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# Mechanisms of Resilience in Common-pool Resource Management Systems: an Agent-based Model of Water Use in a River Basin

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ABSTRACT. The concept of resilience is widely promoted as a promising notion to guide new approaches to ecosystem and resource management that try to enhance a system's capacity to cope with change. A variety of mechanisms of resilience specific for different systems have been proposed. In the context of resource management those include but are not limited to the diversity of response options and flexibility of the social system to adaptively respond to changes on an adequate scale. However, implementation of resilience-based management in specific real-world systems has often proven difficult because of a limited understanding of suitable interventions and their impact on the resilience of the coupled social-ecological system. We propose an agent-based modeling approach to explore system characteristics and mechanisms of resilience in a complex resource management system, based on a case study of water use in the Amudarya River, which is a semiarid river basin. Water resources in its delta are used to sustain irrigated agriculture as well as aquatic ecosystems that provide fish and other ecosystem services. The three subsystems of the social-ecological system, i.e., the social system, the irrigation system, and an aquatic ecosystem, are linked by resource flows and the allocation decision making of actors on different levels. Simulation experiments are carried out to compare the resilience of different institutional settings of water management to changes in the variability and uncertainty of water availability. The aim is to investigate the influence of (1) the organizational structure of water management, (2) information on water availability, and (3) the diversity of water uses on the resilience of the system to short and long-term water scarcity. In this paper, the model concept and first simulation results are presented. As a first illustration of the approach the performances of a centralized and a decentralized regime are compared under different scenarios of information on water availability. Under the given conditions of a regularly fluctuating inflow and compliance of agents with orders from a national authority, the centralized system performs better as long as irrigation is the only type of water use. Diversification of resource use, e.g., irrigation and fishing, increases the performance of the decentralized regime and the resilience of both. Systematic analysis of the performance of different system structures will help to identify properties and mechanisms of resilience. This understanding will be valuable for the identification, development, and evaluation of management interventions in specific river basins.

Key Words: *adaptive management; agent-based model; Amudarya; diversification; fisheries; irrigation; mechanism; resilience; river basin; social-ecological system; water use.*

## INTRODUCTION

In recent years, resilience has been promoted as a concept to guide the integrative study and management of social-ecological systems. Resilience is a property that reflects the capacity of a system to cope with disturbance and reorganize while undergoing change to maintain structure and functioning (Walker et al. 2004). In complex ecosystem or resource management contexts it is often the nature of the interactions between the social and the ecological or resource system that determines the system’s capacity to adapt to change. However, the role of linkages between the social and ecological systems for resilience and factors and mechanisms of resilience in a specific management context are still little understood (Anderies et al. 2004, Perrings 2006). Most resilience studies in real world systems are descriptive, empirical, ex-post analyses of systems that underwent change (Janssen

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et al. 2006). To our knowledge to date little formal analysis of properties and mechanisms that influence a coupled system's resilience has been carried out, with the exception of models for reasonably well defined ecosystems, e.g., Carpenter et al. 1999, Janssen et al. 2000, 2004, Anderies 2000, Janssen 2001, Anderies et al. 2002). Modeling approaches, especially bottom-up approaches, are valuable tools to explore mechanisms on lower levels that might account for the emergence of system level characteristics such as resilience. Based on the management context of the Amudarya River delta, we propose a bottom-up modeling approach to explore structural characteristics and mechanisms that influence the resilience of its social-ecological system to uncertainty and variability in water availability.

The concept of resilience originated in ecology (Holling 1973) where it constitutes one of several stability properties of ecosystems. Growing recognition that ecosystem management has to explicitly consider the human dimension and the linkages between the social and ecological system has shifted the focus of resilience analysis to social-ecological systems (SES). In SES the dynamics of the natural and the social systems are closely intertwined and dependent on each other. They consist of both designed and self-organized components (Anderies et al. 2004) and behave as complex adaptive systems (Folke et al. 2005). For SES it is characteristic that some of the interdependent relationships among humans are mediated through interactions with the biophysical environment or other nonhuman units, e.g., exploitation of a fish stock by several fishers. Interactions between biophysical and social processes, e.g., response of the social system to perceived changes in the environment and visa-versa, determine the capacity of the SES to adaptively respond to stress.

In ecological systems resilience benefits from diversity (Tilman et al. 1997, Levin et al. 1998, Elmqvist et al. 2003, Folke et al. 2004). Diversity may contribute to ecological resilience by adding redundancy of functions within and across scales (Peterson et al. 1998). Investigations of change in social systems have suggested resilience mechanisms similar to those in ecological systems such as the capacity of the social system to maintain institutional diversity and diversity amongst assets (Perrings 2006), or to sustain memory (Anderies et al. 2004). However, social systems are distinctly different from ecological systems given the information-processing capability of human actors, and their ability to engage in purposeful action and reflexive learning. Mechanisms specific for social systems are for example, the capacity to adapt rules when ecological conditions change (Anderies et al. 2004), and to develop a process of experimenting systematically with alternative institutional configurations. Model-based analyses of the behavior of SES have often focused on either the social or ecological component. A clear framework for formal analysis of the coupled systems is still missing (Anderies et al. 2002, 2006, Janssen et al. 2006). Few studies so far explicitly consider the coupled system and how the dynamic nature of the linkages between the ecological and social systems affects resilience. Given the importance of feedbacks between the two systems for learning and adaptation we argue that more systematic analysis of those linkages and their implications is needed.

