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A WATER RIGHTS TRADING APPROACH TO INCREASING INFLOWS TO THE ARAL SEA

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ABSTRACT

Tremendous development of irrigation since the 1960s combined with unbalanced water resources management led to the destruction of the ecosystems in the delta zone and the gradual desiccation of the Aral Sea, once the fourth largest freshwater lake of the world. Command-and-control based water management in the Aral Sea Basin (ASB) inherited from Soviet times did not create any incentives for investing in improved irrigation infrastructure, adopt water-wise approaches, and thus maintain flows into the Aral Sea. This study examined the potential for market-based water allocation to increase inflows to the Aral Sea while maintaining stable agricultural incomes. We find that a water trading system can improve inflows to the Aral Sea but would require significant compensation for agricultural producers. Agricultural producers can use the compensation payments to cope with reduced water supply by improving irrigation and conveyance efficiencies and by developing alternative rural activities such as livestock grazing, agro-processing, and cultivation of low water consumptive crops. We also find that a water trading system would be more efficient if it includes both trade among irrigation sites and between sites and instream uses.

KEY WORDS**:** hydro-economic model; environmental flow; irrigation; water management institutions; Central Asia

INTRODUCTION

Land degradation has been commonly discussed as degradation of croplands due to soil erosion, salinization and reduced water supply, and highlighted as a major problem reducing soil fertility, decreasing agricultural outputs, and worsening environmental conditions and rural livelihoods in many developing countries (Cerdà *et al.* 2009a, 2009b; Zhao *et al.* 2013; Bizoza, 2014; Angassa, 2014). However, land degradation has a broader meaning including also a degradation of wetlands, deforestation, overgrazing of meadows, and desiccation of lakes and rivers. Decreasing ater availability due to inefficient use of water for upstream irrigation and industrial purposes is a major reason for the degradation of downstream ecosystems (e.g., desiccation of lakes, elimination of wetlands and transformation of irrigated lands into fallow lands) (Falkenmark & Rockström, 2004).

The enormous burden of upstream irrigation on downstream ecosystems and livelihoods is nowhere more evident than in the Aral Sea Basin (ASB) of Central Asia (Micklin, 2007). The Aral Sea case is often referred to as one of the worst manmade environmental disasters of the 20th century (Micklin, 2007; Spoor & Krutov, 2003). Diversion of river flows to expand irrigation, particularly cotton production to achieve cotton self-sufficiency in the Soviet Union, led to the drying of the lake and subsequently to the collapse of the local economies in the surroundings of the lake (Micklin, 2010; Spoor & Krutov, 2003). The region which once held popular resorts and was a vibrant fish production center has now turned into a desert-like area covered with a thick layer of salt and the Aral Sea is now (ironically) called the Aral Desert (Aralkum; Breckle *et al.*, 2012). Additional consequences of the desiccation include dissemination of toxic salts blown from the dried bed of the Sea, increasing soil salinization, degradation of irrigated lands, groundwater contamination, increasing seasonal temperature extremes, increasing air-borne diseases, increasing unemployment and migration, and worsening living conditions (Micklin, 2007, 2010).

Given the increased understanding of the irreversible impacts of environmental disasters and the large market and non-market values of ecosystem services, this study aims at assessing the potential of market-based water allocation mechanisms to meet downstream environmental needs in the Aral Sea by compensating agricultural water users for reduced irrigation water use. Specifically, we compare the irrigation impacts and environmental benefits of increasing environmental inflows into the Aral Sea, resulting water and land use changes in irrigation sites, and necessary water rights transactions under two experimental scenarios: with and without introducing water rights trading among the irrigation water user sites. The compensation needs for reduced irrigation water for agricultural producers and options for using these funds to increase water productivity are analyzed as well.

Water rights trading among irrigation sites allows for additional gains from moving water across irrigation sites due to the heterogeneity of irrigated crop production and the possibility that more productive irrigation water users purchase the rights (Debaere *et al.*, 2014). Although administrative water management emphasizes the equity of water sharing it has often led to water overuse and misallocation and poor quality of public agency services (Dinar *et al.*, 1997). Under water rights trading, the value of water is determined through the trade relationships among the users (Rosegrant *et al.*, 2000; Ringler *et al.*, 2004) and reflects not only delivery costs but also scarcity and opportunity costs of water (Rogers *et al.*, 2002) thus incentivizing water users not to waste water (Debaere *et al.*, 2014). Moreover, equity in water distribution can be addressed under water rights trading through compensation to users with low water use efficiency who voluntarily transfer their water use rights to more productive users (Dinar *et al.*, 1997). Market-based approaches for resource management can be of particular interest for transition economies, which often have both the infrastructure and a need for such approaches but have as of yet little experience in this area. To address this gap, this study provides an *ex-ante* analysis of potential economic and environmental benefits from water rights trading in the ASB.

