Adapting to water scarcity: constraints and opportunities for improving irrigation management in Khorezm, Uzbekistan

ABSTRACT
Like many irrigation schemes in Central Asia, the one in Khorezm faces a two-fold challenge: on the one side, the severe problems inherited from the past need to be remedied and on the other side, the rising supply–demand gap driven by sharpening competition for water and climate change must be dealt with. Located in the lower part of the Amu Darya basin, Khorezm irrigation and drainage scheme is particularly vulnerable to supply–demand gaps. Promising solutions towards adaptation comprise modified strategies of land and water use towards higher efficiency and flexibility in combination with measures to lessen the constraints of the system itself, which was initially designed for the management of a few, large and uniform production units and not for many diverse and small units. Solutions consist of flexible, modeling-based approaches, re-arranging institutional settings and establishing economic incentive systems. Flexible modeling allows an integrated use of surface and groundwater resources avoiding or minimizing the impact of water stress on yield. Institutional settings strengthen the position of water users via improved participation and transparency of processes in Water Consumers Associations (WCAs). Economic measures support sustainable resource use strategies and improve the functioning of WCAs. The findings could be extrapolated to other regions of Central Asia with similar conditions and challenges.

Key words | Aral sea, efficiency, irrigation water management, Khorezm, salinity management

INTRODUCTION

The Aral Sea dilemma is a textbook example illustrating the impact of large-scale and long-term unsustainable water management. The irrigated area on the territory of the former Soviet Republics in the Aral Sea basin was expanded from 4.5 Mega hectares (Mha) in 1960 to 7.6 Mha in 1990 and 8.1 Mha in 2004 (SIC ICWC 2011a). Inefficient water management in these huge areas led to high withdrawals from its major tributaries, the Amu Darya and the Syr Darya Rivers. The inflow to the Aral Sea decreased for instance from 43 km³ in the 1960s to 9 km³ during the period 2001–2005 (Micklin 2007). As a consequence, the Aral Sea shrank dramatically. According to Micklin (2007), the lake lost 90% of volume and the salt concentration increased to 100 g/l. These processes resulted in enormous economic losses, disastrous impacts on the ecosystems and severe health problems for the population.

The Uzbek province Khorezm, located in the lower part of the Amu Darya basin approximately 350 km south of the current shores of the Aral Sea, exemplifies the reasons causing the Aral Sea dilemma, its consequences and future challenges to water management in Central Asia. Khorezm is equipped with a large-scale irrigation system developed during the Soviet period. Due to
its downstream location, Khorezm is particularly vulnerable to reductions in water supply. Hydrologically caused reductions of water resources such as for instance in drought years are sharpened by water management in the upstream parts of the basin. This is illustrated by the ratio between (i) withdrawals from the Amu Darya (SIC ICWC 2011b) in the vegetation period (April–September) of a specific year in the period 1999 until 2009, and (ii) the average withdrawal for that period (Figure 1). The annual ratios estimated for irrigation schemes located upstream (Tajikistan), midstream (Karakum canal) and downstream (Khorezm) of the Amu Darya underlines that in drought years (e.g. 2000, 2001, 2008) the ratio for Khorezm had dropped sharply, whereas water supply in e.g. midstream locations was much less impacted and upstream parts of the basin were hardly influenced by these drought strikes.

It is expected that water resources available for Khorezm in the near future will become even more limited and increasingly variable due to climate change and enhancing competition for water in the upper part of the transboundary basin driven by population growth, industrialization and hydropower (Schlüter & Hirsch 2010).

The climate in Khorezm is continental and arid. The reference evapotranspiration amounts to 1,380 mm per year, whereas the annual precipitation is very low with 95 mm (Conrad et al. 2012). Therefore, agricultural production relies completely on irrigation and drainage systems, the latter necessary for salt management. Approximately 275,000 ha in this region are equipped with an irrigation and drainage infrastructure consisting of complex networks of 16,400 km irrigation canals and 8,000 km drainage ditches and collectors (GIS-Lab of the ZEF/UNESCO Project). Cotton, rice, winter wheat, vegetables and fodder dominate the cropping pattern in Khorezm. With the exception of 11%, irrigation canals are not lined (Ibrakhimov 2004) and water is applied to crops mainly by furrows and to a minor extent by basin irrigation (in case of leaching and rice cropping). Agriculture is regulated by the state as illustrated by the state-ordered production of cotton and wheat. Water management is dominated by hierarchically structured and centrally organized administrations (Bobojonov 2008). These administrations allocate water based on areas assigned to grow cotton and wheat and which have fixed production quota. The state-order system creates thus a strong link between the use of soil and water resources. The flexibility of water management is limited also by the lack of detailed knowledge on site-specific irrigation water demand which at present is based on static norms considering crop, soil and groundwater level in a coarse way.

