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Managing water-use trade-offs in a semi-arid river delta to sustain multiple ecosystem services: a modeling approach

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Abstract Managing trade-offs among water uses in a river basin to sustain multiple ecosystem services is crucial for adaptation to changing river flow regimes. Here we analyze the trade-off between irrigation and fisheries in the Amudarya, a semi-arid river basin in Central Asia, using an optimal control and an agent-based modeling approach. With the optimal control approach (OCA), we identify the economic and ecological conditions for water sharing in a regime where a social manager controls water withdrawals and fish harvesting. With the agent-based model (ABM), we relax some of the assumptions of the OCA to investigate how localized, individual agents with varied water use histories adapt their water use activities to local resource conditions. Variation in the farmers' initial labor allocations to the two activities results in regimes with only one activity or both. Global returns and income equality are highest in a mixed regime. The mixed regimes also are more robust to water variability because fishing activities can compensate for decreased agricultural performance in the midstream regions. Thus, allowing for multiple uses can improve the coupled social-ecological system's performance and its resilience. We also observe a lock-in effect similar to the current situation in the Amudarya, where agriculture is the dominant water use and transition to a more balanced allocation has proven to be extremely difficult. As in the ABM, this can to some extent be attributed to the difficulties of achieving sufficient revenues from fishing when agricultural activities upstream are high. Regulations or incentives are needed to overcome those barriers, and to facilitate progress towards integrated water management.

Keywords Trade-off · Ecosystem services · Water management · Agent-based model · Optimization · Resilience

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Introduction

Balancing complex and often conflicting demands for water among different uses and users in a river basin is a difficult task. This is especially true for semi-arid and arid river basins where the available water resources play a crucial role for national economies and are often predominantly used in a single sector—irrigated agriculture. In many river basins, the dominance of agricultural water use has had severe impacts on the development options of other water-related sectors such as hydropower or fisheries, and caused severe alterations to riverine and floodplain ecosystems and a loss of valuable ecosystem services. With increasing pressures on the available resources from climate change and demographic and economic developments competition for the scarce water resources will become stronger, making the management of water use trade-offs even more difficult. However, in face of those anticipated or ongoing changes multi-sectoral, integrated water management may prove better suited than a management regime that focuses on the delivery of a single service, e.g., agricultural production.

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We argue that the management of trade-offs among instream and offstream water uses to ensure the provision of multiple ecosystem services and facilitate the diversification of livelihoods can enhance overall productivity in a river basin. Moreover, it can make the coupled social-ecological systems more resilient to external and internal changes and shocks such as the impacts of climate change or economic development.

One of the water-related ecosystem services often neglected in water management is the provision of fish by riverine floodplains, which is especially important for local livelihoods in the developing world (Millennium Ecosystem Assessment 2005). Floodplain fisheries support millions of people with commercial, subsistence or recreational fisheries but have been severely impacted by alterations to river flow regimes (Godinho et al. 2007; Craig et al. 2004; Halls and Welcomme 2004). Their needs are rarely included in the development of water-allocation strategies, leaving them with what is left after other consumptive (e.g., irrigation) or non-consumptive (e.g., hydropower) water uses. Yet the potential benefits such as income generation and poverty reduction, of sustaining those fishery services can be substantial (Renwick 2001; Jensen 2001b). However, given the dominance of agriculture in many river basins a transition to a more balanced allocation of water can face many barriers.

In this paper we apply both an economic and a computational approach to analyze trade-offs between different water uses in a river basin with the aim to explore the potential for managing them. By illuminating options and impacts of multiple water uses from an integrated economic-ecological perspective, we want to highlight synergies that reduce the conflict between alternative water uses. The analysis is carried out using a stylized example from the lower Amudarya River basin in Central Asia where fisheries compete for water use with irrigation. The study focuses on the economic conditions under which multi-purpose water use is optimized and the social, environmental and management conditions under which it can evolve and enhance the performance and resilience of the coupled systems in the face of increasing variability in water availability, as expected, e.g., with climate change.

To determine conditions under which multiple water use is economically optimal, we develop a bio-economic model of two alternative water use activities—irrigation and fisheries. This optimal control approach (OCA) serves as a benchmark for an agent-based model (ABM) which we use to explore the bottom-up evolution of multi-purpose water use in response to environmental and social change. While there is a social manager with foresight optimizing total returns from water use in the OCA, in the ABM farmer agents take individual decisions on the amount of labor to invest into the two different water use activities based on the returns per effort they received from each activity in past years. Previous agent-based modeling of water use for a single activity has shown that a strong upstream–downstream gradient evolves with upstream individuals becoming very successful while downstream users go bankrupt (Schlüter and Pahl-Wostl 2007). With single-purpose water use the discrepancy in economic power raises quickly, a pattern which was also observed in the real river basin during an extreme drought in 2000; upstream farmers experienced a shortage of 11% of their extraction limits, while downstream farmers had to cope with a shortage of 52% (UNECE/UNESCAP 2004).

Bio-economic models have been used previously to assess the trade-off between agricultural and non-agricultural water uses such as paddy irrigation and reservoir fisheries in Sri Lanka (Renwick 2001) or rice and inland fish production in the floodplains of Bangladesh (Shankar et al. 2004), and to develop integrated water-allocation strategies for multiple sectors in the Mekong (Ringler and Cai 2006; Jensen 2001b). Others have used them to develop strategies for reservoir releases that maximize exploitable fish biomass (Godinho et al. 2007; Halls and Welcomme 2004), or to balance water needs between irrigation and salmon conservation in the western United States (Fisher et al. 1991). All studies conclude that the trade-off between different water uses and the value of water in non-irrigation uses needs to be assessed and recognized in river basin management. Moreover, the gains in the fisheries sectors and improvements of local livelihoods can be significant in exchange for rather little cost in the agricultural sector.

Agent-based models have primarily been used to study interactions among users in coordinating water allocation such as in the irrigation landscape of Bali (Lansing 1991; Lansing and Kremer 1993; Janssen 2007), to resolve upstream-downstream conflicts over water sharing (Becu et al. 2004), or to model water allocation negotiations (Le Bars et al. 2005). We are not aware of another context where optimization and agent-based models have been developed in tandem to address a natural resource management problem. The models and their outputs are complementary, as we show below. Our optimization model provides an analytically tractable articulation of how the social and ecological systems are connected under equilibrium conditions, while the agent-based model enables us to incorporate spatial variation and individual farmer attributes explicitly and to track how the coupled systems responds to resource variability. Together they provide insights on the ecological, economic and historical conditions under which water sharing between agriculture and fisheries can evolve and be maintained and how it affects system performance and resilience.