A river node based hydro-economic model was used to analyze the costs of compensating irrigation water users for relinquishing parts of their water use rights to meet environmental water needs of the Aral Sea. The model combines mass balances of river flow volumes with statistically estimated irrigation water use and environmental flow benefit functions. Environmental flow benefits considered are the sum of benefits from recreation, fishery, navigation, wetlands and agro-ecosystem services (many other environmental benefits, such as maintenance of stable groundwater levels, regulating microclimate, and cultural values are not considered because of data limitations). Since irrigation accounts for more than 90% of total water use and municipal and industrial sectors are prioritized over irrigation in water allocation decisions in the ASB, changes in irrigation supplies are basically the only source for increased flows into the Aral Sea. We therefore analyze water use trade-offs between irrigation and instream flows at the basin level and do not consider other water uses in this analysis.

MATERIALS AND METHODS

River network scheme of the hydro-economic model

For analyzing the potential economic and environmental benefits of water rights trading for the ASB compared to administrative water allocation, we developed a static hydro-economic optimization model. To model river flow and off-takes along the river systems, a river network scheme of the ASB was developed (Fig. 1).

Despite the introduction of management schemes based on basin boundaries in the ASB administrative units (provinces) are still responsible for water offtake from the rivers and internal distribution. Therefore, administrative provinces rather than hydrologic irrigation units are considered as water user (irrigation) sites in the model. The river network scheme of the model considers 12 water user sites and 19 river tributaries in the Syr Darya basin and 14 water user sites and 13 river tributaries in the Amu Darya basin. These sites have been clustered into separate water subcatchments (river nodes; *Syr1*…*Syr4*; *Amu1*…*Amu5*) based on their closeness to one another.

Model assumptions and equations

Since water rights trading between different irrigation sites and environmental uses during the growing season is the main focus of the study, reservoir operation, crop water use scheduling, and monthly or weekly planning time steps were not considered in the model. Furthermore, trading of water use rights is only allowed among irrigation sites within each of the two river basin systems of the ASB since irrigation water users in the different rivers are not connected to each other through a conveyance system. A basin management organization (BMO) was assumed to coordinate and organize water rights trading through buying and selling water use rights while taking into account the willingness of individual water users to pay for or purchase water rights given their demand function. The International Fund for Saving the Aral Sea (IFAS) may represent the environmental agent that raises the funds and compensates irrigators for relinquished water rights at less productive production sites.

The set of variables, parameters and, equations of the model are presented in Tables S1 and S2. The objective function of the model (Eq. 1) considers maximization of benefits from irrigation and environmental water uses (Table S2). Irrigation benefits include agricultural production benefits reduced by conveyance costs and are estimated regressing provincial irrigation profits with total water withdrawals (Bekchanov, 2014) using a quadratic function (Eq. 2). Quadratic irrigation water use functions are commonly used in the literature (Zilberman *et al.*, 1994; Ringler *et al.*, 2006; Qureshi *et al.*, 2007) and are also recommendable here to capture the diminishing marginal returns of increased water use. Environmental benefits are calculated as a linear function that depends on environmental flows (Eq.3). The linear relationship between instream flows and benefits is estimated based on observed water flows to the Aral Sea and benefits from wetlands, fisheries, navigation, recreation, and reduced health and land degradation impacts of the desiccation (see Bekchanov [2014] for more details).

The water balance equation at a river node has been modeled so that the sum of inflows from upstream nodes, local supply sources, and return flow equals the sum of downstream water releases and water offtakes for irrigation and industrial needs (Eq. 4). Total water withdrawals at the province level depend on total irrigated area and the volume of water use per hectare (Eq. 5). Total return flows are estimated as a fixed share of total withdrawals (Eq. 6).