Water management problems are indicated by: (i) substantial water withdrawals from the Amu Darya amounting to 4.4 km³ per year on average (Tischbein et al. 2011), (ii) insufficient supply at farm level in terms of quantity and temporal appropriateness, leading to water stress shown by reduced actual evapotranspiration by 25% in tail-end regions (Conrad 2006), (iii) low depleted fraction of 0.48 (Conrad 2006), and (iv) widespread occurrence of soil salinization. Pre-seasonal leaching accounts for approximately 1 km³ in years with average water availability (Bekchanov et al. 2010a).

Restructuring current water management towards efficient, appropriate and sustainable use of water resources is
a key-intervention to improve the livelihood of approximately 1.5 million inhabitants in Khorezm especially when taking into account the unsolved problems inherited from the Soviet period: the huge expansion of irrigated areas in the Aral Sea basin; cotton monoculture; insufficient adaptation of the irrigation and drainage infrastructure and management to site-specific and dynamic conditions. This is challenged further by the present confrontations of climate change and a sharpening competition for water. Working out options to increase efficiency, appropriateness and sustainability of water management is the major objective of the research described here.

METHODS

Basic features of the approach

Interdisciplinarity

The current problems and future challenges of water management in Khorezm are caused by a mix of bio-physical, technical and socio-economical factors. Hence an adequate solution consists of an interdisciplinary approach combining technical procedures, economical methods and sociological analyses. We use therefore the bio-physical system in the case study region Khorezm as a starting-point to work out modeling approaches and to derive interventions as opportunities towards improving the current water management. These opportunities will then be embedded into the institutional and economic context by considering options to lessen constraints regarding technical, institutional and economic factors.

Focusing on field/farm level

The focus on the field level was guided by two major ideas: (i) providing the farmer with options to cope with variable water supply, as this is urgently needed and becoming increasingly relevant, and (ii) considering the field level reflects a bottom-up approach from field to system level, which has become more appropriate after the restructuring of the production units by the national administration.

Considering the links between surface and groundwater resources (‘sponge phenomenon’)

As a result of high recharges due to heavy leaching and huge irrigation water losses, groundwater is shallow in Khorezm. According to Ibrakhimov et al. (2011) groundwater level fluctuates annually between 2.2 m below ground at the end of the non-irrigation period in winter (January/February) and 1.15 m in the peak irrigation season (July). Driven by irrigation and drainage strategies, the aquifer behaves as a ‘sponge’, as exemplified by the analyses of a representative 850 ha sized sub-unit (Figure 2). The upper part of Figure 2 depicts the irrigation water inflow and drainage outflow. The difference between inflow and outflow (lower part) determines the groundwater dynamics (in interaction with the evapotranspiration being a further major output of the system). The groundwater level referenced to the deepest level in January (lower part), clearly follows the inflow-outflow difference with a delay in the range of a month.

While shallow groundwater tables may be beneficial for meeting crop water demand, it does negatively affect soil salinity management in two ways. Firstly, shallow groundwater accelerates the salt accumulation in the root zone. Secondly, the effectiveness of leaching is reduced due to high water levels in the drainage ditches which constrain discharging the percolated leaching water.

