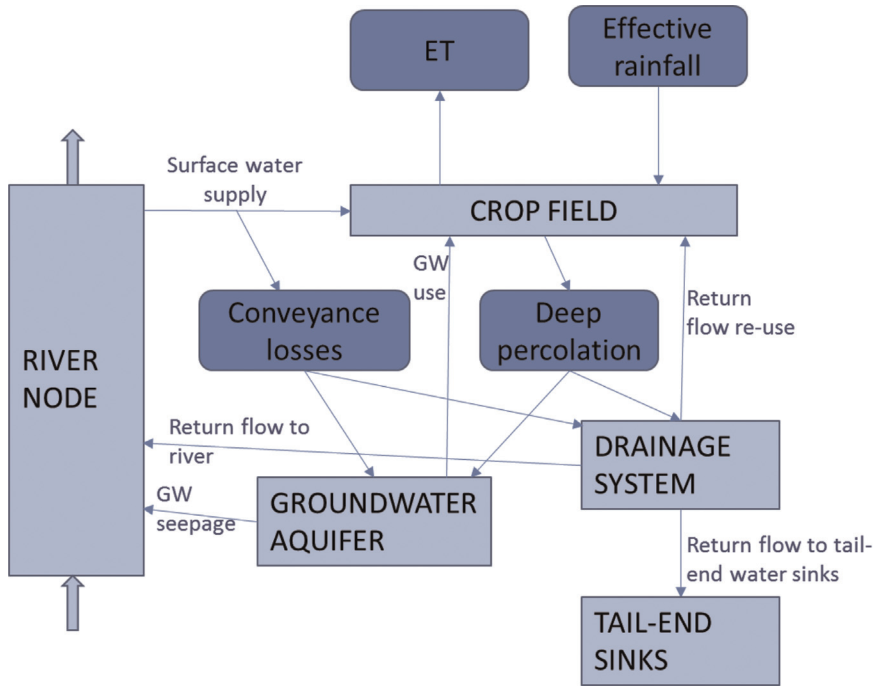

Fig. 2. Water balance relationships on irrigation site.

reservoir-based power production plants depends on the conversion coefficient (ρ), production efficiency of the plant (ε_s), reservoir water releases ($RSN_{v,n,t}$), and the water level in the reservoir [12]:

$$EP_{s,t} = \rho \cdot \varepsilon_s \cdot \left(\sum_{n \in RNLINK} RSN_{v,n,t} + \sum_{w \in DDLINK} RRS_{v,w,t} \right) \left(\frac{H_{v,t} - H_{v,t-1}}{2} - htail_v \right) \quad (4)$$

where $RSN_{v,n,t}$ is river flow from reservoir (v) to node (n) if a link between two of them ($RNLINK$) exists, $RRS_{v,w,t}$ is flow from the reservoir to the next reservoir (w) if there is a link ($DDLINK$) between these, $H_{v,t}$ is water level at the reservoir, and $htail_v$ is the tailwater level of the reservoir.

Electricity generation for run-of-river power stations is estimated as:

$$EP_{s,t} = \rho\ \varepsilon_s \left(\sum_{n \in NPLINK} \sum_{k \in RVLINK} FL_{n,k,t} \right) ry_v \quad (5)$$

where $FL_{n,k,t}$ is river flow from the node (n) to the next downstream node (k) at each moth (t) if a link between the nodes ($RVLINK$) exists and ry_v is the reservoir yield, which indicates the amount of electricity generation per unit of river water flow. Additional constraints related to the maximum electricity generation capacity of hydropower plants are also considered in the model.

2.1.4. Irrigation benefits

Irrigation benefits are determined as the difference between crop production revenues and costs. Costs include irrigation efficiency improvement costs, water conveyance (transportation) costs, return flow use costs, groundwater pumping costs, and the costs of crop production for all non-water-related inputs:

$$\begin{aligned} IB_r = {} & 0.001 \cdot \sum_c \left(A_{r,c} \left(pr_{r,c} Y_{r,c} - pc_{r,c} \right) \right) \\ & - \sum_c \left(itc_{r,c} \left(IE_{r,c} - ie0_{r,c} \right) \sum_t WACP_t \right) \\ & - dsc_r \left(DE_r - de0_r \right) \left(\sum_t \sum_{n \in NDLINK} RW_{n,r,t} \right) \\ & - cc_r \sum_t TWF_{r,t} - ruc_r \sum_t \sum_c RU_{r,c,t} \\ & - wpc_r \sum_{g \in GWDLINK} \sum_t \sum_c WP_{g,r,c,t} \end{aligned} \quad (6)$$

where:

$A_{r,c}$ is area of a particular crop (c) in a certain irrigation site (r) (in thousand ha);
$pr_{r,c}$ is agricultural commodity price (in US$ per ton);
$Y_{r,c}$ is crop yield (in ton per ha);
$pc_{r,c}$ is production cost (not including water inputs) per unit of land (in US$ per ha);
$itc_{r,c}$ is the cost per unit of water saved by improving water application efficiency (in US$ per m^3);
$IE_{r,c}$ is water application efficiency (a dimensionless variable ranging from 0 and 1 depending on technology);
$ie0_{r,c}$ is baseline water application efficiency without any additional improved technology (a dimensionless parameter that varies between 0 and 1);
$WACP_{r,c,t}$ is total water applied to each crop at field level (in million m^3);
$dsc_{r,c}$ is the cost of a unit of water saved by improving conveyance efficiency (US$ per m^3);
DE_r is distribution (conveyance) efficiency with improved technology (a dimensionless variable ranging from 0 and 1 depending on technology);
$de0_r$ is baseline distribution (conveyance) efficiency without any new improved technology (a dimensionless parameters that varies between 0 and 1);

$RW_{n,r,t}$ is water withdrawal from river node (n) to irrigation site (r) at a certain month (t) if there is a link between the irrigation site and the river node ($NDLINK$) (in million m^3);
cc_r is conveyance cost per unit of water supplied (in US$ per m^3);
$TWF_{r,t}$ is water supplied to the field in each month (in million m^3);
ruc_r is cost of reusing return water for irrigation (in US$ per m^3);
$RU_{r,c,t}$ is the amount of re-used return flow (in million m^3);
wpc_r is the cost of groundwater pumping (in US$ per m^3); and
$WP_{g,r,c,t}$ is the amount of water pumped from the groundwater source (g) to irrigate crops (in million m^3) if the irrigation site and the groundwater aquifer is interrelated ($GWDLINK$).

2.1.5. Irrigation: water use and yield relationships

Crop yield levels ($Y_{r,c}$) are estimated considering monthly crop water consumption amounts, using the FAO method [28]:

$$\frac{Y_{r,c}}{my_{r,c}} = \left\{1 - \max\left[kyc_c\left(1 - \frac{\sum_t ET_{r,c,t}}{0.01\cdot\sum_t A_{r,c}\ etm_{r,c,t}}\right), \max_t\left(ky_{c,t}\left(1 - \frac{ET_{r,c,t}}{0.01\cdot A_{r,c}\ etm_{r,c,t}}\right)\right)\right]\right\} \quad (7)$$

where $my_{r,c}$ is the maximum attainable yield (in ton per ha), $ky_{c,t}$ is a set of monthly crop coefficients (a dimensionless parameter), kyc_c is a seasonal crop coefficient (a dimensionless parameter), $ET_{r,c,t}$ is total actual crop evapotranspiration (in million m^3), and $etm_{r,c,t}$ is crop reference evapotranspiration (in mm).

2.1.6. Irrigation: water balance at irrigation sites

Detailed hydrological linkages between surface water, groundwater, and return flows on the one hand, and agricultural production on the other hand, have been incorporated into the model (Fig. 2). Only a fraction of total surface water withdrawals reach irrigation sites (or farm gates), with the remaining fraction being lost during conveyance. A portion of these conveyance losses recharge aquifers, and the remainder becomes drainage water.[6] Groundwater, local rainfall, and recycled drainage water also supply water to irrigated areas.[7]

At the field level, only a portion of the water delivered is used for beneficial crop evapotranspiration. The remaining water that is lost at the field level joins groundwater aquifers through deep percolation or flows into the drainage system. Drainage flows remaining after re-use of return flows (recycled water) either flow back into the river or are delivered to tail-end water depressions. Groundwater seepage also partially increases river flows. The mathematical formulations of these complex hydrological dynamics are described in additional detail below.