Willingness to pay for water (Eq. 7) by irrigation sites is considered as a derivative from irrigation benefit functions. Water use sites either buy or sell water use rights or do not trade (Eq. 8). A market clearance relationship that requires equality of total water use rights supply to the total demand of water use rights is included (Eq. 9). Moreover, water offtakes to the irrigation sites are no higher than the sum of its water use rights and the additional water bought if the user buys, or than the difference between water use rights and the amount of water sold if the user sells (Eq. 10). To prevent economic losses from water rights trading, total payments to buy water use rights are required to be no less than total compensations for relinquished water use rights (Eq. 11).

Scenarios

The model was calibrated to the real conditions of land and water use and hydrologic flows in 1999, a year with normal water supply. The year was chosen based on the average value of the observed water supplies between 1980 and 2008. The initial water rights allocation in the model is also based on water withdrawals by irrigation sites in 1999. For analyzing the impact of water availability on water distribution among users, two alternative water supply scenarios were assumed equivalent to 90% and 80% of the normal supply. The lower water supply (80%) was estimated based on an average of total observed water supplies over the period between 1911 to 2008 (Dukhovny *et al.*, 2008). Based on data availability all economic costs and benefits were considered at price levels of 2006. Model calibration and comparison of the baseline and optimized scenarios were discussed in Bekchanov (2014) and Bekchanov *et al.* (2015) in detail.

Since the environmental benefits from inflows to the Aral Sea estimated from available data at US$0.004 per m^3 were below those of the irrigation sector (optimal marginal benefits vary between US$0.004 and 0.027 per m^3 across the irrigation sites), we analyze the impact of water rights trading for augmenting these flows by gradually increasing the purchase of water use rights for this purpose. The gradual increase of water rights purchases delivered to the Aral Sea and its delta (WBA) allows us to assess the accompanying compensation requirements. Twenty-one cases of environmental flow acquisitions were run varying from 0 to 20 km^3. According to previous estimates, about 33–34 km^3 of water flow is required to maintain minimal environmental conditions in the Aral Sea and its delta (Global Environmental Fund [GEF] 2002). Since the baseline scenario includes 13 km^3 of water flows to the Sea in an average hydrological year, to meet minimum flow requirements would require an additional 20 km^3 of water. Thus, increased purchases of water rights from irrigation demand sites were considered for up to 20 km^3.

To compare the economic and environmental benefits of market-based water allocation, two experimental scenarios–with and without water rights trading among irrigation sites–were run based on the model. For the latter case, the objective function and trading balance restrictions were changed accordingly by setting water purchases by the irrigation sites (WB_{dm}) equal to zero.

Data sources

Multiple sources of data were used to estimate the model parameters (for detailed description of data and the parameters of irrigation and environmental benefit functions, see Bekchanov, 2014, pp. 133-134 and pp. 216-221). Particularly, data on water supplies in the source nodes (tributaries), land availability by irrigation sites, water withdrawals and crop yields were obtained from SIC-ICWC (2011). Municipal and domestic water uses were assumed as fixed amounts equal to 10% of total withdrawals (FAO 2012). Return flow rates across the irrigation sites were taken from EC-TACIS (1997) project reports. Crop production costs, crop prices and revenues were estimated based on the reports of local water management organizations and market surveys of regional research projects (such as ZEF/UNESCO, 2001-2011 [http://www.zef.de/khorezm.0.html]; SIC-ICWC, 2008; Anderson & Swinnen, 2008). Water delivery (conveyance) costs were obtained from MAWR (2007). Approximate environmental benefits per unit of water inflow to the Aral Sea were assessed based on previous studies summing up benefits of fishery, navigation, wetlands, recreation, and reduced irrigation and health degradation impacts (INTAS, 2006; for detailed assessment results, see Bekchanov, 2014).

RESULTS

Since in the short run, estimated marginal benefits of environmental flows were lower than marginal irrigation water use benefits in this study, gradually increasing water use rights for environmental needs would reduce total (sum of irrigation and environmental) benefits (Fig. 2). When water use rights for environmental needs increase from 1 to 20 km^3 in an average water year, overall benefits decrease from US$1,901 to US$1,608 million (-15.4%) and from US$1,644 to US$1,496 million (-9%) with and without considering water rights trading among the irrigation sites, respectively. Likewise, under 80% of normal water availability, overall benefits decline from US$1,528 to US$999 million (-34.6%) and from US$1,292 to US$972 million (-24.7%) with and without considering water rights trading among the irrigation sites respectively. While increased allocation of water rights for the Aral Sea and its delta decrease total benefits, benefits remain larger, when water rights trading among the irrigation sites is allowed, indicating significant gains from trading across irrigation sites. Allowing more productive producers to buy water use rights while compensating for the reduced water uses of less productive producers provides higher basinwide benefits than under the case without water rights trading among the irrigation sites.