Modeling approaches at field level

Modeling soil water fluxes

As an alternative to the static norms presently dominating the estimation of the irrigation water distribution in Uzbekistan, a modeling approach considering explicitly the components of water and salt balances was used. Based on the HYDRUS model (Simunek et al. 2005) and FAO’s dual crop coefficient concept (Allen et al. 1998), the approach allows modeling of the water fluxes and salt dynamics including the relevant capillary rise. Forkutsa (2006) applied the approach to establish water balances and to derive net irrigation amounts and irrigation timing. The dual crop coefficient enables a differentiation between evaporation and transpiration and consequently measures can be derived to reduce non-productive evaporation (by
practices of conservation agriculture) and base irrigation scheduling explicitly on the transpiration. As the modeling describes the hydrological processes in detail, the approach has the potential to be used with a high spatial resolution considering even within-field variability. This is in particular advantageous in a situation of increased number of water users with diversified requirements (compared with the past setting in Khorezm with large and uniform production units) as emerged in the study region.

**Linked irrigation scheduling–groundwater model**

The implementation of flexible irrigation strategies at schemes level needs to be supported by tools taking the groundwater dynamics into account. Awan (2010) developed a tool linking the irrigation scheduling model CROPWAT (Clarke et al. 1998) and the groundwater model FEFLOW (Diersch 2002). To overcome the missing consideration of the capillary rise in CROPWAT, the HYDRUS model (Simunek et al. 2005) was used. This configuration allows establishing the field water balance, deriving optimal irrigation schedules and quantifying the spatio-temporal behavior of groundwater. In contrast to the currently, rigid irrigation scheduling based on static norms only, this tool allows us to respond adequately to temporal changes in water availability, meteorological situation and groundwater (Awan 2010). The expected increase in variability of these factors underlines the relevance of the approach. Furthermore, the tool enables us to derive site-specific solutions and to consider conjunctive use of surface and groundwater resources.

**AquaCrop for deficit irrigation**

To adapt to limited and non-reliable supply at farm level, a tool minimizing the impact of non-avoidable under-supply on the crop yield by controlled deficit irrigation is urgently needed to assist farmers. As the AquaCrop model (Steduto et al. 2009) has clear advantages in estimating the crop
yield depending on water stress compared with CROPWAT, Akhtar (2011) combined the AquaCrop and HYDRUS models and developed a tool to work out deficit irrigation strategies and to compare these with full irrigation.

Salt management at field level

HYDRUS allows modeling of salt dynamics (salt accumulation and leaching). As a consequence, site-specific and flexible leaching dates and amounts can be derived aiming at highest possible leaching effectiveness and ensuring non-exceedance of crop-specific salt tolerances (Forkutsa et al. 2009).

Application process

According to field analyses by Forkutsa (2006) and Awan (2010), the application efficiency in Khorezm ranges between 40 and 50% only. Measures for improvement consist thus of: (i) adapting the application discharge to field size, soil conditions, slope and irrigation amount based on modeling the advance, recession and infiltration of applied irrigation water (Horst et al. 2005), (ii) introducing advanced handling of furrow irrigation (e.g. surge flow, alternate furrow (Pereira et al. 2007, Bekchanov et al. 2010b), and (iii) laser-guided land leveling. Due to very flat topography in Khorezm, directing the water from both ends of the furrow (double-side irrigation) provides also a feasible option (Poluasheva 2005) to increase uniformity and in turn efficiency of water application (at respective locations in Khorezm).

RESULTS AND DISCUSSION

Technical measures

Irrigation scheduling at field level

Combining HYDRUS and FAO’s dual crop coefficient concept allowed modeling of water fluxes and balances with high spatio-temporal resolution. At a field typical of the study region (size of ca 4 ha; sandy loam texture), capillary rise contributes 37% to actual evapotranspiration on average over the field (Forkutsa 2006). Spatial variation of capillary rise showed a considerable variability within the field, ranging from 92 to 277 mm over the vegetation period of cotton (Forkutsa 2006). As a consequence, accumulation of soil salinity mainly driven by capillary rise is spatially variable within the field. Knowledge on the within-field variability provides the informal base to adapt irrigation and leaching amounts to site-specific conditions as a prerequisite for water saving. Furthermore, the simulations revealed a reduction of actual evapotranspiration to 65–70% of the potential level. It became obvious, that transpiration was reduced over one month before the first irrigation event was applied. As a consequence, the model allows determining appropriate irrigation timing. Optimized irrigation timing has the potential to mobilize water saving in the range of 20% without increasing water stress (Forkutsa 2006).