2.1.6.1. Total water application at field level. Total water applied to each crop at field level ($WACP_{r,c,t}$) must be equal to the sum of surface water application ($WCP_{r,c,t}$), groundwater application ($WP_{g,r,c,t}$), and re-use of return flows ($RU_{r,c,t}$):

$$WACP_{r,c,t} = WCP_{r,c,t} + \sum_{g\in GWDLINK} WP_{g,r,c,t} + RU_{r,c,t} \quad (8)$$

2.1.6.2. Seasonal water supply to crops. Total seasonal water supply to crops in each region ($TWACP_{r,c}$) is equal to the sum of total water application for the use of each crop ($WACP_{r,c,t}$) and total effective rainfall over the months:[8]

$$\sum_t \left(WACP_{r,c,t} + 0.01\cdot A_{r,c} er_{r,c,t}\right) = TWACP_{r,c} \quad (9)$$

where $er_{r,c,t}$ is effective rainfall measured in mm.

2.1.6.3. Irrigation water consumption by crops. Irrigation water that is effectively used by crops is equal to the difference between seasonal actual crop evapotranspiration ($ETS_{r,c} = \sum_t ET_{r,c,t}$) and seasonal total effective rainfall, adjusted for the application efficiency:

$$IE_{r,c}\left(\sum_t WACP_{r,c,t}\right) = ETS_{r,c} - 0.01\cdot\sum_t (A_{r,c}\ er_{r,c,t}) \quad (10)$$

2.1.6.4. Total water consumption for irrigated crops. Actual crop evapotranspiration by months ($ET_{r,c,t}$) must be less than or equal to the sum of water that is actually used by crops and total effective rainfall:

$$ET_{r,c,t} \le IE_{r,c}\ WACP_{r,c,t} + 0.01\cdot A_{r,c} er_{r,c,t} \quad (11)$$

2.1.6.5. Maximum feasible water consumption by crops. Actual crop evapotranspiration by months ($ET_{r,c,t}$) must be less than or equal to the total crop reference evapotranspiration:

$$ET_{r,c,t} \le 0.01\cdot A_{r,c} etm_{r,c,t} \quad (12)$$

where $etm_{r,c,t}$ is crop reference evapotranspiration measured in mm.

2.1.6.6. Seasonal water consumption. For each crop, seasonal actual crop evapotranspiration ($ETS_{r,c}$) must be less than or equal to the total seasonal water application ($TWACP_{r,c}$) net of seasonal deep percolation ($DP_{r,c}$):[9]

$$ETS_{r,c} \le TWACP_{r,c} - DP_{r,c} \quad (13)$$

2.1.6.7. Surface water delivery. Total surface water delivered to a demand site ($TWF_{r,t}$) was calculated considering conveyance efficiency and water withdrawals from the river node:

$$TWF_{r,t} = \sum_{n\in NDLINK} RW_{n,r,t} DE_r \quad (14)$$

2.1.6.8. Surface water application at field level. The sum of total surface water applied to all crops in each site ($WCP_{r,c,t}$) must balance with water actually delivered to the site ($TWF_{r,t}$):

$$\sum_c WCP_{r,c,t} = TWF_{r,t} \quad (15)$$

2.1.6.9. Monthly deep percolation. Monthly deep percolation depends on irrigation efficiency ($IE_{r,c}$) and total water delivered to the field for each crop ($WACP_{r,c,t}$):

[6] Given data limitations evaporation losses from conveyance infrastructures are not explicitly considered but rather are modeled through losses that join the drainage system and finally reach tail-end water sinks.

[7] The proportion of these sources are very limited compared to surface water supply. For instance, groundwater uses are only 3–4% of total irrigation water supply. Rainfall occurs mainly during the non-vegetation period and thus has limited impact on beneficial water consumption by crops. Because of the high salinity of drainage waters farmers usually only blend them with surface water to improve water supply for crops during abnormally dry years.

[8] The term 'seasonal' is used to mean "spanning each annual growing season" throughout the text

[9] We note here that non-beneficial evapotranspiration is not explicitly modeled because of lack of data but is implicitly considered through losses to the drainage system.

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$$DPSTG_{r,c,t} = WACP_{r,c,t}(1 - IE_{r,c}) \tag{16}$$

2.1.6.10. Seasonal deep percolation. Total seasonal deep percolation ($DP_{r,c}$) is the sum of monthly deep percolation across months within the season ($DPSTG_{r,c,t}$):

$$DP_{r,c} = \sum_{t} DPSTG_{r,c,t} \tag{17}$$

2.1.6.11. Groundwater seepage into surface water. Groundwater discharge to the river system depends on the water volume in the aquifer and the transitivity coefficient ($trs_{g,n}$):

$$DSCH_{g,n,t} = trs_{g,n}\, gws_g\, agw_g\, GH_{g,t} \tag{18}$$

2.1.6.12. Groundwater storage balance. The groundwater storage in subsurface aquifers increases due to water percolation from fields and irrigation canals, and declines due to groundwater withdrawals ($WP_{g,r,c,t}$) and water seepage to the river ($DSCH_{g,r,c,t}$):

$$0.01\, gws_g\, agw_g\left(GH_{g,t} - GH_{g,t-1}\right) = \sum_{r\in GWDLINK}\sum_{c} DPSTG_{r,c,t}\left(1 - drn_r\right) + \sum_{r\in GWDLINK}\sum_{n\in NDLINK}(RW_{n,r,t}(1 - DE_r)(1 - drn_r)) - \sum_{r\in GWDLINK}\sum_{c} WP_{g,\,r,c,t} - \sum_{n\in GWRLINK} DSCH_{g,n,t} \tag{19}$$

where gws_g is yield of groundwater aquifer, agw_g is the surface area of groundwater aquifer, $GH_{g,\,t}$ is groundwater depth, $DPSTG_{r,c,t}$ is deep percolation from crop fields in each month, and drn_r is the proportion of water losses flowing to drainage networks.

2.1.6.13. Generation of return flows. Return flows generated from each irrigation site across months ($RF_{r,t}$) come from water percolation from crop fields ($DPSTG_{r,c,t}$) and irrigation canals that are adjusted considering the proportion of water losses flowed to the drainage networks (drn_r):

$$RF_{r,t} = \sum_{c} DPSTG_{r,c,t}drn_r + \sum_{n\in DNLINK} RW_{n,r,t}(1 - DE_{r,c,t})drn_r \tag{20}$$

2.1.6.14. Discharge of return flows to surface water. Part of this return flow ($RF_{r,t}$) is discharged into the river node ($RFR_{r,n,t}$) and the remaning goes to tail end depressions or lakes ($RFL_{r,t}$):

$$RF_{r,t} = \sum_{n\in DNLINK} RFR_{r,n,t} + RFL_{r,t} \tag{21}$$

2.1.6.15. Maximum discharge of return flows. To prevent unrealistic return flows back to the river channel (which would not be allowed by irrigation canal managers due to concerns over water quality), an additional constraint on return flows discharged into the river is introduced:

$$\sum_{n\in DNLINK} RFR_{r,n,t} \le rr_{r,t} \sum_{n\in NDLINK} RW_{n,r,t} \tag{22}$$

where $rr_{r,t}$ is the maximum ratio of return flows discharged into the river to the regional water withdrawal.

2.1.6.16. Constraint on use of return flows. Only a portion of return flows ($RFL_{r,t}$) can be re-used for irrigation since full re-use is not acceptable due to the high salinity of return flows:

$$\sum_{c} RU_{r,c,t} \le rru_r RFL_{r,t} \tag{23}$$

where rru_r is the rate of return water re-use (this is a dimensionless parameter that varies between 0 and 1).[10]

2.1.7. Surface water balance (flow continuity equations)

2.1.7.1. Simple river nodes. The water balance in the river nodes is formulated as:

$$\sum_{m\in RVLINK} F_{m,n,t} + s_{n,t} + \sum_{v\in RNLINK} RSN_{v,n,t} + \sum_{r\in DNLINK} RFR_{r,n,t} + \sum_{g\in GWRLINK} DSCH_{g,n,t} = \sum_{k\in RVLINK} F_{n,k,t} + \sum_{v\in NRLINK} NRS_{n,v,t} + \sum_{r\in NDLINK} (RW_{n,r,t} + idw_{n,r,t}) \tag{24}$$

where:

$F_{m,n,t}$ is river flow to the river node (n) from the upper river node (m) if there is a link between these nodes ($RVLINK$);
$s_{n,t}$ is the water supply from source nodes that flow into the river (e.g., tributaries);
$RSN_{v,n,t}$ is river flow from an upstream water reservoir to river node;
$RFR_{r,n,t}$ is return water from irrigation sites to the river node;
$DSCH_{g,n,t}$ is the amount of water that seeps into the river from groundwater sources (gw) if there is a link ($GWRLINK$) between a groundwater reservoir (g) and river node (n);
$NRS_{n,v,t}$ is river flow from a river node (n) to a downstream water reservoir;
$RW_{n,r,t}$ and $idw_{n,r,t}$ are water withdrawals from a river node (n) to an irrigation site (r) and municipal-industrial water use, respectively, if there is a link between the node and the water user site ($NDLINK$). Municipal-industrial water demands are taken as exogenous and must be met first since these sectors are prioritized in national water distribution practices. All water use and flow variables are in million m^3.