The remainder of the paper is organized as follows. After a short introduction to the social-ecological system in the Amudarya River Basin we present the optimization approach under stable water flow conditions in order to investigate the economic trade-off between two alternative water uses. It provides some general insights about the economic and ecological conditions which enable multi-purpose water use and sets the overall frame for the agent-based model of water allocation with variable water flows. With the agent-based model we explore the evolution of different water use regimes from variable initial conditions and assess the performance of these regimes under stable and variable water flows. Finally, we compare the results of both models and discuss their implications for future water management.

The social-ecological system of the Amudarya River Basin

The Amudarya River Basin is located in an arid climate with precipitation in the lowlands as low as 50–100 mm per year. Agriculture in the lowlands therefore depends on irrigation, which uses more than 90% of the water resources and generates approximately one-third of the GDP of the downstream countries. All water resources are generated in the upstream areas, largely by glacier and snowmelt, but primarily are used in the desert lowlands to produce irrigated crops, mainly cotton and wheat. Water flows in the river basin vary greatly among years, and this is likely to increase with climate change (Savitsky et al. 2007). Moreover, predicting both the natural and anthropogenic drivers of water flow variability is fraught with uncertainty. The strong dependence on one income source (agriculture) makes the coupled social-ecological systems vulnerable to changes in water availability, as was demonstrated by several extreme events in the past years, e.g., an extended drought in 2000 and 2001.

Conflicts over water allocation arise among the demands of wetland fisheries in the delta area and the needs of irrigated agriculture, but also among those of upstream hydropower generation and irrigation. The dominance of irrigation has led to significant degradation of wetland and aquatic ecosystems in the river delta and the Aral Sea (Schlüter et al. 2006). Those ecosystems and the goods and services they provide, including the provision of fish, reeds, muskrat, birds, fire and construction wood, groundwater recharge and protection against desertification are important for the livelihoods of the local population and the biodiversity of the region. However, trade-offs in water use to rehabilitate and conserve those services are currently not being dealt with, causing further degradation of ecosystems and upstream–downstream conflicts.

In particular, the viability and productivity of the fish populations in the many lakes in the river delta are strongly dependent on the quantity and spatio-temporal distribution of freshwater inflows from the river (Joldasova et al. 2002). Besides determining the extent of available lake habitat, the incoming floods transport large amounts of eggs, larvae and young fish into the deltaic lakes from more suitable habitats upstream. This natural stocking mechanism is extremely important for the viability of the fish populations in the delta given the highly fluctuating water regimes and lack of suitable habitat for reproduction in downstream areas (Joldasova et al. 2003).

In modeling these coupled social-ecological systems, we focus on the flow of water for agriculture and fisheries. Individual farmers can engage in both production activities and harvest crops and fish. A social manager (in the OCA) or the individual farmers (in the ABM) decide on the amount of water and labor to invest in each activity in order to maximize returns from water use (OCA) or to find the water use strategy which performs best at a specific location along the river (ABM).

Model descriptions

Optimization model (OCA)

We applied an optimal control approach (OCA) to determine the optimal system-level allocation of the available water resources to the two competing sectors under equilibrium conditions. Returns from irrigated agriculture are modeled as the net returns from the use of the water for the production of a single crop. The returns from the fisheries are the net revenues from selling the fish catch at market price. Fish population growth is enhanced by the inflow of water which transports fish from upstream habitats to the lake fish population. The model extends a standard fish population growth model with Ricker type recruitment to include this natural stocking effect. Stocking is formalized as an addition of fish from an external source to the fish stock similar to other approaches investigating the effect of stocking on catch dynamics (Borsuk et al. 2006; Jensen 2001a; Laukkanen 2001). We assume a social manager who optimizes the allocation of the water resources to the two alternative uses according to the following objective function (Eq. 1) and constraints (Eqs. 2–4) (following Clark 1990):

$$\max \int_{t=0}^{\infty} [P_A \times W_A(t) + P_X \times h(t)] e^{-\delta t} \mathrm{d}t \quad (1)$$

subject to

$$\dot{X} = \alpha \times X \times e^{-bX} - m \times X + \frac{\lambda \times W_x}{V + W_x} - h \quad (2)$$

$$W_A + W_X = \bar{W} \quad (3)$$

$$0 \le h(t) \le h_{\max} \quad (4)$$

$$X_{t=0} = X_0 \quad (5)$$

$$P_X = P_F - C \quad (6)$$

where $\bar{W}$ is total water available, W_A, W_X is the amount of water allocated to agricultural production and fisheries, respectively; P_A is the market price for crops produced per unit of water used in agriculture; P_X is the net revenue per unit of fish, P_F is the market price per unit of fish, C the costs of labor in fishing, δ is the discount rate; X is the fish stock, α the reproduction rate of the fish population, m its natural mortality, b describes the strength of the density-dependent regulation of the fish stock, λ is the maximum number of fish that can enter the population with the water inflow, V is the amount of water inflow at which the immigration of fish is $\lambda/2$, and h is the number of fish harvested (Table 1).

Agent-based model (ABM)

The agent-based model (ABM) was developed to explicitly incorporate the directional flow of water from the inflow to the fish lake and the resulting sequential access of the users to the resource (Fig. 1). Unlike the optimal control approach (OCA) above, where a social manager determines the allocation to each activity, in the ABM, the labor allocations of individual farmers and their performance (returns/effort) determine water withdrawals and subsequent allocation to agriculture and fishing activities. Farmers adapt to the local resource conditions, which in turn determine the benefits of the two alternative income generating activities. For more details about the general modeling framework, see (Schlüter and Pahl-Wostl 2007).

Sequence of activities in one season (Fig. 2)

At the beginning of each year a monthly runoff time series is generated. Farmers assess the last year's success in both activities and their financial reserve and then chose the proportion of labor to allocate to farming and fishing in the upcoming year. Both farming and fishing activities involve costs, e.g., for planting the crops or acquiring the necessary gear for fishing. During the irrigation season, farmers one after the other try to withdraw water for irrigation each month according to the needs of their crops. If there is not enough water available crops will experience water stress which in turn lowers the yield. The water remaining after all irrigation withdrawals have taken place is allocated to the fish population, which grows accordingly. At the end of the season farmers harvest the crops and fish, consume a fixed amount and save the rest as financial reserves.

In the following the individual steps, calculations and decision-making are explained in detail. The default parameter values are given in Table 2.