Akhtar (2011) simulated deficit irrigation strategies, differentiating proportional and stage-specific reduction of irrigation amounts. With respect to the impact on yield, proportionally reduced irrigation is a lower risk choice. For instance, a 20% proportional reduction proved a promising option to raise crop-water productivity of cotton. Despite a 10% loss in biomass, the yields could be kept in the same range of yields occurring at full supply of irrigation due to an improved irrigation timing, which in turn stimulated yield relevant growth components. Hence, low to moderate deficits are a first choice when conceiving effective and feasible deficit irrigation strategies. This is in-line with previous findings by Pereira et al. (2009) opting for mild deficits derived from field experiments in Fergana/Uzbekistan and by the application of the irrigation scheduling model ISAREG.

Rice irrigation

Rice cultivation in Khorezm is conducted in permanently flooded basins. Therefore, rice cropping demands up to 30% of the total water supply, although rice occupies only 10% of the cropped area in Khorezm (Manschadi et al. 2010). Improving the management of rice fields has a huge water saving potential, which in turn allows raising considerably the water productivity (Bekchanov et al. 2010b). With respect to fields on loamy sand and sandy loam, Devkota (2011) compared intermittent irrigation of rice fields...
combined with conservation agriculture practices. Intermittent irrigation consequently applied in the vegetation period and conservation agriculture practices enabled a 68–73% water saving potential. Although yield was reduced by 30–56%, water productivity was nearly doubled. These numbers indicate the maximum achievable range of the water saving potential by intermittent rice irrigation under the agro-ecological conditions predominating in Khorezm.

Favored by bio-physical (flat topography, shallow groundwater), economic (high price) and cultural (nutrition behavior) conditions Khorezm developed a rice cultivation tradition and became a major rice producing region in Central Asia. Decreasing the area cropped with rice would imply an over-proportional potential of water savings (see above mentioned numbers on the area of and the water directed to rice cropping). On the other hand, rice is the most profitable crop in the region as illustrated by its large economic benefits (Djanibekov et al. 2010) and restricting rice production would become a major administrative issue. More promising than completely omitting rice cultivation seems the introduction of a combination of technological, economical and institutional measures addressing for instance the selection of the most appropriate fields for rice cultivation, precise land preparation by laser-leveling, application of dry–wet strategies in periods with low sensitivity of yield and information on alternative crops (especially when anticipating seasons with low water availability). These all can lower water requirements considerably with minor impact on yield and income of farmers. Also the introduction of a rational incentive–disincentive system (see below) is an economic mechanism, of which higher impacts can be expected when combined with institutional re-arrangements mainly aiming at raising the flexibility in the decision-making of farmers.

Salt management at field level

Forkutsa et al. (2009) simulated the soil salinity with the HYDRUS model (Simunek et al. 2005), which was parameterized for representative fields in Khorezm. Figure 3 (upper part) depicts the soil salinity at characteristic times (before leaching, after leaching, end of the vegetation period) with respect to a 2 m layer differentiating the root zone (0–0.8 m) and the layer below influencing the root zone via capillary rise (0.8–2 m).

Pre-season leaching lowered the salt contents in the root zone, which accumulated during the vegetation period. The salt content in the 2 m layer reached at the end of the vegetation period the same level as before leaching. The salinity in the layer below the root zone shows ineffectiveness of leaching, because the salts were shifted from the root zone to the layer below rather than removed from the 2 m layer.

The parameterized HYDRUS model was used to assess the impact of an improved management option. The option comprises the application of crop residues (to reduce soil evaporation), lowering the groundwater table to 2 m, re-scheduling leaching and irrigation (saving the non-effective part of leaching water and using it in the vegetation period).

Regarding the root zone (0–0.8 m), the improved system has the potential to increase leaching effectiveness; soil salinity decreased from 28.5 to 8 tons per layer per ha compared with 29 to 10 tons per layer per ha by the current strategy (Figure 3/lower left). The improved system is capable of nearly avoiding salt accumulation in the vegetation period. In contrast, the current strategy leads to a clear accumulation of salts in the root zone. With respect to the 0–2 m layer, the improved strategy leads to an overall decrease of salt compared with a currently more or less balanced situation (Figure 5/lower-right).