In addition, the model considers a one year time horizon with monthly time steps, such that reservoirs are assumed to operate to distribute flows seasonally but not inter-annually. Thus end-of-year reservoir storage is constrained to be equal to the initial reservoir storage to prevent unrealistic drawdown of reservoirs at the end of the optimization period.

2.1.7.2. Reservoir nodes. The water level in a reservoir ($H_{v,t}$) depends on the reservoir storage volume ($V_{v,t}$):

$$H_{v,t} - htail_v = d0 + d1\, V_{v,t} + d2\, V_{v,t}^2 \tag{25}$$

where $d0$, $d1$, and $d2$ are the parameters of the elevation-storage function, which are determined based on goodness of fit statistics.

Similarly, the surface area of the reservoir is related to its storage volume following the functional relationship of:

$$S_{v,t} = c0 + c1\, V_{v,t} + c2\, V_{v,t}^2 + c3\, V_{v,t}^3 \tag{26}$$

where $c0$, $c1$, $c2$, and $c3$ are the parameters of the function.

The water balance in reservoirs is then modeled as:

[10] Note that we do not model water quality and salinity tolerance, but rather impose this constraint based on assumed tolerance for re-use as revealed by existing practices in the region.

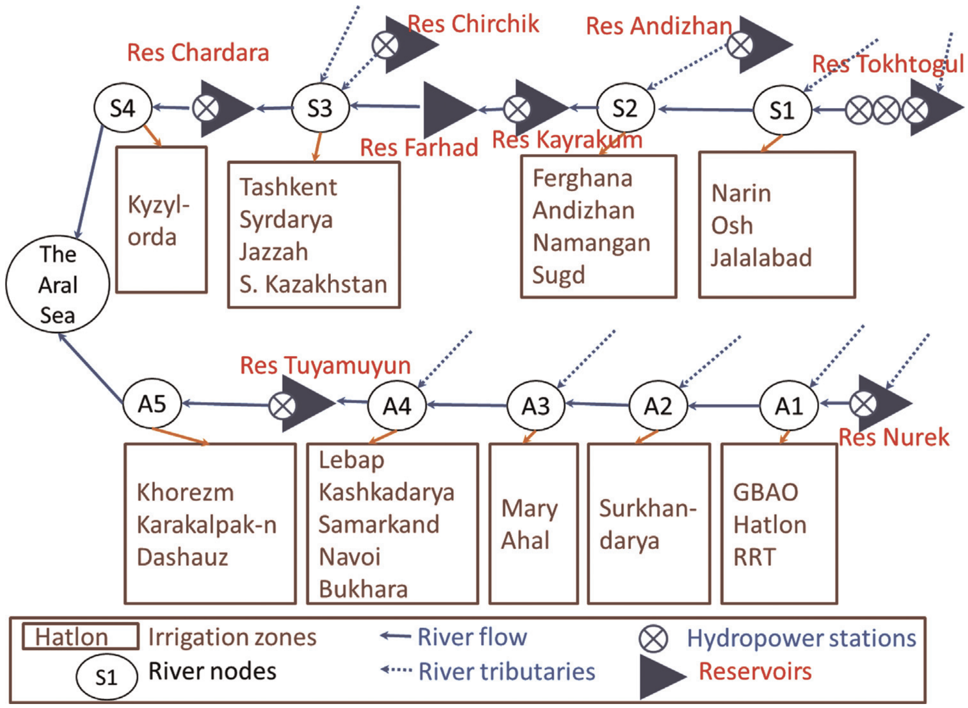

Fig. 3. River basin scheme.

$$V_{v,t-1} + \sum_{n \in NRLINK} NRS_{n,v,t} + \sum_{u \in DDLINK} RRS_{u,v,t} = V_{v,t} + \sum_{n \in RNLINK} RSN_{v,n,t} + \sum_{w \in DDLINK} RRS_{v,w,t} + 0.001 \cdot \varphi_{v,t}\,(0.5\,S_{v,t-1} + 0.5\,S_{v,t}) \quad (27)$$

where $RRS_{u,v,t}$ is the flow to the reservoir (v) from an upper reservoir (u), $\varphi_{v,t}$ is the rate of evaporation from the surface of the reservoir, and $S_{v,t}$ is the surface area of the reservoir. Considering the maximum size of the reservoirs constraints on reservoir water storage capacity is additionally included in the model.

2.2. River node scheme

The schematic used in the hydro-economic basin management model comprises 32 river tributaries, 9 river nodes (where inflows from tributaries enter and water withdrawals occur), 26 irrigation sites (provinces), 7 water storage reservoirs, and 11 hydropower production units (Fig. 3). Although there are more than 80 water reservoirs operating or planned in the ASB, only the largest and most important reservoirs were explicitly modeled in this study. Most of these reservoirs serve both for hydroelectricity generation and seasonal water flow regulation. Moreover, the five key run-of-the-river power stations are modeled.

The agricultural production model includes key crops grown in the basin: cotton, wheat, maize, rice, fodder crops, fruits, vegetables and gourds and other crops (sugar beet, sunflower). Crop patterns vary across irrigation sites: rice is more common in downstream reaches of both sub-basins while fodder crops, cereals and horticultural crops are more common in upstream reaches.

2.3. Model data

Due to the significant geographic extent of the model and the fact that it spans multiple countries, a large and consistent database had to be constructed from a variety of data sources (Table 1). Monthly water availability estimates at supply nodes, and water withdrawals for irrigation and municipal-industrial use were sourced from the CAREWIB database [29]. CAREWIB also includes estimates of cropping areas and crop yields across irrigation sites. Data on potential evapotranspiration coefficients and effective rainfall were taken from IFPRI's IMPACT model [30]. The costs and benefits of crop production across the provinces of Uzbekistan come from statistical reports of national water management organizations [31]; due to lack of data, those for other ASB countries are approximated using the costs and benefits in the closest

Table 1
Sources of data used in the model.

#	Data	Source
1	Monthly water supply by tributaries, water withdrawals for irrigation, industry and municipal sector	SIC-ICWC [29]
2	Cropping areas and yields	SIC-ICWC [29]
3	Crop ET and Effective rainfall	IFPRI [30]
4	Crop production costs, benefits, conveyance costs	Local water management organization including SIC-ICWC 2008 [31], MAWR [32],
5	Water application and conveyance efficiency by site	GEF [33], Cai [34], EC-TACIS [35]
6	Hydropower production capacity, electricity prices, and reservoir storage capacities	Cai [34], EC IFAS [36] and SIC-ICWC [37]
7	Environmental flow and benefits	INTAS 2006 [38]
8	Costs of water conservation by water application and conveyance efficiency improvements	Cai [34], SIC-ICWC 2002 [39]

province of Uzbekistan. MAWR provided water conveyance costs for irrigation sites [32]. Conveyance and water application efficiency across the sites are based on GEF [33], Cai [34] and EC-TACIS [35]. Hydropower production capacity, electricity prices, and reservoir storage capacities are based on Cai [34] and updated using the BEAM [36] and ASBOM [37] model databases. Parameters for the functional relationships between reservoir head, surface area and volume are from EC IFAS [36] and SIC-ICWC [37]. Environmental flows and benefits are based on INTAS report [38]. Finally, the annualized costs per unit of water saved through improving irrigation and conveyance efficiencies, and the costs per unit of groundwater and return flow uses, are estimated based on data from Cai [34] and SIC-ICWC [39]. Since most of data on costs and benefits are available for 2006, all parameters and model results are reported in 2006 US$.