Table 1 Parameters of the optimization model

	Description
Resources	
$\bar{W}$	Total available water
Fish population	
α	Reproduction rate
m	Mortality rate
b	Factor for the density-dependent regulation of reproduction
λ	Maximum number of fish in water inflow
V	Amount of water inflow at which the number of fish in the inflow is $\lambda/2$
h	Number of fish harvested
Agents	
P_A	Net revenue per unit of water in agriculture
P_F	Market price per unit of fish
C	Costs of labor in fishing
P_X	Net revenue per unit of fish
δ	Discount factor

Water resources

The water resource is represented as a uni-directional flow from upstream to downstream. The inflow in month m of year t ($W_{I,t,m}$) is the proportion of the mean annual inflow ($\bar{W}_I$) for the respective month according to a mean annual hydrograph (H_m) for the lower Amudarya River (Eq. 7). In scenarios with variable water flows monthly runoff is varied by multiplying it by a random number (r_t) drawn from a normal distribution with mean 1 and a variance (σ) determined by the scenario. Each farmer sequentially withdraws water for irrigation every month of the growing season according to his allocation of labor devoted to agricultural activities (see below). The total agricultural labor by all farmers determines the amount of irrigated land, and thus the amount of water withdrawn (Eq. 8). The remaining water (W_X) is delivered to the terminal fish lake downstream (Eq. 9).

$$\text{Inflow}: \; W_{I,t,m} = r_t \times \bar{W}_I \times H_m \tag{7}$$

$$\text{Agriculture}: \; W_{A,t,m} = \sum_{j=1}^{F} W_{D,j,t,m} = \sum_{j=1}^{F} \omega \times L_{A,j,t} \times A_{max} \times W_c \tag{8}$$

$$\text{Fisheries}: \; W_{X,t,m} = W_{I,t,m} - W_{P,t,m} \tag{9}$$

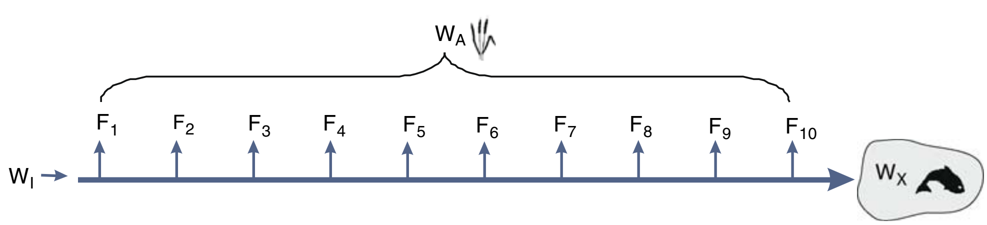

Fig. 1 Scheme of the environmental setup of the agent-based model. The water inflow enters the system at the location of farmer 1 and ends in the lake with the fish population. Farmers sequentially withdraw water for their agricultural activities. Water that is not used in irrigation enters the fish population with new fish if the flow is above a certain inflow threshold (see text for details). W_I, water inflow; W_A, water use in agriculture, W_X, water delivered to fish population; F_i, Farmer i

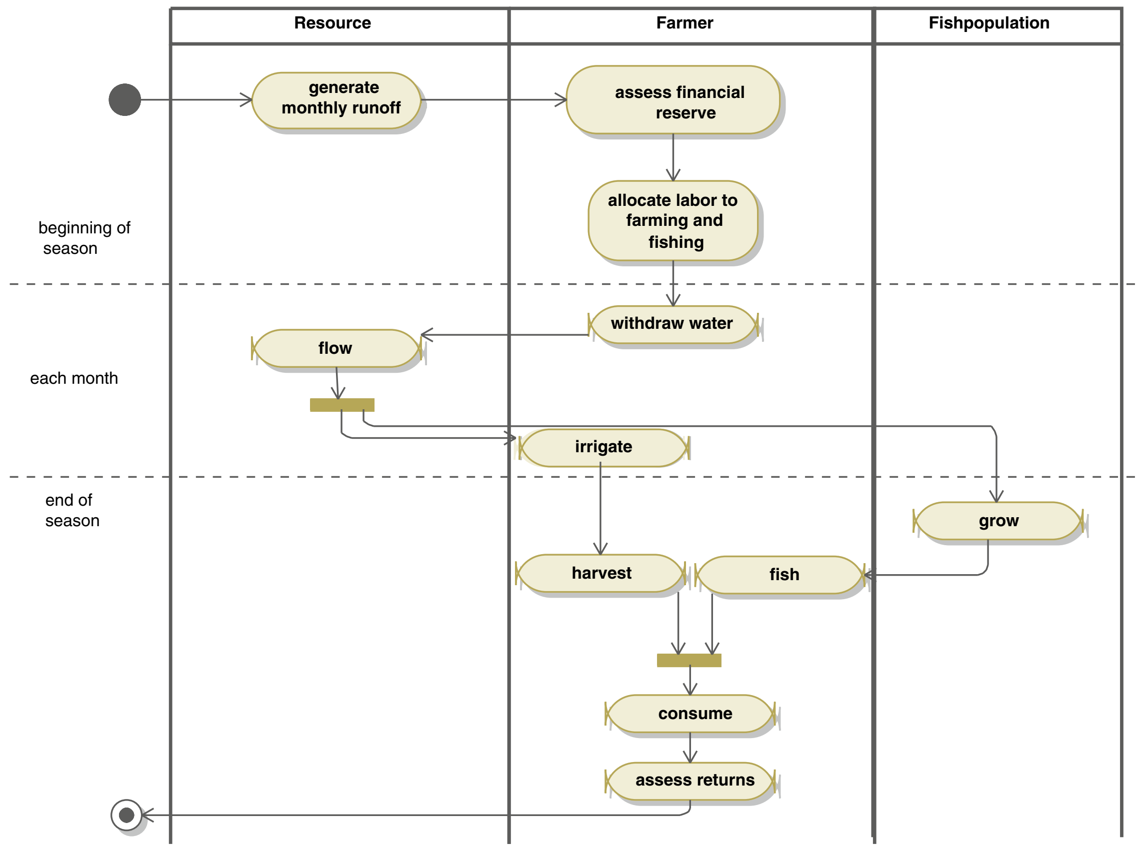

Fig. 2 Flowchart of the major interactions in one season in the agent-based model

where $W_{I,t,m}$: inflow to system in month m of year t; $\bar{W}_I$: mean annual inflow; r: random number from normal distribution with mean = 1, variance = σ; H_m: value of hydrograph for the respective month; F: total number of farmers; W_D: water delivery to agriculture, ω: percentage of water demand that is met (determined by water availability and withdrawals by upstream farmers), L_A: labor allocated to agriculture, W_C: water needs per ha of crop; W_X: water delivered to the fish lake.

The model has been calibrated such that the maximum total water needs when all farmers are farming at 100% exceeds the available water resources of a mean water year by 20% (Table 2). This reflects the situation in the real river basin where water resources are already overused.