Application process

The flat topography in Khorezm allowed testing of double-side furrow irrigation as a low-cost option. Compared with 300 long conventional furrows, double-side irrigation resulted in a more uniform water distribution along the furrows, improved application efficiency and saved around 20% of the seasonal gross irrigation water input to the field (Poluasheva 2005). In addition, the sharp increase in salt accumulation, which was observed at the end of conventionally irrigated furrows, could be halved. The higher uniformity of water application and a reduced peak in salt accumulation increased the cotton yield by 30–35% (Poluasheva 2005).

Mid-term simulation (‘sponge concept’)

The current irrigation strategy in Khorezm includes the capillary rise from shallow groundwater, which is
recharged by percolation as a consequence of heavy leaching and high irrigation losses (‘sponge concept’). To test the mid-term impact of the ‘sponge concept’ on soil moisture and salinity, a year with low water availability (dry) and one with average-high water availability (normal) were analyzed for soil moisture and salt dynamics in the root zone using the HYDRUS model. As the irrigation strategy drives the water and salt dynamics, the years were defined as ‘hydrological’ years: beginning with the winter period without considerable irrigation in October until the end of the irrigation and vegetation season in the following September. In the dry year (October 2000 until September 2001) the surface water supply in Khorezm was reduced to 50% of the average, whereas the hydrological year 2004/2005 was above the average (SIC ICWC 2014). The simulations were performed for silt loam and sandy loam and referred to cotton.

The major parameters used in the simulation are shown in Table 1. Leaching is performed by three events and irrigation by four events.

For a silt loam soil texture (SL), soil moisture content does not fall below the allowable depletion (Allen et al. 1998) indicated by the horizontal line, ensuring that no water stress occurs (Figure 4; left part). The sufficiency of soil moisture content is not only achieved in the normal year, but also for the dry year. The findings showed that by nearly halving the surface water supplies, the soil moisture status in the root zone is still adequate to meet the crop water demand.

For sandy loam (SDL), in the normal year, farmers often are late in applying the first irrigation (Figure 4; right part). The situation becomes worse for the dry years: the first irrigation usually is too late and the second and third irrigation are insufficient. As a
consequence, soil moisture drops considerably below the allowable depletion level, even approaching the wilting point towards the end of the season.

During normal years, an excessive amount of water is supplied to SL and SDL soils. For example, when water supply was reduced by half (dry), the ‘sponge phenomenon’ failed for the SDL. Soil moisture in the SL was still above the threshold value but there was significant increase in the soil salinity of the root zone.

### Lessening constraints

#### Infrastructure and bio-physical system

The Khorezm irrigation system was designed for providing water to a small number of large and uniform production units. Because of additional insufficient maintenance and as the network is lacking appropriate hydraulic structures, water distribution to a high number of water users with

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**Table 1** | Soil hydraulic parameters (upper part) and major input on hydrological and water management parameters (lower part) with $\theta_s$ and $\theta_r$: saturated and residual soil water content, $\alpha$ and $n$: empirical parameters in the soil water retention function, $K_s$: saturated hydraulic conductivity, $l$: tortuosity parameter in the conductivity function

<table>
<thead>
<tr>
<th>Soil type</th>
<th>$\theta_s$ (cm$^3$cm$^{-2}$)</th>
<th>$\theta_r$ (cm$^3$cm$^{-2}$)</th>
<th>$\alpha$ (cm$^{-1}$)</th>
<th>$n$ (-)</th>
<th>$K_s$ (cm/day)</th>
<th>$l$ (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silt loam</td>
<td>0.067</td>
<td>0.45</td>
<td>0.02</td>
<td>1.41</td>
<td>10.8</td>
<td>0.5</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>0.065</td>
<td>0.41</td>
<td>0.075</td>
<td>1.89</td>
<td>106.1</td>
<td>0.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Groundwater level (cm below ground)</th>
<th>Evapotranspiration of cotton (mm/day)</th>
<th>Irrigation (mm/month)</th>
<th>Leaching (mm/month)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>229</td>
<td>190</td>
<td></td>
</tr>
<tr>
<td>February</td>
<td>231</td>
<td>195</td>
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<tr>
<td>March</td>
<td>157</td>
<td>140</td>
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<tr>
<td>April</td>
<td>153</td>
<td>121</td>
<td>2.75</td>
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<tr>
<td>May</td>
<td>182</td>
<td>125</td>
<td>2.47</td>
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<tr>
<td>June</td>
<td>165</td>
<td>117</td>
<td>6.61</td>
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<tr>
<td>July</td>
<td>159</td>
<td>103</td>
<td>8.91</td>
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<tr>
<td>August</td>
<td>163</td>
<td>102</td>
<td>6.65</td>
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<tr>
<td>September</td>
<td>173</td>
<td>123</td>
<td>4.31</td>
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<tr>
<td>October</td>
<td>189</td>
<td>154</td>
<td>0.31</td>
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<tr>
<td>November</td>
<td>197</td>
<td>172</td>
<td></td>
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<tr>
<td>December</td>
<td>218</td>
<td>191</td>
<td></td>
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</tbody>
</table>