2.4. *Model calibration, scenarios and solution*

The model uses a normative mathematical programming approach that is calibrated to the water availability, use, and total cropland levels of 1999, since this year had the median water supply over the period between 1980 and 2008. The model is coded and solved in GAMS. In the analyses reported in this paper, the results of two scenarios are compared: a) optimal water allocations and benefits with existing conveyance and field irrigation technologies ($IE_{r,c} = ie0_{r,c}$ and $DE_{r,c} = de0_{r,c}$); and b) optimal water allocations and benefits allowing for economically efficient improvements in conveyance and field irrigation improvements ($IE_{r,c} > ie0_{r,c}$ and $DE_{r,c} > de0_{r,c}$). The difference between the benefits generated under these two scenarios corresponds to the net economic gains from implementing technical water savings interventions.

Because of the implicit modeling of technological improvements through water application and conveyance efficiency changes, we here provide a table that indicates how improved irrigation efficiency maps to specific technological improvements (Table 2). Note that these are examples for technological improvements and that a wider range of options is available in practice.

The economic gains from water use efficiency improvements are estimated for three scenarios of water availability, characterized by normal supply (1999 flows, $src_{n,t}$), as well as synthetic years based on uniform 10% and 20% reductions (in space and time) in the pattern of inflows for that year ($0.9\,src_{n,t}$ and $0.8\,src_{n,t}$, respectively). In addition, given the relatively limited data on the cost of water saving technologies and on the benefits of environmental flows, we conduct additional analysis to test the sensitivity of results to a) the weight on environmental benefits in Eq. (1), and b) the irrigation efficiency cost parameters in the model. In the former analysis, we varied the relative weight on environmental benefits (ω) over a range increasing from 1 to 20. Using a weight of 1 as the lower bound can be justified by the fact that the assumed benefits only correspond to a partial accounting, as described in Section 2.1. In the latter analysis, different combinations of efficiency improvement costs per unit of saved water were varied from 0.25 to 5 times their baseline levels. In the first analysis, only the conveyance improvement costs ($itc_{r,c}$) were modified. The second analysis then considered only changes in the application efficiency costs (dsc_c), and the third included both.

3. Results and discussion

Before turning to a summary of the net economic gains from the analyzed investments in water use efficiency improvement, we first discuss the place and magnitude of these improvements and their implications for agricultural land expansion (adjustment on the extensive margin) versus modification of existing cropping patterns

Table 2
Conveyance and water application efficiency (WAE) improvement options.Source: Authors' assessments based on previous studies [10, 19, 20, 21, 22, 39].

Efficiency improvement measures	Efficiency			
	50–60%	60–70%	70–80%	80–90%
Conveyance efficiency	Periodic silt removal and canal reconstruction; reduced operating losses through basic gate and other infrastructure maintenance	Partial lining (lining the parts of the canal with very high seepage losses); continued maintenance and infrastructure repair	Plastic lining, continued maintenance and repairs	Lining with concrete; automated (i.e. computer operated) canal infrastructure
WAE of cotton	Short furrow, double furrow	Alternate dry furrow, mulching, surge flow	Sprinkler irrigation	Drip irrigation, subsurface irrigation
WAE of rice	Deficit irrigation and laser-guided land leveling	Alternate wet/dry irrigation	Transplanting rice	Transplanting rice and alternate wet/dry irrigation; improved rice varieties, drip irrigation
WAE of wheat	Deficit irrigation and laser land leveling	Mulching	Sprinkler irrigation	Drip irrigation
WAE of maize and fodder crops	Deficit irrigation	Manuring and deficit irrigation	Sprinkler irrigation	Drip irrigation
WAE of fruits, vegetables and gourds	Deficit irrigation	Manuring and deficit irrigation	Sprinkler irrigation	Drip irrigation, subsurface irrigation

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Table 3
Conveyance efficiency (CE) and water application efficiency (WAE) rates for cotton, wheat, and rice across irrigation sites in the ASB, with and without optimal efficiency improvement and under varying water supply conditions.

Sites	Conveyance efficiency			Cotton WAE			Wheat WAE			Rice WAE		
	CE without	CE with		WAE without	WAE with		WAE without	WAE with		WAE without	WAE with	
		normal	80% of normal		normal	80% of normal		normal	80% of normal		normal	80% of normal
Amu Darya Basin												
GBAO	0.64	0.64	0.64	0.00	0.00	0.00	0.62	0.62	0.62	0.22	0.00	0.00
Khatlon	0.64	0.64	0.64	0.62	0.80	0.90	0.62	0.90	0.90	0.22	0.90	0.90
RRP	0.64	0.64	0.90	0.62	0.62	0.62	0.62	0.62	0.90	0.22	0.90	0.90
Surkhandarya	0.64	0.64	0.64	0.62	0.62	0.62	0.62	0.62	0.90	0.22	0.90	0.90
Mary	0.70	0.70	0.70	0.58	0.58	0.58	0.58	0.58	0.58	0.18	0.00	0.00
Ahal	0.70	0.70	0.90	0.58	0.58	0.90	0.58	0.65	0.90	0.18	0.00	0.00
Lebap	0.70	0.70	0.83	0.58	0.58	0.58	0.58	0.58	0.58	0.18	0.90	0.90
Kashkadarya	0.64	0.64	0.79	0.62	0.62	0.90	0.62	0.62	0.90	0.22	0.00	0.00
Samarkand	0.64	0.64	0.90	0.62	0.62	0.62	0.62	0.62	0.62	0.22	0.90	0.90
Navoi	0.65	0.65	0.65	0.52	0.52	0.52	0.52	0.52	0.52	0.15	0.00	0.00
Bukhara	0.65	0.65	0.65	0.52	0.52	0.52	0.52	0.52	0.52	0.15	0.00	0.00
Khorezm	0.65	0.90	0.90	0.52	0.52	0.52	0.52	0.52	0.52	0.15	0.90	0.90
Karakalpakstan	0.70	0.90	0.90	0.48	0.48	0.48	0.48	0.48	0.48	0.15	0.90	0.90
Dashauz	0.70	0.90	0.90	0.53	0.53	0.53	0.53	0.53	0.53	0.16	0.90	0.90
Narin	0.73	0.74	0.73	0.00	0.00	0.00	0.55	0.55	0.55	0.17	0.00	0.00
Syr Darya Basin												
Osh	0.73	0.77	0.83	0.55	0.90	0.90	0.55	0.55	0.55	0.17	0.90	0.90
Jalalabad	0.73	0.73	0.86	0.55	0.90	0.90	0.55	0.63	0.55	0.17	0.90	0.90
Ferghana	0.73	0.73	0.77	0.55	0.78	0.90	0.55	0.61	0.55	0.17	0.90	0.90
Andizhan	0.73	0.73	0.73	0.55	0.76	0.90	0.55	0.90	0.63	0.17	0.90	0.90
Namangan	0.62	0.64	0.63	0.63	0.90	0.90	0.63	0.90	0.90	0.23	0.90	0.90
Sugd	0.73	0.75	0.75	0.55	0.90	0.90	0.55	0.90	0.90	0.18	0.90	0.90
Tashkent	0.73	0.90	0.85	0.55	0.55	0.90	0.55	0.55	0.55	0.18	0.90	0.90
Syrdarya	0.71	0.90	0.90	0.73	0.73	0.89	0.73	0.73	0.73	0.24	0.90	0.90
Jizzah	0.70	0.90	0.90	0.63	0.63	0.76	0.63	0.71	0.63	0.23	0.00	0.00
S. Kazakhstan	0.70	0.90	0.90	0.63	0.63	0.90	0.63	0.63	0.90	0.23	0.90	0.90
Kyzylorda	0.70	0.90	0.90	0.00	0.00	0.00	0.48	0.48	0.48	0.15	0.90	0.90