When water rights trading among the irrigation sites is allowed irrigation water users could reduce total water use by 5 km^3 and release it to the Aral Sea for US$67.8 million in a normal year (Fig. 3). The compensation cost of delivering 20 km^3 of water into the Aral Sea and its deltaic zones is estimated at US$467 million. Compensation requirements of providing additional environmental supplies increase with reduced water availability (river runoff) since the value of water increases under water scarcity.

Increased environmental flow acquisitions would require a substantial reduction of irrigation water withdrawals in many parts of the basin (Table I). When environmental flow requirements of 20 km^3 need to be satisfied and water rights trading is not allowed among irrigation sites, the less productive upstream zones (Syr1 and Amu1) in both river basins would reduce their water uses by 52% and 35%, respectively. Even higher water use reductions of 44% and 60% are required from the downstream irrigation subcatchments (Syr4 and Amu5) that are located in arid zones and are characterized by high water losses. In absolute terms, a larger volume of the environmental flows are acquired from the irrigation catchments located in the Amu Darya Basin. For instance, downstream irrigation sites of the Amu Darya Basin (Khorezm, Karakalpakstan, and Khorezm) are required to relinquish a total of 6.4 km^3 of their water use rights to meet environmental flow needs of 20 km^2. Water use reductions are expected to occur through irrigated land use reductions in the irrigation subcatchments of the midstream Amu Darya (Amu3), through per hectare water use reductions in the upstream and downstream reaches of the Syr Darya basin (Syr1 and Syr4), and through both irrigated area and per hectare water use reductions in the upstream and downstream reaches of the Amu Darya basin (Amu1 and Amu5).

When water rights trading among irrigation sites is allowed some irrigation subcatchments in the midstream reaches of the Amu and Syr Darya (Amu2, Syr2, Syr3) can increase their water withdrawals and expand their irrigated lands (Table I). However, increasing environmental flow acquisitions reduces irrigation water and land access to these irrigation subcatchments.

As it is seen from the results, substantial irrigation water and land use reductions are required to maintain minimum environmental flows to the Aral Sea. However, this is not necessarily translated into abandonment of irrigated areas or substantial increases in unemployment. Given the enormous water losses both in conveyance and during water application because of very low distribution (<60%) and irrigation efficiency (<70%) (Bekchanov 2014) the potential of water use reductions is as high as 60-70% in many irrigation sites along the Amu and Syr Darya rivers if suitable technologies and management practices are adopted.

DISCUSSION

Interpretation of model results for water and land use change to identify site-specific options of reducing water demand

Based on the model results of water and land use changes (Table I), several options of using compensation payments to improve water and land productivity and maintain rural incomes can be recommended for each irrigation subcatchment considering their geographic, physical and socio-economic characteristics (Table II). While interpretation of changes in total water and land uses is straightforward reduced water use per hectare suggests multiple options such as improving irrigation and conveyance efficiencies, replacing high water intensive crops (e.g., paddy rice) with less water intensive crops, replacing irrigation with rainfed based crop production, and deficit irrigation. Increased water use per hectare can be interpreted as implementation of double harvesting or expansion of the production of high-value, high-water intensive crops.