**Figure 4** | Average soil moisture content for 1 m depth for silt-loam (SL; left part) and sandy loam (SDL; right part) in normal and dry years (the horizontal line indicates allowable depletion limit).
diversified water requirements cannot be ensured. As a pre-requisite for introducing any type of flexible irrigation schedules, the system needs thus to be equipped with structures to measure and regulate the discharge.

Implementing optimal application discharges to raise the currently low application efficiencies and realize proper dosing, adequate infrastructure for discharge control needs to become available at farm level. As irregular micro-topography severely constrains uniform water distribution, laser-guided leveling has a water saving potential in the range of 20–30% (Bekchanov et al. 2010b). Considering the financial limitations of the farming population in Uzbekistan, Bekchanov et al. (2010b) concluded that less-capital demanding, but often also less water efficient measures, have the highest potential to be adopted. Although extremely effective in increasing water productivities (Bekchanov et al. 2012), the implementation of high efficiency irrigation technologies such as sprinkler and drip is constrained not only by the low farm capital and reserves of the farmers, but also by the overarching non-reliability of water provision which discourages long-term planning, and their attitude to investing in assets and innovations (Djaniebekov et al. 2012). Therefore, capital intensive innovations are presently implemented at specific locations (e.g. home gardens, greenhouses, household plots) only. It is also advantageous to reflect on incentives to implement high-cost-water-wise options in the water-rich upstream regions where presently farmers are better off (Bekchanov et al. 2010a, b) and where the problem of temporal non-reliability of supply is comparatively much lower. Long-term strategies should aim at creating an enabling environment allowing the introduction of innovations that increase water productivity such as: (i) demonstrating modern technologies and informing local farmers on costs and benefits, (ii) ensuring a long-term planning reliability and creating thus space to unfold innovation potential of farmers (see below/sub-section ‘institutions’), and (iii) easing the issue of non-reliable water provision by institutional re-arrangements (e.g. strengthening WCAs) or installing decentralized reservoirs, or using the storage capacity of the aquifer.

As the current irrigation performance is characterized by temporal non-reliability of supply, indicated by a reduction of actual evapotranspiration (Conrad 2006), and by a high deviation of planned versus realized supply in the irrigation network (Awan 2010), decental reservoirs at the level of Water Consumers Associations (WCAs) and farms are an option to assist farmers to adapt to variable supply. In particular, the implementation of deficit irrigation strategies could be supported by the consideration of such reservoirs, although the practical financial feasibility still needs to be explored.

**Institutions**

Implementing strategies towards the sustainable use of resources requires long-term planning reliability with respect to farmers. Assuring the currently uncertain land use rights is a prerequisite to raise farmers’ willingness to invest in measures needed to introduce efficient irrigation as postulated recently (e.g. Djanibekov et al. 2012). Long-term planning reliability creates furthermore space for mobilizing the innovation potential of farmers (Hornidge et al. 2011). As the total abolition of the state-order system is not realistic in the near-future, partial transition of the state-order system is considered as a measure to enhance the innovation process: (i) developing the strict area-based production quota of cotton and wheat towards a production-based quota (keeping the production target, but leaving the decision where to produce cotton or wheat within the farm to the farmer), or (ii) defining the quota for several years (Djanibekov et al. 2010).