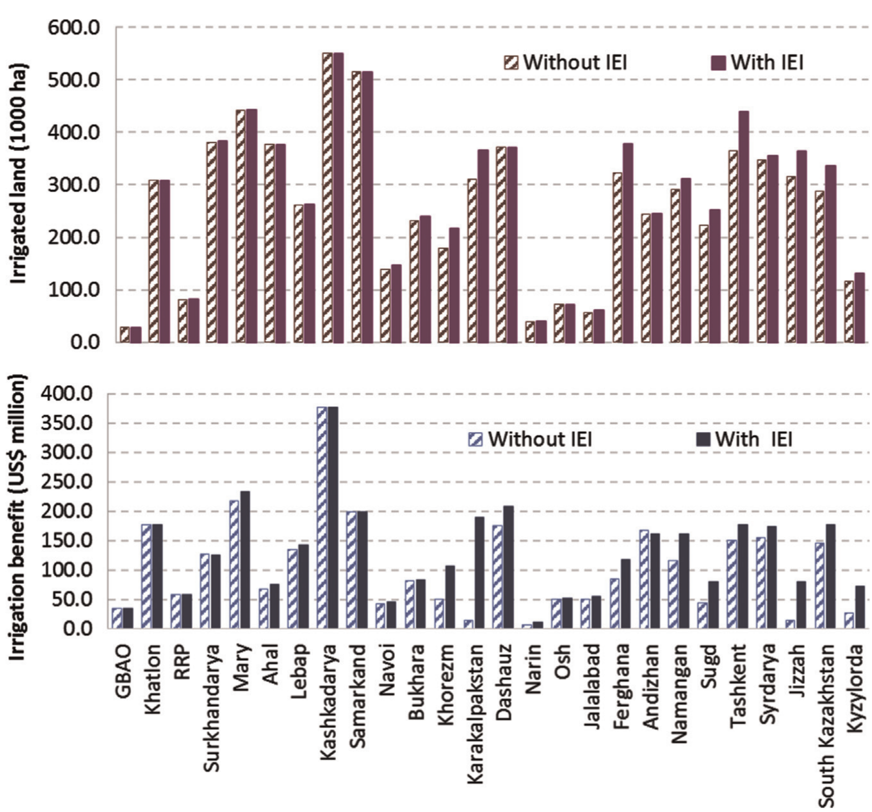

Fig. 4. Irrigated area and irrigation benefits with and without irrigation efficiency improvements (IEIs) across the sites under normal water supply.

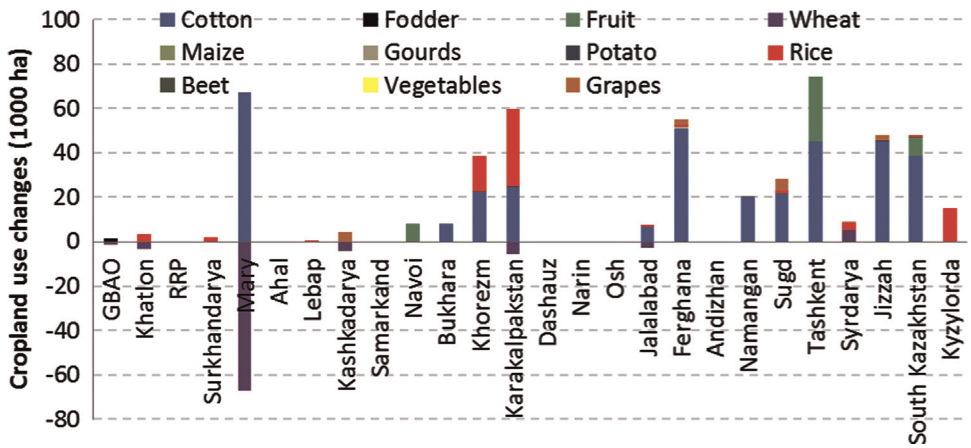

Fig. 5. Cropland pattern changes with and without irrigation efficiency improvements (IEIs) across the sites under normal water supply.

(adjustment on the intensive margin), under the different water availability scenarios.

3.1. Optimal level of conveyance and water application efficiency improvements

According to the model results, the improvement of conveyance efficiency of many irrigation canals, particularly in downstream provinces of the Amu and Syr Darya Basins, would increase economic net benefits (Table 3). Specifically, canal systems in Khorezm, Karakalpakstan and Dashauz provinces (Amu Darya Basin) and Syrdarya, Jizzakh, South Kazakhstan, and Kyzylorda provinces (Syr Darya Basin) should be fully upgraded. The preferential conveyance improvements for these downstream irrigated areas are largely driven by the fact that losses are higher in these zones due to their largely sandy soils.

The findings also indicate that there would be considerable basin-wide benefits from improving the efficiency of water application (on-farm) in cotton, rice and wheat fields (Table 2). Because of the high fiber quality and higher yields of cotton production in up- and mid-stream provinces (Ferghana Valley) of the Syr Darya Basin [40], cotton production in these zones generates larger net benefits. The results indicate that the costs of improvements in water application efficiency of cotton production in these zones up to levels of 0.8 to 0.9 (drip irrigation) would be recovered and would deliver substantial basin-wide economic benefits. These findings are consistent with previous research that demonstrates the profitability of adopting drip irrigation technologies for growing high value crops [10].

Furthermore, the optimal magnitude of water application efficiency improvements increases in tandem with reduced water availability. The economics of more efficient water use improve under such conditions because the increased marginal value of water under reduced water supply offsets the higher marginal costs of increasing water conservation. If water availability decreases to 80% of normal supply, for example, irrigation efficiency improvements for cotton production become beneficial in several additional regions of the Amu Darya Basin – Khatlon, Ahal, and Kashkadarya – and in all cotton-producing regions of the Syr Darya Basin except Jizzakh. Under these drier conditions, the water application efficiency of irrigation for wheat production should also be fully improved in a number of regions – Khatlon, RRT, Surkhandarya, Ahal, and Kashkadarya in the Amu Darya Basin and Namangan, Sugd, and South Kazakhstan in the Syr Darya Basin. The use of transplanting for rice production (this is technically not an irrigation technique but rather a farming method that substantially reduces water requirements) or implementing drip irrigation (it is not practiced currently in the study region) is similarly beneficial in all rice producing regions under these drier conditions.

Table 4
Rebound effects of water use efficiency improvements.

Water and land use indicators	Scenarios	
	Without technological improvements	With technological improvements
Total irrigation water withdrawals at river nodes (km^3)	109.5	105.0
Irrigation water delivery to the fields (km^3)	63.9	66.9
Total surface, groundwater and return flow diversion (km^3)	73.4	75.6
Groundwater pumping (km^3)	4.7	3.8
Irrigated land (million ha)	6.8	7.2
Effective evapotranspiration (km^3)	42.2	52.0
Deep percolation (km^3)	31.1	28.8
Return flows (km^3)	46.0	36
Return flows discharge to tail-end depressions (km^3)	35.0	26.5
Return flows discharge to river (km^3)	11.0	10.3
Flows to the Aral Sea (km^3)	14.3	16.6

Table 5
Comparing the economic benefits of optimal water allocation with (OPT−) and without irrigation modernization (OPT+) under different levels of water supply.

Scenarios	Water supply			Change compared to the optimal (baseline) scenario		
	Normal	90% of normal	80% of normal	Normal	90% of normal	80% of normal
Agricultural benefits (US$ million)						
OPT−	2776	2558	2213	0.0	0.0	0.0
OPT+	3378	3283	3131	21.7	28.4	41.5
Hydropower production benefits (US$ million)						
OPT−	395	349	320	0.0	0.0	0.0
OPT+	413	366	323	4.6	5.0	0.9
Environmental benefits (US$ million)						
OPT−	39	30	27	0.0	0.0	0.0
OPT+	47	36	27	20.8	21.7	2.0
Total benefit (US$ million)						
OPT−	3210	2937	2560	0.0	0.0	0.0
OPT+	3839	3685	3481	19.6	25.5	36.0

3.2. Adjustments in irrigated areas and crop types

We next consider adjustments along the intensive (crop choice and intensity) and extensive (cultivated land area) margins of irrigation. Regarding the latter, irrigation efficiency improvements supports irrigated area expansion in the more productive sites in the ASB (Fig. 4 top). For example, irrigated areas – mainly for rice and cotton production – increase in Khorezm and Karakalpakstan in the Amu Darya Basin after conveyance efficiency improvements (Fig. 5). Similarly, cotton area expands in Ferghana, Namangan, Sugd, Tashkent (which also sees expansion of orchards), Jizzakh, and South Kazakhstan of the Syr Darya Basin. Because of the relatively low assumed value for environmental flows compared to irrigation benefits in our base case, most of the water that is saved is re-allocated to this irrigation expansion.