Under increased environmental flow acquisitions when water rights trading among irrigation sites is not allowed upstream irrigation sites (GBAO, Khatlon, RRT in the Amu Darya Basin and Narin, Osh, Jalalabad in the Syr Darya Basin) can consider improving irrigation efficiency (drip irrigation of fruits and vegetables), increasing rainfed areas while reducing irrigated lands, developing the livestock sector, and replacing water intensive crops, such as cotton, with low water consumptive ones, such as wheat and oats. In midstream irrigation sites of the Amu Darya Basin (Lebap, Kashkadarya, Samarkand, Navoi, Bukhara), improving irrigation efficiency (drip irrigation, laser guided land leveling [Abdullaev *et al.*, 2007], alternate dry furrows), reducing water intensive crop production, such as replacing cotton with maize, and legumes, and other food crops, and implementing deficit irrigation can help to improve water productivity. In the midstream irrigation sites of the Syr Darya Basin (Tashkent, Syrdarya, Jizzakh, South Kazakhstan) improving irrigation efficiency through laser guided land leveling and drip irrigation, and replacing water intensive crops with low water consumptive ones would help reduce irrigation water demand. In downstream regions (Khorezm, Karakalpakstan, Dashauz in the Amu Darya basin and Kyzylorda in the Syr Darya Basin), in addition to reducing irrigated areas and improving irrigation efficiency (laser guided land leveling) increasing conveyance efficiency through lining irrigation canals, developing the livestock sector (Bekchanov *et al.*, 2012), and replacing rice production with the production of less water consumptive crops such as maize, sorghum, melons and gourds (Bobojonov *et al.*, 2013) can play a great role to reduce irrigation water demand. In highly saline marginalized lands in these downstream irrigation sites cotton production could be entirely eliminated since it does not cover the production costs and salt resistant trees that provide additional economic and soil fertility improvement benefits such as Russian olive (*Eleagnus angustifolia* l.) could be grown (Djanibekov *et al.*, 2012; Dubovyk *et al.*, 2014). Similarly, growing licorice, whose deep roots help flush away the salt in the soil, can help reclaim degraded lands and offers farmers a profitable return for a relatively modest investment (Andrew Noble, personal communication, April 15, 2015). Given the substantial post-harvest losses for fruits and vegetables across growing sites in the ASB developing agro-processing industries, especially in rural areas, can also boost incomes and improve water productivity across the food supply chain (Bekchanov *et al.*, 2014).

When water rights trading is allowed among irrigation sites while increasing environmental flow acquisitions some more productive irrigation sites in the midstream reaches of both river basins are recommended to expand irrigated areas and increase cropping intensity. Expansion in Surkhandarya of the Amu Darya Basin could focus on double harvesting of vegetables and expansion of citrus orchards given the longer period of warmer temperatures in this region. In Tashkent, Syrdarya, and Jizzakh of the Syr Darya Basin, considering the closeness of these regions to the major urban centers (Tashkent economic zone), expansion of fruits, vegetables and other food crops, and development of greenhouses for extended, water-wise production could be considered to meet the demand of close-by cities.

Uses of acquired environmental flows

As a result of relinquished irrigation water uses environmental flows in a normal year could reach 33 km^3 of water, which is still quite low compared to the annual Aral Sea inflows of 50 km^3 in the 1950s. However, this amount of water should be sufficient to reinstate some of the ecosystem values and services in the Aral Sea and surrounding areas. Considering the greater benefits from the wetland areas in the Aral Sea delta than the direct benefits of shipping and fishery from the sea itself (Bekchanov 2014), environmental restoration policies and projects should prioritize improving the environmental conditions in the deltaic zone. Considering the limited availability of water resources, particularly in the downstream reaches of the Amu Darya and Syr Darya Rivers, the possibilities of improving water use efficiency and introducing effective institutions to enhance water availability in the delta should be further investigated.

Newly launched campaigns of oil and gas drilling on the exposed areas of the Aral Sea bed may reduce the political will to increase water inflow to the southern Aral Sea, thus intentionally preventing restoration efforts of the sea (Micklin & Aladin, 2008). However, since the environmental resources benefit the entire society over generations, favoring unilateral benefits from oil and gas mining should be reconsidered. Although environmental benefit estimates provided in this study are quite low compared to irrigation benefits and thus seem to justify the lack of governmental interest to increase flows into the sea, these estimates addressed only a limited set of ecosystem services. Avoiding underestimation of the environmental benefits in further research efforts by including the non-utilitarian values of environmental inflows, which can be much higher than the utilitarian values (Freeman, 1993; Dziegielewska *et al.*, 2009), may show an improved balance of water for natural versus irrigation needs. Particularly, additional benefits from increased environmental flow and reduced irrigation withdrawals for the local microclimate, sustainable groundwater levels in the lower reaches, and reduced return flows and river flow contamination should be taken into account in future studies in addition to benefits from wetlands, fishery, navigation, recreation, and reduced health and land degradation impacts of the desiccation.