Fish resources

The fish population is modeled with a Leslie-type age structured model that includes six stages. Stage 0 receives the larvae produced by the fifth, reproductive, stage, and the larvae that enter the population with the inflowing water during spring floods in May, as observed in the river basin (Joldasova et al. 2002). Each year millions of larvae enter the delta region with the first spring flood; however, larvae often do not reach the lakes because of water diversion to the fields or mortality caused by low flow velocities. Based on those empirical observations we formalize the inflow of larvae into stage 0 as the immigration of individuals proportional to the inflow after a minimum threshold has been passed (Eq. 10). Reproduction is density dependent following a Ricker type function (Eq. 11). During the juvenile phase of 4 years fish experience an environmental mortality as well as density dependent competition for food and hiding spaces (Eq. 12). When they enter the sixth stage fish mature and are harvested (Eq. 13). While the stage duration of stages 0–5 is 1 year, fish remain in stage 6 for 6 years. Fish older than 12 years die.

$$I_t = \frac{W_{X,t,5}}{\varphi} \text{ if } W_{X,t,5} > WT \tag{10}$$

$$N_{0,t} = I_t + \sum_{i=5}^{12} \alpha \times e^{-b\sum_{i=5}^{12} N_{i,t-1}} \times N_{i,t-1} \tag{11}$$

$$N_{i,t} = (1-\beta_{i-1})N_{i-1,t-1} - \mu \times \left(\sum_{i=0}^{4} N_{i,t-1}\right)^2 \quad \text{for } 0 < i < 5 \tag{12}$$

$$N_{5,t} = (1-\beta_4)N_{4,t-1} + (1-\beta_4)N_{5,t-1} - h_{t-1} \tag{13}$$

where I_t: inflow of larvae in year t; $W_{X,t,5}$: water inflow to the lake in May of year t; φ: scaling factor; WT: flow threshold beyond which there are fish larvae in the inflow; $N_{i,t}$: abundance of fish in age class i at time t; α:

Table 2 Parameters and initial values of the agent-based model

	Description	Default value
Resources		
$\bar{W}_I$	Mean annual inflow (million m^3)	37,243
H_m	Value of hydrograph for each month	0.044, 0.034, 0.038, 0.063, 0.122, 0.151, 0.187, 0.14, 0.076, 0.048, 0.045, 0.052
W_C	Water needs per ha of crop, includes transport losses to field (million m^3)	0.01
$Y_{\max}$	Maximum yield/ha	0.01
Fish population		
α	Reproduction rate	2.0
β_0	Density independent mortality rate in age class 1	0.6
β_1	Density independent mortality rate in age class 2	0.5
$\beta_{2,3,4}$	Density independent mortality rate in age class 3, 4 and all following age classes	0.2
μ	Density dependent mortality rate in age classes 1–4	0.00001
b	Factor for the density-dependent regulation of reproduction	0.0
φ	Scaling factor for inflow of larvae	1.00
WT	Flow threshold beyond which there are fish larvae in the inflow	675
Agents		
K_j	Consumption	931
$A_{\max,j}$	Max number of ha/farmer	372,430
$E_{\max,j}$	Maximum fishing effort	100
C_A	Cost of labor in farming	0.005
C_F	Cost of labor in fishing	0.5
γ	Scaling factor to relate fish to crop income	75
Initial values		
$N_{0,0}$	Fish population – initial abundance in age class 0	1,000
$N_{1,0}$	Fish population – initial abundance in age class 1	500
$N_{2\text{–}12,0}$	Fish population – initial abundance in age class 2–12	100
$F_{0,j}$	Agent – initial financial reserve (=costs of 2 years of 100% agricultural production)	3,724
$L_{A,0}$	Agent – initial proportion of labor in agriculture	0–1 (increment 0.1)

reproductive rate, β_i: density independent mortality rate in age class i, μ: density dependent mortality rate in age classes 1–4, b: factor for the density regulation of reproduction; h: fish harvest.

The model is parameterized such that the fish population is only viable if there is an inflow of larvae with the floods. This reflects the actual state of the fish populations in the Amudarya River delta, which are dependent on the inflow of larvae and young fish from upstream habitats because of lack of suitable habitat and conditions for reproduction downstream.

Farmers fish sequentially, with the downstream farmer closest to the lake accessing it first. Each farmer attempts to catch fish according to the proportion of labor he has allocated to fishing. However, his chances of catching a fish decline as more farmers fish before him.

Returns from agriculture and fishing

Farmers engage in agriculture and fishing according to the proportion of labor they allocated to each activity. The actual effort devoted to each activity is the proportion of the maximum effort determined by the labor proportion. For example, if a farmer decides to reduce agricultural activities from 100 to 90%, he will plant only 90% of the maximum amount of hectares he can irrigate ($A_{\max}$) and additionally will fish for 10% of the maximum fishing effort ($E_{\max}$). Both activities are costly (C_A, C_F). The total returns to each farmer are the sum of his returns from both activities decreased by his annual consumption (K_j), which is assumed constant. For simplicity we assume here that farmers accumulate returns that exceed their consumption in savings that constitute their financial reserve (FR) in the next year. When the financial reserve of a farmer is zero he turns bankrupt.

$$\begin{aligned} &\text{Agriculture}: R_{A,j,t} = Y_{t,j} - L_{A,j,t} \times A_{\max,j} \times C_A \\ &\qquad Y_{t,j} = Y_{\max} \times \frac{1}{6}\sum_{m=4}^{9} \frac{W_{D,j,m}}{W_{N,j,m}} \end{aligned} \tag{14}$$

$$\begin{aligned} &\text{Fisheries}: R_{F,j,t} = \gamma \times h_{t,j} - L_{F,j,t} \times E_{\max,j} \times C_F \\ &\qquad h_{t,j} = \tau \times L_{F,j,t} \times E_{\max,j} \times X_{5,t} \\ &\qquad L_A + L_F = 1 \end{aligned} \tag{15}$$

$$\begin{aligned} &\text{Total}: R_{\text{total},j,t} = R_{A,j,t} + R_{F,j,t} - K_j \\ &\qquad \text{FR}_{j,t} = \text{FR}_{j,t-1} + R_{\text{total},j,t} \end{aligned} \tag{16}$$

where R_A: returns from agriculture; R_F: returns from fisheries; R_{total}: total returns in 1 year, FR: accumulated financial reserve, L_A: proportion of labor in agriculture; L_F: proportion of labor in fisheries; $A_{\max}$: maximum number of ha per farmer; $E_{\max}$: maximum fishing effort;

Y: Yield; h: fish catch; γ: scaling factor; τ: probability of catching a fish (determined by fishing activities of farmers that have accessed the lake before and the age structure of the fish population); C_A, C_F: cost of labor in farming or fishing; K: consumption.

The model is calibrated such that the maximum total returns from fishing and the maximum total returns from farming are equal when there is no interannual variability in water flows.