At the intensive margin, we observe more modest changes. The spatial crop patterns in many irrigation sites shift somewhat toward more water-intensive crops for which the marginal net gains from additional water availability are higher (Fig. 5). For instance, cotton cropping increases at the expense of wheat in Mary. Wheat areas decrease somewhat in several other areas, including GBAO, Khatlon, Kashkadarya, Karakalpakstan, and Jalalabad, and this crop is replaced by rice, cotton, and grapes. Cotton expansion is also recommended in Ferghana, Namangan, Sugd, Tashkent, Jizzakh and South Kazakhstan of the Syr Darya Basin.

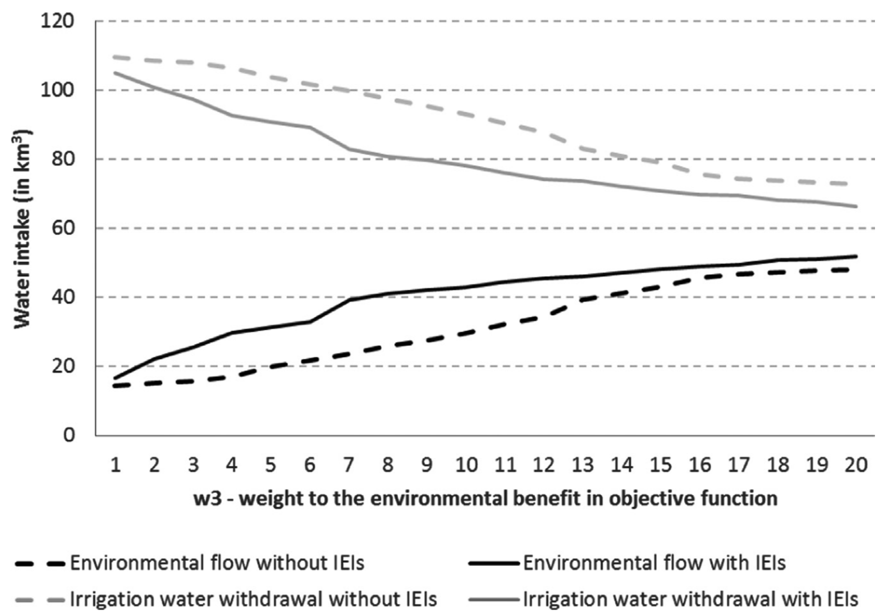

Fig. 6. Water withdrawals for irrigation and water allocated for environmental flow purposes, with and without irrigation efficiency improvements (IEIs), as a function of the weighting parameter for environmental flows in the objective function of the model, under normal supply.

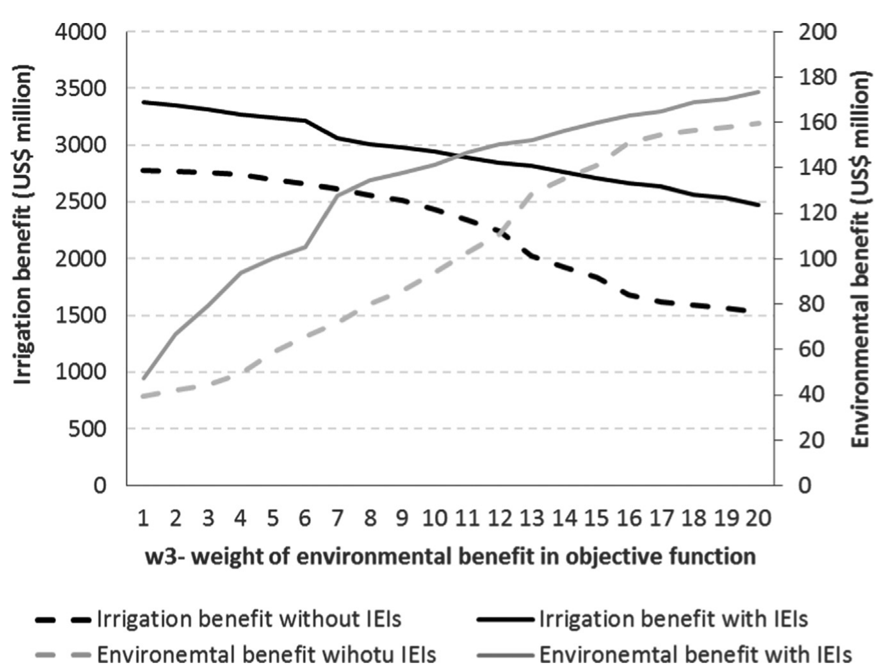

Fig. 7. Irrigation and environmental benefits, with and without irrigation efficiency improvements (IEIs), as a function of the weighting parameter for environmental flows in the objective function of the model, under normal supply.

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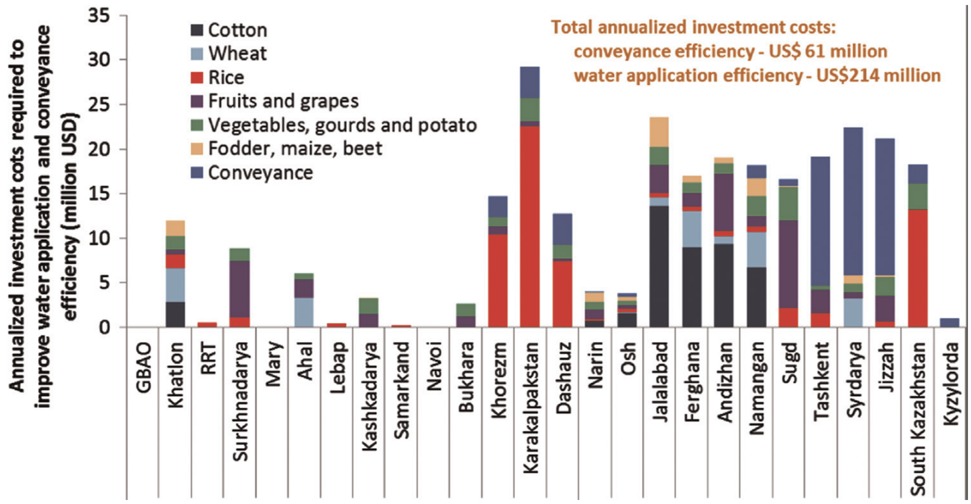

Fig. 8. Optimal annualized investment costs of improving conveyance and water application efficiency (US$ million per year) under normal water supply.

3.3. Implications for water conservation and rebound effects

Irrigation technology improvements clearly lead to water saving at the field or local level, but some specialists question whether these savings translate into measurable basin scale savings [41]. This basin scale effect is ambiguous because a) irrigation efficiency improvements can reduce return flows that also contribute to downstream water supply, and b) behavioral adjustments may translate into additional abstractions and area expansions by upstream irrigators. The latter change, or rebound effect, is driven by the fact that increased water use efficiency effectively increases water availability for irrigated area expansion or more crop water consumption, since marginal value of water for maintaining environmental flows is low. This potential for rebound effects can be analyzed using a river basin scale model such as the one employed in this study.

In fact, the model results show that water abstractions from river nodes decrease considerably following the irrigation improvements (Table 4). Nonetheless, the greater conveyance efficiencies in canals translate into greater irrigation water availability at the farm gate (irrigation water supply increases from 63.9 to 66.9 km^3). This additional water then translates into both increased per hectare water use, and irrigation expansion. The total irrigated land area increases from 6.8 to 7.2 million ha, and the most significant changes along this extensive margin occur at sites where the irrigation efficiency improvements are concentrated. Overall, the beneficial water consumption by irrigated crops thus increases from 42 to 52 km^3. At the same time, deep percolation decreases somewhat, from 31.1 to 28.8 km^3. This reduced deep percolation however primarily affects the return flows discharged to tail-end depressions, rather than those that return to the river. As such, the rebound effects or increased upstream water consumption that is induced by these technological improvements have relatively small consequences for downstream users and only slightly increase environmental flows into the Aral Sea. Of course, these effects on environmental flows are partly reflective of the prevailing limited allocations and value ascribed to flows into the Aral Sea.