Barriers for institutional change

Even though tradability of water rights among irrigation water users might provide higher incomes than a system without tradable water use rights, as previously mentioned, setting appropriate initial water use rights for each user, the rule of law, stakeholder participation, and well developed irrigation infrastructure are prerequisites for the successful performance of water rights trading (Debaere *et al.*, 2014). Otherwise, additional gains from water rights trading are not achievable or can prevent further market-based reforms as has been seen in the case of Chile (Dellapena, 2005).

Within the last three decades, several initiatives have been launched to reduce the ecological and economic problems in the ASB (Vinogradov & Langford 2001; Weinthal, 2001). Particularly, the establishment of Basin Management Organizations (BVOs) in the late 1980s, followed by the organization of the Interstate Committee for Water Coordination (ICWC) in the early 1990s, and the adoption of several agreements on improving livelihoods in the Circum-Aral Sea region since 1990 all fully or partially aimed at preventing the ecological degradation in the ASB. Donors and international organizations such as the World Bank, USAID, GIZ and the International Fund for Saving the Aral Sea (IFAS) with its multi-year basin management programs supported several research projects and strongly influenced the introduction of Water User Associations (WUAs) and water legislation improvements. Despite all these institutional changes and organizational re-arrangements, the inherited administrative management system was barely affected and no considerable improvement in water resources allocation has occurred to date.

Increased understanding of the large potential benefits from incorporating economic and market-based principles into water management and growing environmental consciousness might nevertheless eventually lead to the implementation of water rights trading in the basin. At present, basic steps towards market-based management in the water sector have been realized in the ASB through introducing payments for water use by irrigating farmers although the performance of these new institutional rules vary across the involved countries. In Kazakhstan, where agricultural markets are more liberalized and farmers can gain high incomes (Anderson & Swinnen, 2010), paying for irrigation water is more accepted than in other ASB countries where revenues of the majority of farmers hardly cover their production costs. At the basin scale additional intergovernmental agreements and the need for increased knowledge on river basin hydrology, resources, and production levels may increase transaction costs of establishing market-based water allocation. Previous estimates indicated that water rights trading cannot provide additional benefits in the ASB when transaction costs exceed US$0.05 per m^3 (Bekchanov *et al.*, 2015).

While compensation costs to irrigation farmers for reduced water consumption seems a low-cost option compared to infrastructure development related options, such as interbasin water transfers, raising funds for acquiring additional flows to the Aral Sea can be a challenging task. Interested parties to improve the ecological and economic conditions in the surroundings of the Aral Sea such as the riparian country governments, international donors, private enterprises, and local communities are expected to contribute to raise the funds for compensating for the irrigation water use reductions. The countries in the ASB should closely collaborate and cooperate with each other to raise these funds and allocate them to those irrigation sites who are reducing irrigation water use.

Regional cooperation which is essential for improved ecosystems, mutual benefits from integrated energy and water use, and gains from trade are however not easily achievable given the current unilateral development objectives of the Central Asian countries (Djanibekov *et al.*, 2015; O'Hara, 2000). Particularly, using reservoirs initially built in Soviet times with the aim of improving downstream irrigation water supply to meet upstream energy demand while neglecting the consequences on downstream reaches (settlements, irrigated areas, and ecosystems) (Wegerich *et al.*, 2007; Wegerich, 2008; Dukhovny & de Shutter, 2011) and following nationalistic policies of further irrigation expansion by individual countries while ignoring the needs of other riparians (O'Hara, 2000) are just two examples that explain the reluctance or indifference of the riparian countries to cooperate. Although there are inter-state agreements, laws, and institutions on regional water allocation these laws are not adequately reflected in national legislations and consequently inter-state water coordination organizations are not authorized to exercise power to manage basin resources (O'Hara, 2000; Weinthal, 2001). The command-and-control system inherited from the Soviet period does not create incentives for efficient water use through optimal coordination of basin resources (Weinthal, 2001). Thus, introduction of tradable water use rights and generating benefits from basin-wide coordination will take time in these transition countries and requires substantial pre-reforms in institutions in contrast to the case of developed economies where market-based management principles have been in practice for a long time. Increased awareness and understanding of market-based management principles and environmental benefits, empowering water stakeholders in water allocation processes, developing national water management and development policies consistent with regional development goals and boosting regional economic integration (Djanibekov *et al.*, 2015) are pre-requisites for a successful initiation of market-based water and environmental management policies in the ASB.