Agent decision-making

A farmer bases his labor allocation decision on an evaluation of the returns per effort obtained from his farming and fishing activities in the previous year. Hence, he adapts his strategy by learning from past experiences to find the mixture of activities that yields the highest returns per effort. Because the production functions are linear one can also say he chooses the activity or mixture of activities that has the highest wage rate. All farmers can freely divide their labor between farming and fishing activities.

$$\text{IF } R_{A,t-1}/L_{A,t-1} < R_{F,t-1}/L_{F,t-1} \text{ OR } R_{A,t-1}/L_{A,t-1} < R_{A,t-2}/L_{A,t-2} \text{ THEN } L_{A,t} = L_{A,t-1} - 0.1 \tag{17}$$

$$\text{IF } R_{A,t-1}/L_{A,t-1} > R_{F,t-1}/L_{F,t-1} \text{ AND } R_{A,t-1}/L_{A,t-1} \geq R_{A,t-2}/L_{A,t-2} \text{ THEN } L_{A,t} = L_{A,t-1} + 0.1 \tag{18}$$

Results

Optimization of the water use trade-off (OCA)

The current value Hamiltonian for the optimization problem stated in Eqs. 1–5 is:

$$H_C = P_A \times (\bar{W} - W_X) + P_X \times h + \mu \times \left(\alpha \times X \times e^{-bX} - mX + \frac{\lambda \times W_X}{V + W_X} - h\right) \tag{19}$$

According to the maximum principle the optimal control must satisfy the following first order conditions:

$$\frac{\partial H_C}{\partial h} = 0 \quad \rightarrow \quad \mu = P_X. \tag{20}$$

Since the Hamiltonian is linear in the control the harvest $h(t)$ follows the most rapid approach to equilibrium, i.e., if the initial fish population size is smaller than optimal there will be no harvesting until the optimal stock size is reached. Fish harvest follows the following law:

$$h = \left\{ \begin{array}{l} h^* \text{ when } P_X(t) = \mu(t) \\ 0 \text{ when } P_X(t) < \mu(t) \end{array} \right\}. \tag{21}$$

Thus, when the net revenues for using the water to produce fish is less than the opportunity cost of agriculture it is optimal not to harvest fish but rather to let the population grow and possibly allocate water to it to accelerate growth. The amount of water allocated to the fish population is given by the following necessary condition:

$$\frac{\partial H_C}{\partial W_X} = 0 \quad \rightarrow \quad \mu \times \frac{V \times \lambda}{(V + W_x)^2} = P_A \tag{22}$$

Substituting Eq. 20 in Eq. 22 gives

$$W_x = \sqrt{\frac{P_X}{P_A} \times V \times \lambda} - V \quad \rightarrow \quad W_x > 0 \quad \text{if} \quad \frac{P_X}{P_A} > \frac{V}{\lambda} \tag{23}$$

Hence, whether there is multi-purpose water allocation ($W_x > 0$) in this economic scenario depends on the value of water used to produce a unit of fish in relation to the ecological parameters of the stocking function that determine the increase of the fish population with water inflows. If the water value is larger than the ratio of the half-saturation value and the maximum amount of natural stocking water will be allocated to the fish population.

From the costate equation 24 we can infer the relationship of the fish population size and the discount rate at steady state (Eq. 25).

$$\dot{\mu} = \delta\mu - \frac{\partial H_C}{\partial X} \tag{24}$$

$$\rightarrow \delta = -(bX - 1) \times \alpha \times e^{-bX} - m \tag{25}$$

Equation 25 is transcendental and cannot be solved analytically. The slopes at the extreme values are easily shown to be $-e/b$ when $(\delta + m)/\alpha = 0$ and $-1/2b$ when $(\delta + m)/\alpha = 1$. The full numerical solution is shown in Fig. 3. We can see that the equilibrium size of the fish population decreases with the increase of the ratio $(\delta + m)/\alpha$, which represents the relation of the discount

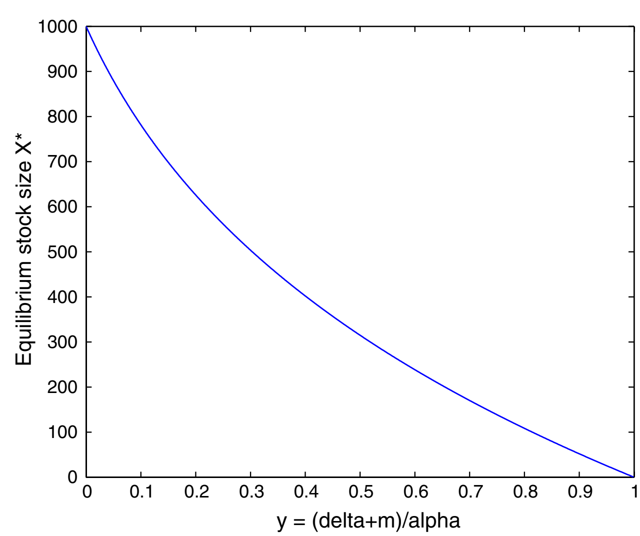

Fig. 3 Numerical solution for the equilibrium stock size of the optimization model as a function of $y = (\delta + m)/\alpha$

or interest rate of the capital received when selling the fish to the net fish population growth. Only when $\delta < \alpha - \mathrm{m}$, i.e., the net growth rate of the population is larger than the discount rate, is the fish population conserved. Otherwise, all fish are harvested immediately and no water is allocated to the fishery. Thus, myopic strategies (large delta) focusing on short term returns can shift water allocation to agriculture and eliminate the fish population and fishery.

Evolution of the water use trade-off (ABM)

The choice of water use activities of each farmer in the ABM is mainly driven by his location along the river and past returns from both activities. The location determines his access to the resources and his exposure to the aggregated impacts of upstream water use decisions. The past returns per effort determine whether he shifts his activity pattern or enforces the one that was successful in the last year. A farmer thus tries to find his individual optimal mix of activities by trial and error. Here we compare scenarios with different initial shares for the two activities, ranging from only fishing to only farming. For simplicity we assume that in each scenario all farmers have the same initial labor allocations. We assess the resulting distribution of activities and the water allocation to the two sectors as well as the resulting individual and global returns at the end of the simulation.

Distribution of labor and water between sectors and farmers

Global returns are lowest when the initial proportion of labor allocated to fishing is high and there are no or only very little agricultural activities, i.e., the ''fisheries dominance'' scenario ($L_{A,0}$ = 0–0.1) (Fig. 4a). Global returns are highest when there is a high initial proportion of labor allocated to fishing but some small inclination for agriculture as well, i.e., the ''mixed'' scenarios ($L_{A,0}$ = 0.2–0.5). When the initial proportion of labor in agriculture is high, i.e., the ''agricultural dominance'' scenarios, the returns level off. In the most successful mixed scenarios the percentage of water allocated to the fish population is between 38% ($L_{A,0}$ = 0.2) and 15% ($L_{A,0}$ = 0.4). The overall proportion of farming increases from 0.6 ($L_{A,0}$ = 0.2) to 0.8 ($L_{A,0}$ = 0.8) (Fig. 4b).