3.4. Economic impact of irrigation technology improvements

We next compare the optimal economic benefits for the two scenarios described above, i.e., with and without investment in optimal irrigation efficiency (Table 5). Under normal supply and without any efficiency improvements, the optimal total economic benefits reach US$3.2 billion (2.8 billion from irrigated agriculture, with the remainder in hydropower and ecosystem gains). With efficiency improvements, total benefits increase by 20% to US$3.8 billion (with irrigation, hydropower and ecosystem benefits increasing by 22%, 5% and 21%, respectively). Under the most constrained water supply conditions (80% of normal flow), the optimal basin-wide benefits from the set of modeled efficiency improvements increase by 36% (with irrigation, hydropower and ecosystem benefits increasing by 42%, 1% and 2%, respectively). The impact of adopting water conservation technologies on hydropower benefits and environmental water supply appears modest, however. This is because most hydropower production occurs upstream of large scale irrigation, and because of the low estimated value (relative to the alternative use in irrigation) of environmental flows in our base case analysis. In drier years, the water saved due to irrigation efficiency improvements are thus primarily allocated to maintaining agricultural production.

As increased benefits are mainly in the agricultural sector (Table 5), we can expect that improved irrigation efficiency would increase irrigation benefits across locations (Fig. 4, bottom). The extent of the changes in the distribution of benefits would depend on how the various efficiency improvements were paid for, but improved irrigation would make more water available for high-value cash crops such as rice in downstream sites such as Khorezm and Karakalpakstan. Expansion of rice production would also occur through planting of improved rice varieties and use of transplanting methods. Similarly, water application efficiency improvements would substantially increase agricultural incomes in mid- and downstream reaches of the Syr Darya Basin.

3.5. Environmental impact of irrigation technology adoptions

Since long-term environmental benefits are uncertain and may have been mischaracterized in the objective function of the model (i.e., the magnitude of these largely nonmarket benefits is not well known), the model was re-estimated with a higher weight on the environmental benefits term of Eq. (1). According to the results of this sensitivity analysis, the releases of water to the environmental system are sensitive to this weighting factor, and such releases come at the expense of reduced irrigation water withdrawals (Fig. 6). Introduction of irrigation efficiency improvement measures reduce optimal irrigation water withdrawal requirements considerably and increase optimal environmental flows.

Similarly, and mirroring the water withdrawal trends, optimal irrigation benefits decrease and environmental benefits increase

Table 6
Sensitivity analysis for key outcomes as a function of the costs of conveyance efficiency (CEI) and water application efficiency improvements (WAEIs).

Land and water use and economic variables	Simulated parameters	Relative change in efficiency improvement costs							
		0.25	0.5	0.75	1	2	3	4	5
Irrigated land (hectare)	CEI	7.3	7.3	7.3	7.3	7.2	7.2	7.2	7.2
	WAEI	7.3	7.3	7.3	7.3	7.2	7.1	7.1	7.1
	CEI+WAEI	7.3	7.3	7.3	7.3	7.1	7.0	7.0	7.0
Environmental flow (km^3)	CEI	25.4	17.1	16.5	16.6	16.6	16.6	16.6	16.6
	WAEI	27.3	22.5	19.4	16.6	15.5	15.4	15.3	15.2
	CEI+WAEI	29.5	22.6	19.3	16.6	15.6	15.3	15.1	15.1
Irrigation water withdrawal at river node (km^3)	CEI	95.0	104.1	105.1	105.0	105.1	105.1	105.1	105.1
	WAEI	93.0	98.5	102.1	105.0	106.7	106.9	107.1	107.3
	CEI+WAEI	88.7	98.3	102.0	105.0	107.0	107.3	107.6	107.8
Water delivered to crop fields (km^3)	CEI	71.2	69.6	68.0	67.0	64.8	64.7	64.7	64.7
	WAEI	56.5	60.4	63.9	67.0	70.9	71.1	71.2	71.3
	CEI+WAEI	57.5	62.2	64.9	67.0	66.2	66.6	66.8	66.9
Beneficial crop evapotranspiration (km^3)	CEI	52.4	52.1	52.0	52.0	51.4	51.4	51.4	51.4
	WAEI	53.8	53.5	52.9	52.0	49.9	49.1	49.0	48.9
	CEI+WAEI	54.1	53.6	53.0	52.0	48.4	46.8	46.3	46.2
Return flow to the tale-end lakes (km^3)	CEI	20.3	26.0	26.5	26.5	26.8	26.8	26.8	26.8
	WAEI	18.1	21.6	23.9	26.5	28.3	28.8	28.9	29.1
	CEI+WAEI	16.1	21.5	23.9	26.5	29.0	30.2	30.6	30.8
Irrigation benefits (US$ million)	CEI	3.4	3.4	3.4	3.4	3.4	3.3	3.3	3.3
	WAEI	3.6	3.5	3.4	3.4	3.3	3.2	3.1	3.1
	CEI+WAEI	3.6	3.5	3.4	3.4	3.2	3.1	3.0	3.0

as the weight on environmental benefits in the objective function increases (Fig. 7). Irrigation benefits are higher with the introduction of irrigation efficiency improvement measures, due to the increased beneficial crop consumption despite reduced water intake. Environmental benefits are also higher with the efficiency improvements because of higher water release for environmental needs. The most important implication of this analysis is that additional units of water saved through technological improvements could be effectively delivered for environmental needs if these were found to be of higher value, but that such a re-allocation would require institutions that effectively alter water rights. Specifically, compensation to farmers would likely be required in order for them to relinquish or trade their water use rights [42], since quantity limits would be politically difficult. Alternatively, introducing taxes on water consumption beyond specific thresholds might be effective for increasing environmental flows and the feasibility (and political economy) of this option should also be investigated in future studies.

3.6. *Investment costs of technological improvements*

Implementing the irrigation improvements discussed in this paper requires substantial investment (Fig. 8). The annualized investment costs (US$61 million per year) required to improve conveyance efficiency[11] are substantial, especially in the mid-stream areas of the Syr Darya Basin and the downstream reaches of the Amu Darya Basin. Similarly, the annualized investment costs of improving the full set of field-level water efficiency improvements[12] (US$214 million per year) are substantial. These costs are concentrated in the rice-producing downstream provinces of the Amu Darya such as Khorezm, Karakalpakstan, and Dashauz and in cotton-producing mid-stream provinces in the Syr Darya such as Ferghana, Andizhan, Namangan, Sugd and Tashkent. An earlier study also indicated a high potential of water savings in the provinces of the Ferghana Valley (Ferghana, Andizhan, and Namangan) through covering furrows with plastic films for cotton, implementing drip irrigation for orchards, and introducing alternate dry furrow for vegetables [43]. While incentives are generally well aligned for individual farmers to make beneficial field-level investments, paying for conveyance enhancements poses significant coordination challenges, since spatial asymmetries lead to an uneven distribution of benefits across farms.

In addition, our model does not include capital constraints, which may be a significant barrier to efficient technology adoption in the region for both farmers and the government [15, 16, 44]. Thus, it may be necessary in the short term to prioritize lower cost irrigation efficiency improvements, based on rankings of relative annualized investment cost per unit of water saved [25] (Fig. 9). Such an ordering of cost effectiveness favors conveyance efficiency improvements in downstream sites such as Khorezm, Karakalpakstan, Dashauz, South Kazakhstan and Kyzylorda, and more limited ones in mid- and upstream sites. Such investments would deliver a short-run savings of more than 7 km^3 of water, or almost half of the current average inflow to the Aral Sea.

Beyond these relatively cheap investments, the choice of which irrigation efficiency improvements to make, given financial constraints, becomes more difficult. To help guide such decisions, we derive the relationship between water savings and total costs across the set of potential changes in the ASB (Fig. 9). In Fig. 9, the lowest-cost annualized investment requirement for a given level of water savings can then be estimated as an integral function of the derived cost curve. For instance, efficient investment of US$ 60 million would allow savings of up to 7.4 km^3 of water, while US$ 277 million would be required to save 14.7 km^3 of water (e.g., for doubling the environmental flows and maintaining adequate flow levels to sustain the downstream environmental system).

Of course, there may be significant challenges in achieving economically optimal investments in irrigation efficiency, particularly when low cost savings stem from conveyance (rather than on-farm) improvements. Conveyance infrastructure has characteristics of a public good; they are non-exclusive for farmers within the affected zone, and generate positive externalities at the basin level due to reduced water withdrawal requirements.[13] There are thus significant risks of free riding and therefore

[11] Calculated as: $\sum_r [dsc_r(DE_r - de0_r)(\sum_t \sum_{n \in NDLINK} RW_{n,r,t})]$.