In principle, WCAs are the platform to link the water requirements by farmers with the water distribution. Practically, current performance of the processes within the WCAs needs to be improved. Transdisciplinary action research in a WCA in Khorezm proved to be an appropriate approach for raising the feeling of ownership regarding the WCA among users (Hornidge et al. 2011). The introduction of local water inspectors supporting the district inspectors in detecting water wastage proved to be successful as well, in particular when combining inspecting and sanctions with intensive on-site training on concrete water saving strategies (Hornidge et al. 2011).

**Economy**

Currently, many WCAs are in danger of enter a ‘vicious cycle’: inadequate funds limit the performance of WCAs
with respect to providing farmers with appropriate water supply - delivery problems lower the willingness of water users to pay fees and in turn capacities of WCAs decrease further.

Introducing a ‘Reciprocal responsibility’ is a promising measure to improve the functioning of the WCA, because WCA as well as water users are addressed concurrently: in case the WCA fails to deliver water, the water user is released from water fees; water users being reluctant to pay are excluded from water delivery as recently postulated (Manschadi et al. 2010). Extending the service functions of WCAs towards others such as providing micro-credits or insurances in additional to conventional services is another promising approach to raise willingness to pay WCA fees (Hornidge et al. 2011).

The introduction of volumetric water fees has the potential to enhance water saving and improve the financial situation of WCAs. Bobojonov (2008) simulated a water saving potential of 5–6%, which can be mobilized by volumetric water fees. On the other side, a cost-covering fee, which would be in the range of 9 US $ per 1,000 m², would overburden many water users in Khorezm.

Instead of water pricing as an isolated measure, Rudenko & Lamers (2006) argue for an overall concept combining water fees and partial loosening of the quota system. An innovative system of incentives–disincentives by tax boni and mali is suggested to support sustainability and long-term productivity (Akramkhanov et al. 2010). Water users introducing strategies for water saving and improving salt management at the same time would become eligible to high boni. Interventions either for water saving or improved salt management would lead to medium boni whereas water users neglecting any interventions would be confronted with mali.

To come into effect, concepts towards water saving at the level of water users and WCAs need to be complemented by institutional and financial provisions at national and interstate/basin level (Dukhovny 2003). According to Sokolov et al. (2008), applying the principles on Integrated Water Resources Management facilitates reforming water management in Central Asia.

**SUMMARY AND CONCLUSIONS**

Intensified water use in upstream parts of the Amu Darya basin and the predicted effects of climate change for Central Asia are expected to impact water supply in Khorezm towards a lower availability and increased variability. To adapt to these changes, water management in regions located at the tail ends such as Khorezm needs in particular to become more efficient and flexible. Technical approaches (e.g. model-based irrigation scheduling), re-arranging institutional settings (e.g. strengthening the water user’s participation in WCAs) and appropriate economic incentive structures (e.g. water fees) need to be conceived and implemented hand-in-hand. Partial loosening of the state-order system in combination with assuring land use rights would support more than now options for long-term planning and in turn enable the water user to unfold innovation potential and strengthen the introduction of sustainable resource management strategies.

Despite raised efficiency and flexibility, future limitations of and variability in water resources may dictate the need for controlled deficit irrigation strategies. To minimize the unavoidable impact of water stress on crop yields, the application of irrigation scheduling models could be considered which would become even more effective in combination with crop models taking the groundwater as a buffer into account. Implementing deficit irrigation strategies can be facilitated by technical approaches aiming at a higher uniformity of water application (e.g. through laser-guided land leveling) and tackling the temporal burden of the present water distribution by e.g. strengthening water users and WCAs. Integrating small-scale water storages such as lakes into irrigation concepts and considering decentral reservoirs are options, especially in periods with non-reliable water supply. Furthermore, the acceptance of deficit strategies can be improved by transparent rules governing the water allocation processes in the WCAs, enabling participation of water users.

A combination of modeling the mid-term behavior of the linked surface and groundwater system (‘sponge’) and mid-term forecast regarding the available water resources in the Amu Darya basin, provides an option to derive adapting strategies at an early stage.
Bundling technical interventions towards flexible irrigation/leaching scheduling and advanced handling of the water application process, institutional re-arrangements ensuring a better coordination between irrigation activities especially at the interface between farm and network level (WCA) and economic incentives are an appropriate answer to future water scarcity.

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