In all scenarios the population of farmers splits into two or three groups along the water flow gradient (Fig. 5). Farmers 1–5 upstream engage in agriculture in all but the ''fisheries dominance'' scenarios where they go bankrupt. The midstream farmers 6–8 capitalize on the fisheries in the ''fisheries dominance'' scenarios but then switch to farming as soon as the initial shares of agriculture increase. They can sustain their income in all scenarios; however, returns are higher when they rely on fisheries. Downstream farmers 9 and 10 mainly fish, since they have the best access to the lake. They have highest fishing returns in the ''fisheries dominance'' scenarios. In the ''agricultural dominance'' scenarios Farmer 9 devotes some labor to agriculture but his returns decline drastically, while farmer 10 goes bankrupt.

When initial labor proportions move from ''fisheries dominance'' to including a small proportion of labor for agriculture ($L_{A,0}$ = 0.1), upstream farmers accumulate sufficient returns to expand their agricultural activities to 100% and avoid bankruptcy. At the same time there is enough water left for the downstream farmers 7–10 to receive high returns from fishing. When initial proportions of labor in agriculture increase even more farmers 7 and 8 also switch completely to agriculture. With $L_{A,0} > 0.5$ the inflow to the fish population decrease below the level that sustains fish population growth. As a consequence, farmers 9 and 10 lose their fishing income and overall performance of the coupled system decreases significantly. The analysis at the individual level shows that income inequality is lowest in the mixed scenarios where there is a stratification of resource use activities along the gradient of resource access and availability.

The fish population abundance is highest in the ''fisheries dominance'' scenarios ($L_{A,0}$ = 0–0.1) (Fig. 5). It decreases by more than half when agricultural activities increase and thus less water enters the lake. While there is still water inflow to the lake in the ''agricultural

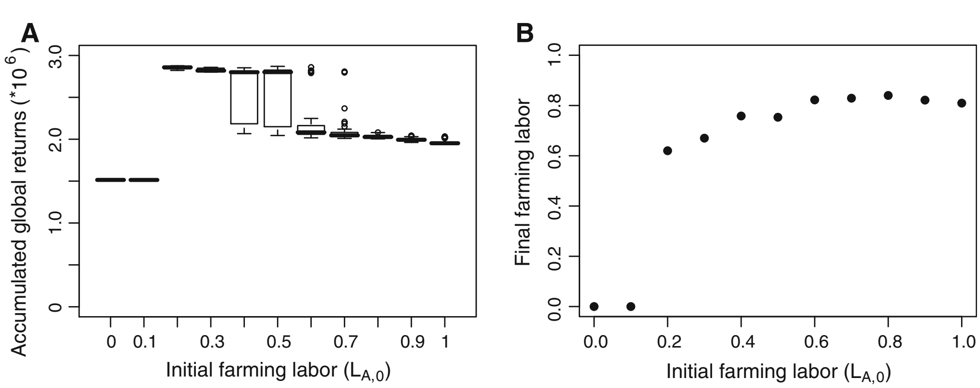

Fig. 4 **a** Global accumulated returns of 50 runs of the scenarios with stable inflow and different initial proportion of labor allocated to agriculture ($L_{A,0}$). **b** Resulting mean proportion of labor in agriculture for the same scenarios at the end of the simulation

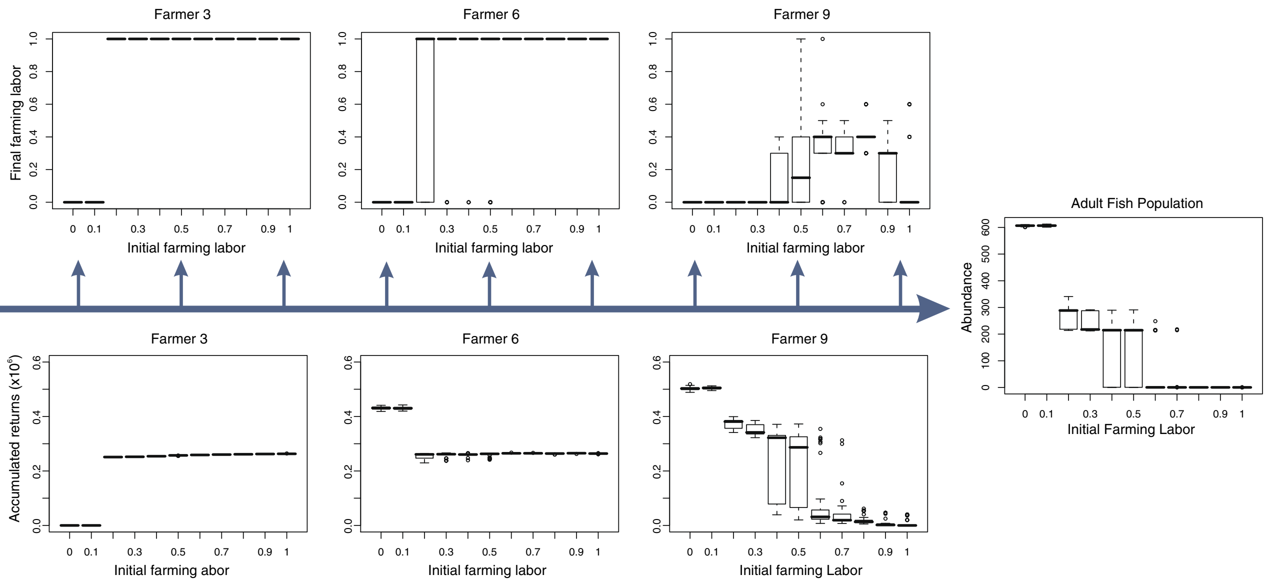

Fig. 5 *Top* Proportion of labor devoted to agriculture at the end of the simulation for farmers 3, 6 and 9, for the scenarios with stable inflow and changing initial farming labor ($L_{A,0}$). *Bottom* Individual accumulated returns of farmers 3, 6 and 9 in the same scenarios (*bottom*). *Right* Abundance of the adult harvestable fish population in the same scenarios