[12] Calculated as: $\sum_r [\sum_c (itc_{r,c}(IE_{r,c} - ie0_{r,c})FCW_{r,c})]$.

[13] Negative externalities may also occur because of reduced discharge of aquifers; but groundwater use is only 3–4% of total irrigation water withdrawals in the ASB so this negative effect is very limited.

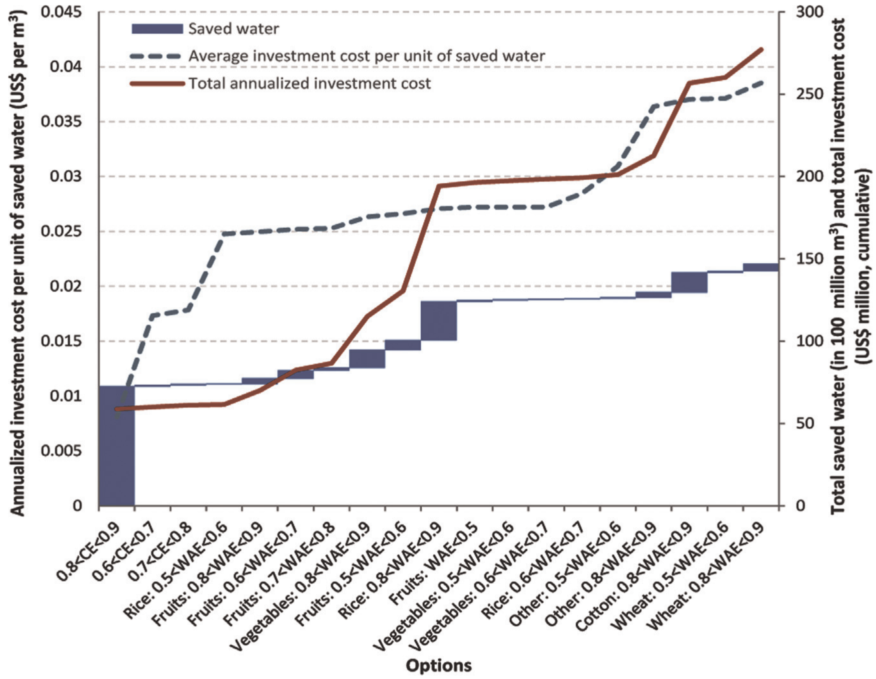

Fig. 9. Prioritization of the conveyance efficiency (CE) and water application efficiency (WAE) improvement options according to their average annualized investment cost per unit of saved water.

underinvestment in such technologies. Implementing them will require institutions that facilitate coordination among farmers but also account for the asymmetries inherent in canal systems. Thus, improvement of conveyance efficiencies is expected to be largely funded by government agencies.

Government funds and financing could also help in covering the fixed costs of establishing local (and currently missing) markets for drip irrigation or laser guided land leveling technologies, and facilitating farmers' ability to finance such improvements at the field level [10]. Private farms should be primarily responsible for investments in improved field application efficiency and increased efficiency of on-farm canals, but often have limited incentives to make such improvements due to a lack of effective price signals for water conservation. Agricultural price liberalization accompanied by better pricing of water supplied to farms would make adoption of irrigation technologies more profitable for private farmers, increasing incentives to boost water and crop productivity. Finally, improved training of those working in the agriculture and irrigation sectors would better ensure that farmers are aware of the value of these technological improvements. Cooperation of both governmental sector and private farmers thus seems essential to achieve optimal basin-wide gains.

Since the territory and water resources of the ASB are shared by five Central Asian countries, additional challenges concern agreement over the fair distribution of irrigation benefits, appropriate coordination of upstream reservoir water releases, and the value of downstream restoration of ecosystems [45]. The problem of effective transboundary water management suffers from many of the same challenges – spatial asymmetries, disputes over what is equitable, resource salience, and transaction costs – as that of coordinating conveyance improvements across farmers and other stakeholder interests (e.g., hydropower versus irrigated agriculture). Increased interdependence through enhanced regional trade of power and agricultural commodities may help to enhance incentives to cooperate. In this regard, institutional and legal arrangements that facilitate integrated management of irrigation and hydropower production [45] and improve the consistency of national and regional laws on water [46] across Central Asian countries appear critical.

3.7. Sensitivity analysis of water use efficiency improvement costs

Given the significant uncertainty over the costs of irrigation efficiency improvements, we also tested the sensitivity of the results to the cost assumptions in the model (Table 6). According to this sensitivity analysis, the optimal irrigated area decreases only slightly with higher costs. Land expansion is mostly constrained by irrigable area, while increased costs tend to lead to substitution into low value and less water-intensive crops rather than contraction of irrigated area.

Water allocation and drainage flows change more substantively. In particular, reduced costs result in substantially lower water withdrawals from river nodes and higher environmental flows but more modest changes under increasing costs. These sensitivities follow from the assumed low value for environmental flows in the base case, which makes improving irrigation efficiency for the purpose of generating higher environmental flow economically optimal only when the efficiency improvement costs are low. Meanwhile, water delivery to fields increases when conveyance efficiency costs alone decline, but decreases when field application improvements become cheaper (since less water is required at the field level). Lower water withdrawals from river nodes and improved field application efficiency also lead to reduced drainage flows to tail end lakes in the system. In general, water withdrawals, water delivered to fields, and return flows to the tail-end lakes are most responsive to changes in conveyance efficiency improvement costs, while environmental flows, crop evapotranspiration, and irrigation benefits are more responsive to changes in water application efficiency improvement costs.

An important implication of this sensitivity analysis is that reducing costs for irrigation efficiency improvements would increase both environmental flows and irrigation benefits. Cost reductions could perhaps be achieved by improving local production capacity for technologies such as drip irrigation, through greater investment in agricultural and water management research, and through training of local people to work in the irrigation technology sector. Additional study of the costs and benefits and effectiveness of such measures is warranted.

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4. Summary and conclusions

Irrigated agriculture is the dominant water user in the ASB, but is highly inefficient, due to very low conveyance and water application efficiencies. Estimates of losses from the sector range from 35 to 44 km^3 of water per year [26, 47]. Using a basin-wide hydro-economic optimization model, we find that modernizing irrigation networks and improving water application at the field level could substantially reduce these losses, to roughly 26 km^3 in a normal year without compromising salinity levels of irrigation water. This could generate large economic net benefits (US$ 600 million in a normal year) and go a long way toward alleviating basin-wide water scarcity. The benefits of modernizing irrigation systems also increase as water supply decreases, in both absolute and relative terms, from 20% of total benefits under normal water supply, to 40% when supply is reduced by 20%. The increased value of efficiency improvements with reduced water availability is particularly important given the expectation that climate change will lead to reduced precipitation and water availability in this region [48].

The most significant benefits from conveyance efficiency improvements would come from canal system improvements in downstream irrigation sites. Meanwhile, advanced irrigation techniques at the field level, such as drip irrigation in cotton production and laser guided land leveling in cotton, wheat and rice cultivation [10], would reduce water use and enhance yields in a number of mid-basin and downstream locations in the ASB. These collective improvements would save water, which could then be optimally reallocated for crop production and/or for maintenance of downstream ecosystem services around the Aral Sea, depending on the relative value of each of these benefits.

Implementing irrigation efficiency improvements (and maintenance) poses substantial policy challenges due to the misalignment of costs and benefits of water conservation. This is apparent in the present lack of maintenance of irrigation networks, which exacerbates their deterioration and increases losses, and is evidenced by the growing number of silted up and damaged canals, broken gates, outdated pumps, lack of spare parts, and so on. It seems likely that the widespread adoption and effectiveness of water saving technologies, particularly at the field level, would depend on a series of reforms related to irrigation water and crop pricing, as well as reform of land use rights, which would increase incentives for the required capital investments and for more productive use of water resources. In addition to this, conveyance efficiency improvements would require collective action among farmers. The incentive to organize would be bolstered by government support and financing, which could reduce problems of free-riding and help farmers to better internalize the significant positive externalities they would generate. Developing regional agricultural commodity and energy markets might also create incentives for inter-state cooperation that would further increase the mutual benefits from irrigation sector modernization. Such improvements would deliver benefits across the basin, by improving food and energy security, boosting income, and contributing to protection of the environment.

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