Model shortcomings

Despite the provision of useful insights on water use trade-offs between irrigation and instream flows to the Aral Sea, the model developed in this study is not free of shortcomings. The model used here was developed to assess water use trade-offs between agriculture and the environment at a macroeconomic scale and thus detailed accounts of monthly water uses were not considered. However, additional insights on cropping patterns and water uses over months can be further analyzed by developing an additional regional agricultural production model. Inclusion of monthly flows and crop patterns in future studies would allow more detailed analysis of crop pattern changes and seasonal water uses as a response to increased re-allocation of water resources to Aral Sea flows. Consideration of capital and labor inputs in addition to water in the crop production function can also improve the results.

Land use reductions, agricultural labor demand decrease, reduced food production, and environmental changes are possible because of water use reductions in those sites that are less productive and thus first sell water use rights to instream flows. However, since these sites do receive compensation for their reduced benefits this income can be used to invest in efficient irrigation technologies (Bekchanov *et al.*, 2010) and agro-processing and service industries that require less water (Bekchanov *et al*., 2014). Compensations can also be used to purchase food from other, more productive irrigation sites through reliance of the regions on each other's comparative advantages. Increased production in more productive regions may increase labor demand in these provinces and can divert additional labor from the regions where agricultural production decreases. However, the current version of the model does not allow for an analysis of non-agricultural sector expansion, inter-regional migration and commodity trade relationships which can be considered in future studies with the availability of additional data.

The approximate environmental benefits in the model are based on a previous study (INTAS 2006). However, this research project (INTAS 2006) seems to have determined most ecosystem service benefits based on updating the results of surveys from the 1980s. Therefore, more careful analysis of ecosystem service benefits in the ASB and delta zones should be done by experts.

Despite its shortcomings, our model provides additional insights on the amount and location of the required compensation payments for reduced irrigation water to improve environmental flows into the Aral Sea and the potential of improved water allocation efficiency through market-based water distribution. This study is also one of the first studies to promote market-based management in transition economies where administrative management principles, which often result in inefficient resource allocation and use, are dominant.

CONCLUSIONS

An improvement of the environmental system in the Aral Sea and surrounding areas can likely be achieved by an additional average annual supply of 20 km^3 of water to the Aral Sea through compensating agricultural producers for voluntarily relinquishing irrigation water rights. Compensation costs for additional environmental flows can be used by farmers to cope with reduced irrigation water supply through improving water use productivity and thus maintain stable incomes. Considering the local climate and geographical conditions, farmers in different reaches of the rivers can choose those water demand reduction measures that are most suitable to their local conditions. These include improving irrigation and conveyance efficiencies, developing the agro-processing and livestock sectors while reducing reliance on raw agricultural production, expanding rainfed agriculture in feasible sites, introducing deficit irrigation, and replacing water intensive crops, such as rice, with less water-consumptive crops (e.g., maize, gourds, legumes). Although total irrigation and environmental benefits decrease with additional environmental flow acquisitions since the estimated value of water for environmental needs is lower than the value of irrigation water additional water acquisitions for environmental needs can be more beneficial if additionally water rights trading among water user sites is allowed. However, since market-based water management principles are quite new to both water stakeholders (irrigation water users) and managers in water management organizations these institutional, economic, and technical changes will take time to materialize. Increased research efforts involving water stakeholders and scientists from all riparian countries, increasing environmental consciousness, and nourishing regional cooperation and economic integration are also essential for the success of water and environmental reforms in the ASB.

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Supporting Information

Table S1. Model parameters and variables

Table S2. Model equations

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Tables

Table I. Water withdrawals, water rights sold or bought by irrigation sites, and changes in irrigated area under increasing water acquisitions for the Aral Sea with and without water rights trading among irrigation sites