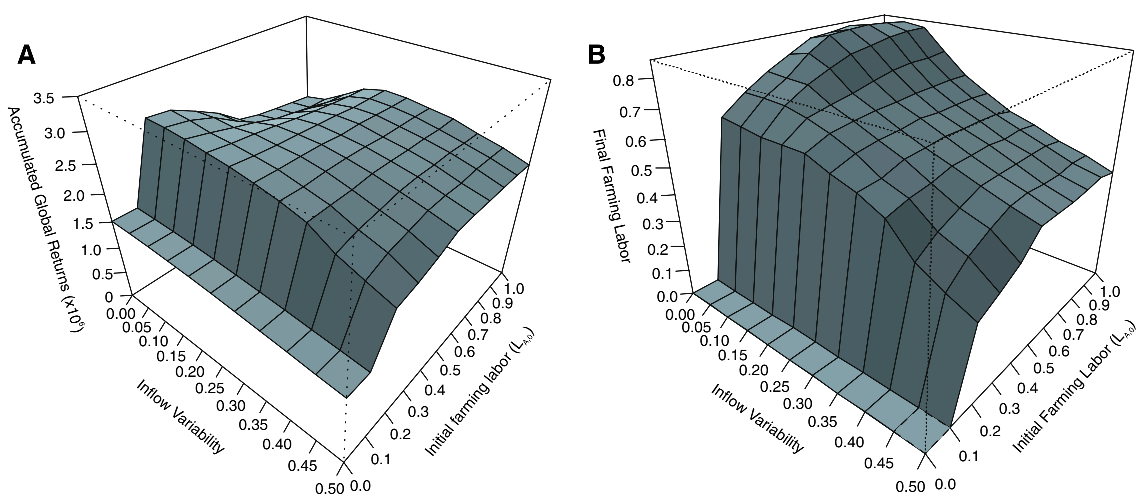

Fig. 6 **a** Global accumulated returns at the end of the simulation with increasing inflow variability (σ) and increasing initial proportion of labor allocated to agriculture ($L_{A,0}$). **b** Proportion of labor in agriculture at the end of the simulation for the scenarios with increasing flow variability (σ) and increasing initial proportion of labor allocated to agriculture ($L_{A,0}$)

dominance'' scenarios, the flow is too low to transport larvae. Consequently, the fish population is overexploited and goes extinct.

A sensitivity analysis of the initial financial reserve shows that with larger initial financial reserve high global returns can be achieved even in the ''fisheries dominance'' scenarios, because upstream farmers do not go bankrupt when initial labor proportions in farming are low (see Appendix, Fig. 8). However, all scenarios show a decrease in global returns when the initial shares of labor allocated to agriculture increase.

Next we assess the impact of interannual variability in water flows on the given water management regime and compare it with a scenario where water resources are used only in the agricultural sector.

Effect of multi-sectoral water use on the resilience of the system to inflow variability (ABM)

The response of the social-ecological system to interannual inflow variability varies depending on the magnitude of the variability and the initial labor allocations of the farmers (Fig. 6a). When farmers are locked into a fisheries dominance regime, global returns decline with increasing variability. The same occurs when there is a

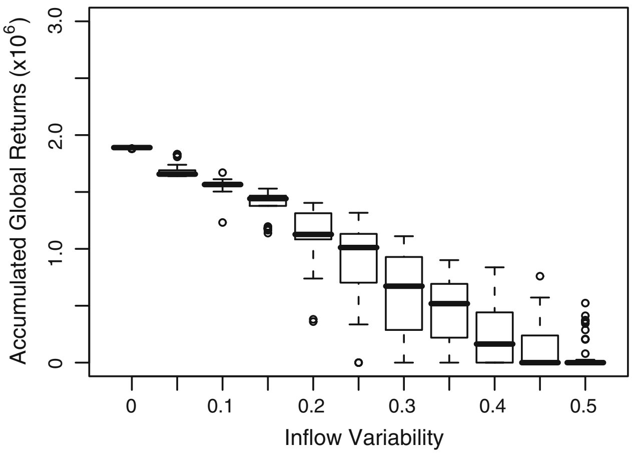

Fig. 7 Global accumulated returns for the scenario with increasing inflow variability when farmers can only engage in agriculture

small initial proportion of labor in agriculture ($L_{A,0} = 0.2$) which provided highest returns under stable inflow conditions. Scenarios in which initial agricultural labor shares are rather high can cope best with variability. In some cases returns even increase with variability. This can be attributed to the fact that failures in agriculture in low water years allow the fisheries and downstream farmers to survive and thus a more mixed regime emerges. Only when variability is larger than 0.25 or 0.35 (for large $L_{A,0} = L_{A,0}$ values) do global returns decrease again. Patterns of labor and thus water allocation to the two sectors change with increasing inflow variability. With stable inflow and high initial labor proportions in agriculture, agriculture dominates with up to 80% and downstream farmers go bankrupt. With inflow variability we see a shift towards more fishing, which allows the downstream farmers to stay in business and compensate for the global losses in agriculture (Fig. 6b). Under variable inflow conditions the midstream farmers have to adjust their activities most by changing from agriculture to fisheries. The transition to a more mixed regime with increasing inflow variability occurs as regular agricultural failures of the midstream farmers encourages them to allocate more labor to fishing. This process creates a positive feedback: more water flows to the lake, thereby sustaining the fish population, which in turn is available for exploitation.

For comparison we analyzed a regime where only agriculture is possible. Here total returns decline continuously until, with high variability they reach zero (Fig. 7). At this point, even upstream farmers close to the inflow, e.g., farmer 3, go bankrupt.

Discussion

We have developed an optimal control and an agent-based modeling approach to assess the conditions under which the management of the trade-off between two water use activities, one agricultural and one non-agricultural, is either optimal on the system level or evolves from the local decisions of multiple agents. Moreover we use the agent-based approach to explore which regime provides highest overall performance and resilience to inflow variability. With the optimization model we show that delivering water to the fisheries is optimal when the value of the water per fish harvested is larger than the amount of water needed to produce an additional fish (Eq. 23). Under a solely economic perspective the water delivery to the fish lake is determined by the ecological properties of the link between the river flow regime and fish reproduction and the price of the fish per water invested and the opportunity costs of agriculture. However, whether the fish population will be conserved also depends on its net growth in relation to the interest rate of the capital received from harvesting (Eq. 25). The higher the value of short term returns, the smaller the equilibrium size of the fish population and thus the harvest.

In the agent-based model the trade-off in water use is not directly managed. Instead, the social-ecological system evolves a water use regime—either mixed or single sector—based on the initial labor allocations to both sectors and the adaptation of individual allocation patterns to local resource conditions. The latter are determined by the locations of farmers along two resource gradients. If the system starts with farmers devoting all their activities to a single sector, the other sector will not develop. This is because the strong dominance of one sector will prevent farmers located in the most suitable positions for the other activity from gaining enough financial resources for its development. However, when the mixed regime evolves global returns and the equality of income distribution are highest. When upstream (with fisheries dominance) or downstream (with agricultural dominance) farmers go bankrupt, and the overall performance of the coupled systems declines significantly.

The two approaches are complementary in that they determine conditions for the coexistence of multiple water use focusing on various aspects of the management of this trade-off under different simplifying assumptions on system structure and management decision-making. Together they inform about relevant factors influencing the establishment and maintenance of integrated water resources management. The OCA provides insights about economic and ecological factors and their interaction in determining the economically optimal water allocation strategy. It is a standard approach often used for the development of natural resource management strategies; however, it is based on a number of critical assumptions: (a) there is complete information on total water availability and fish population dynamics; (b) space does not matter; (c) the future outcomes of all possible choices can be calculated; (d) there is a single manager managing the water and fish resources; (e) previous water use patterns do not matter. Moreover, in the optimization transient dynamics are not considered. With the ABM we relaxed some of those assumptions based on empirical evidence from the case study to shed light onto their impact on the management of water use trade-offs. The ABM thus complements the results of the optimization by exploring conditions that include more details of the actual river basin context such as the resource gradient that favors upstream water users, the lack of mechanisms that enforce a system-wide optimal allocation strategy, or the path dependency of allocation decision-making, and details of the nature of human decision-making. For example, under the current highly uncertain and variable circumstances in the Amudarya River Basin, farmers often do not plan ahead, but rather select their strategies ad hoc in a trial and error fashion based on past experiences or experiences of their peers and the constraints of local resource availability and institutional boundary conditions (personal observation). In the ABM individual agents take decisions based on the past performance of their allocation strategies and engage in a trial and error process to find the optimal strategy mix for their location along the resources gradient. Compared to the macroeconomic optimization in the OCA this searching behavior reflects the incomplete knowledge of individual actors of what is optimal on the local and the system levels and their inertia in changing their water use activities. This learning process and its transient dynamics can lead to suboptimal outcomes when agents do not have enough time or capital to adapt their strategy to the local conditions before going bankrupt. The ABM shows that the development of a multi-sector water management regime depends critically on initial conditions, where lock-in effects will need to be overcome by management interventions. However, including more realism in the ABM comes at a cost of an increase in sensitivity to assumptions on initial values, e.g., initial endowment of an agent, and model structure, which we have addressed by sensitivity analysis.

We further expanded the analysis of water use with the ABM from treating the water resource as static to incorporating resource variability. The ABM allowed us to easily explore the response of the system to interannual variability in water inflow. With multiple water uses and agents that allocate their labor based on individual local experiences the system appeared to be more resilient to disturbances than with single water use. The diversification of livelihood options allows the farmers to take advantage of the fact that the fish stock acts as a buffer in low water years to weather agricultural losses. The fish population on the other hand can survive because reoccurring low water years keep agricultural activities below their maximum level, enhancing fish production and thus creating a positive feedback. The advantage of diversification of water use activities under variable water flow conditions can also be seen in an increase in multiple water use activities of single agents under variable flow conditions as opposed to a collection of agents using a single strategy with diversification only along the resource gradient with no resource variability.

In the Amudarya River Basin, the coupled social-ecological systems are currently locked into an agricultural dominated state that delivers high returns for some, keeping the labor allocations for agriculture and thus the water deliveries for this sector high (Schlüter and Herrfahrdt-Pähle 2007). As in the scenario with high initial proportions of labor allocated to agriculture the fisheries sector does not have a chance to develop and generate returns that can compete for the scarce water resources. A shift to a more balanced regime will require additional measures to overcome the lock-in. Possible strategies include, economic incentives, regulating institutions, or negotiations and analyses to identify possible synergies between irrigation and fisheries (Nguyen-Khoa and Smith 2004). Besides the lock-in effect caused by historical water use preferences, a multitude of other factors can complicate the implementation of a more integrated water management approach, including the lack of scientific, technical and managerial capacity to develop other water use activities or implement water sharing, the transaction costs of switching to other activities, and the constraints of the larger institutional settings and national and international policies.

The increased resilience of a mixed regime to resource variability indicates that it would be useful to create institutions that promote integrated, multi-sector water use to develop adaptation options to changing water flow conditions in the Amudarya River Basin. Water use for irrigation should be constrained so as to provide opportunities for the development of fisheries and other non-agricultural water uses. One step towards achieving a more integrated approach would be to investigate the link between water flows and fish productivity and carefully value and compare the costs and benefits, both in water and monetary terms as well as in terms of creating adaptation options, of the use of water resources for different sectors. A first valuation of the ecosystem services of the deltaic wetlands in the Amudarya River Basin, carried out in relation with the restoration of the Sudoche wetland in the eastern part of the delta, has concluded that the benefits from the wetlands for the population are large enough to justify financial investments into its rehabilitation (GEF/Worldbank 2000). The situation described here for the Amudarya River Basin is symptomatic of that in many other river basins, and thus our findings have broader relevance to those seeking to develop integrated water management approaches.

New forms of water management promote a transition to approaches that move beyond command and control strategies common in technocratic natural resource management regimes, and instead emphasize the need to enhance the resilience and adaptive capacity of river basins and the social ecological systems of which they are part. Such shifts in perspective and management strategies will better enable both people and ecosystems to cope with change (Pahl-Wostl et al. 2008). Diversification of water use by balancing the needs of different water users as demonstrated here can contribute to an enhancement of adaptive capacity and thus resilience. The given models support an assessment of the current situation and trade-offs in the river basin and the identification of options and barriers for an integrated management. Particularly agent-based modeling is increasingly being used in participative settings (Ekasingh and Letcher 2008; Gurung et al. 2006) to support social learning which is critical for the realization of adaptive management approaches. Our results contribute to the growing knowledge of how integrated water management can develop, ecologically, socially, and institutionally.

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Appendix: sensitivity analysis of initial financial reserve

When the initial financial reserve of each farmer at the beginning of the simulation isincreased the losses of upstream farmers in the "fisheries dominance" scenarios can becompensated, farmers stay in business and thus the global returns are higher than withstronger budget constraints (Fig. 8). However, global returns still decrease withincreasing initial preference for agriculture and once the global returns are increased bythe effect described above there is no significant increase in returns with increasing initialfinancial reserve.

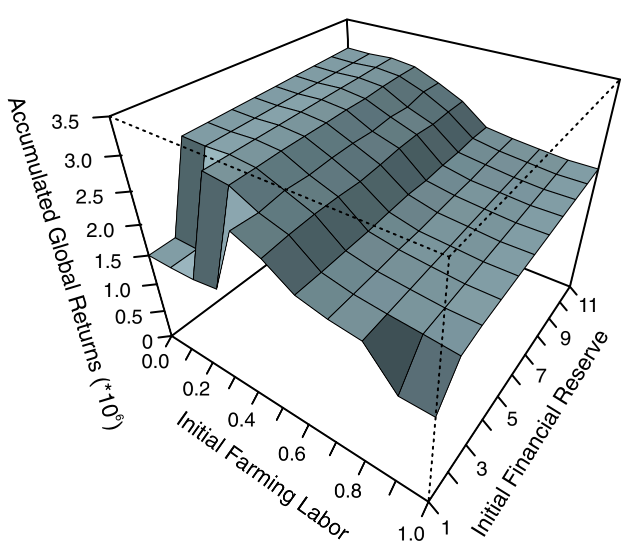

Fig. 8 Global accumulated returns at the end of the simulation with increasing initialproportions of labor allocated to agriculture ($L_{A,0}$) and increasing initial financial reserveof each farmer

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