	Water withdrawals					Water rights sold (-) or bought (+) (km^3) by irrigation sites					Irrigated land use					Options for reducing water demand**
		Change (%)					Scenarios*					Change (%)				
A group of irrigation sites	Base (km^3)	Sc5	Sc10	Sc15	Sc20	Base (km^3)	Sc5	Sc10	Sc15	Sc20	Base (mln ha)	Sc5	Sc10	Sc15	Sc20	
Without water rights trading among irrigation sites																
Amu1	5.6	-31	-41	-50	-52	-0.6	-2.3	-2.8	-3.4	-3.5	444	-6	-12	-12	-12	w↓L↓
Amu2	3.1	0	0	0	0	0.0	0.0	0.0	0.0	-0.0	344	0	0	0	0	0
Amu3	7.6	2	-16	-18	-19	-0.1	0.0	-1.4	-1.5	-1.6	721	0	-17	-17	-17	L↓
Amu4	13.8	-6	-9	-13	-15	0.0	-0.9	-1.2	-1.7	-2.1	1922	0	0	0	0	w↓
Amu5	14.6	-2	-11	-20	-44	0.0	-0.3	-1.5	-2.9	-6.4	905	0	-5	-5	-21	wL↓
Syr1	1.5	4	-26	-32	-35	-1.2	-1.2	-1.6	-1.7	-1.8	182	31	0	0	0	w↓
Syr2	9.9	0	-1	-9	-14	-0.1	-0.1	-0.1	-0.9	-1.4	1078	0	0	-4	-4	wL↓
Syr3	9.1	0	-7	-12	-12	-0.3	-0.3	-0.9	-1.4	-1.4	1418	0	0	0	0	w↓
Syr4	3.1	0	-13	-45	-60	0.0	0.0	-0.4	-1.4	-1.9	131	0	0	0	0	w↓
With water rights trading among irrigation sites																
Amu1	5.6	-52	-52	-53	-54	-0.6	-3.5	-3.5	-3.5	-3.6	444	-12	-12	-12	-12	w↓L↓
Amu2	3.1	31	30	26	22	0.0	1.0	0.9	0.8	0.7	344	18	18	18	18	w↑L↑
Amu3	7.6	-8	-9	-13	-22	-0.1	-0.7	-0.9	-1.2	-1.8	721	-9	-9	-9	-13	w↓L↓
Amu4	13.8	4	-1	-15	-30	0.0	0.5	-0.2	-2.0	-4.1	1922	1	1	1	1	w↓
Amu5	14.6	-16	-44	-61	-70	0.0	-2.3	-6.4	-8.9	-10.3	905	1	-21	-21	-21	w↓L↓
Syr1	1.5	-43	-43	-43	-43	-1.2	-1.9	-1.9	-1.9	-1.9	182	0	0	0	0	w↓
Syr2	9.9	13	13	12	8	-0.1	1.3	1.3	1.2	0.7	1078	13	13	13	13	L↑
Syr3	9.1	31	31	30	26	-0.3	2.5	2.5	2.5	2.1	1418	11	11	11	11	w↑L↑
Syr4	3.1	-60	-60	-60	-60	0.0	-1.9	-1.9	-1.9	-1.9	131	0	0	0	0	w↓

Notes: *Sc5, Sc10, Sc15, Sc20 are scenarios for water acquisitions for the Aral Sea of to 5, 10, 15, and 20 km^3, respectively.

**0-no change, w↓ -per hectare water use reduction if total water use decreased but total land use did not change; L↓ - land use reduction if total land and water use decreased at similar rates; w↓L↓ - both per hectare water use and total land use reduction if total water use reduction rates are higher than total land use reduction rates; L↑ - land use increase if total land and water use increased at similar rates; w↑L↑ - both per hectare water use and total land use increase if total water use increase rates are higher than total land use increase rates.

Table II. Improved water management strategies for irrigation sites with and without water use rights trading when environmental flow acquisitions are increased

	Water use reduction options						Increased irrigation water withdrawals	
A group of irrigation sites	Improving irrigation efficiency	Improving conveyance efficiency	Replacing high water intensive crops (e.g., paddy rice) with less water intensive crops	Increasing rainfed areas	Deficit irrigation	Reducing irrigated areas	Irrigated area expansion	Extending high water intensive crops with high profitability (vegetables, fruits, double harvesting in urban area peripheries)
Without water rights trading among irrigation sites								
Amu1	+		+	+		+		
Amu2								
Amu3						+		
Amu4	+		+		+			
Amu5	+	+	+		+	+		
Syr1	+		+	+	+			
Syr2	+		+		+			
Syr3	+		+					
Syr4	+	+	+					
With water rights trading among irrigation sites								
Amu1	+		+	+		+		
Amu2							+	+
Amu3	+	+			+	+		
Amu4	+		+		+			
Amu5	+	+	+		+	+		
Syr1	+		+	+	+			
Syr2							+	
Syr3							+	+
Syr4	+	+	+					