We propose a bottom-up modeling approach that explicitly addresses the two-way interactions between the human actors represented by their resource allocation decision making and the environmental system in a river basin represented by water resources and aquatic ecosystems. The goal is to use the model to test various assumptions on resilience mechanisms in a systematic way. Agent-based modeling (ABM) approaches are especially suitable methods for the analysis of human-environment interactions in environmental management (Janssen 2002, Gotts et al. 2003, Bousquet and LePage 2004, Barreteau et al. 2004, Janssen and Ostrom 2005) because they allow explicit consideration of changes in the behavior of individual actors that arise from perceived changes in the natural or social environment. ABMs have the advantage that social and institutional relations between human actors can be represented at different scales. They have been applied to the study of irrigation systems e.g. by Barreteau et al. (2004) who concluded that they constitute a suitable architecture to study theoretically irrigated systems's viability using simulation.

Of the many potential factors that affect resilience of the social-ecological system in a river basin we want to focus on structural characteristics and functional mechanisms of different water management regimes. They are characterized by the degree of distribution of decision making expressed as the number of actors and organizational levels involved in water allocation decisions, the degree of coordination among actors, the diversity of resource use, and the level of information of actors. Our interest in the effect of those characteristics is motivated by the hypothesis that devolution of decision making in combination with strong cross-scale interactions between different levels of management, i.e., multilevel governance, can make systems more flexible and adaptive to change and thus enhance resilience and sustainability (Pahl-Wostl 2002, Folke et al. 2005, Lebel et al. 2006, Walker et al. 2006, Pahl-Wostl et al. 2007).

In this paper we present the conceptual foundations and structure of the agent-based model and an example of its implementation. The main goal is to present the potentials and limitations of using an agent-based modeling approach to study the behavior of SES and enhance our understanding of the dynamics of system properties such as resilience. The context of the water management system is taken from the irrigation system in the delta area of the Amudarya River in Central Asia. The social-ecological system is modeled in a stylized way focusing on major elements of the system to allow for systematic analysis of the effect of changes in the structure and institutions of the social system on system resilience (for other examples see Carpenter et al. 1999). To illustrate the approach we compare two examples of extremely simplified management regimes, i.e., a centralized vs. a decentralized regime, and test the effect of uncertainty of water availability and diversification of water use on the resilience of both regimes. We use the performance, e.g. agricultural and fish production, of a regime under fluctuating resource availability as a proxy for its resilience. It is assumed that measures of system performance indicate the maintenance or loss of functioning. In a real management context identification of indicators of resilience and decisions as to which functions are desirable and should be retained ultimately have to be carried out by the actors themselves (see also Lebel et al. 2006). We use resilience in a non normative way as a measure of the capacity of the given social system to retain the functionality of the agricultural production system, to sustain all its members and the aquatic ecosystem. The comparison of the two management extremes will help to distinguish structural attributes and functional characteristics of the interactions of actors with resources, the ecosystem, and other actors that are important for an adaptive response of the social-ecological system to uncertainty and change in water availability.

The remainder of the paper is structured as follows. After a short description of the social-ecological system that serves as a case study for this modeling exercise, the general structure of the model is described. It is then applied to a simple experimental setting of two different water management regimes. Their performances under different scenarios of water use and availability of information of water availability are compared. Finally, the results of this experiment, the general model structure, and model assumptions are discussed in view of the use of the model to systematically analyze mechanisms of resilience and conclusions are drawn.

## THE SOCIAL-ECOLOGICAL SYSTEM: WATER USE IN THE AMUDARYA RIVER BASIN

The irrigation systems in the Amudarya River basin are among the most highly developed and complex irrigation systems in the world (Fig. 1). More than 90% of the surface water resources are currently used for irrigation. Water distribution in the delta area is controlled by a reservoir at its entrance and a network of canals diverting water to the irrigation areas, farms, and fields. The inflow to the delta varies strongly interannually, e.g., between 17 km$^3$ in 2001 and 59 km$^3$ in 1998. In high and mean water years, water availability is sufficient to serve irrigation needs of all users in the delta. However, in low water years the demand exceeds availability, and users experience water shortages. In high water years, excess water is diverted into an interconnected system of deltaic lakes to store it for later use or into depressions in the desert. A variety of agricultural crops are cultivated, but cotton, wheat, and rice dominate. The massive expansion of irrigated agriculture has caused severe degradation of riverine ecosystems and impacted the economic and health situation of the local human population. In the delta area of the river, water withdrawals for irrigation conflict with the supply of water to sustain semiarid deltaic ecosystems. The livelihoods of the local human population depend to a large extent on services provided by those ecosystems, e.g., by deltaic lakes in the form of fish, livestock fodder, and habitat for muskrat and bird hunting, or riverine Tugai forests for wood, pasture, and medicinal plants. In this harsh semiarid environment, the linkages between the social and the ecological system are very strong. Current mono-purpose water management has caused severe degradation of the ecosystems and livelihood options of the local human population. At present water allocation is managed in a centralized way with the national authorities of the riverine countries taking all major allocation decisions. Water needs of sectors other than agriculture, e.g., industry, fish farming, etc., are only marginally considered.

The given situation in the Amudarya River delta is an interesting case for the study of resilience mechanisms of coupled social-ecological systems. Both, water resources and harvested fish populations in the deltaic lakes are common pool resources. Thus, there is a need for collective action to manage the common goods (Ostrom 1990). Historically, top-down approaches with strong involvement of the government have been considered appropriate in common goods management to prevent overuse of the resources. In water management, especially in irrigated catchments, there is traditionally substantial involvement of the government (Dinar et al. 1997). However, many large-scale irrigation schemes have failed (Ostrom 1992). Unresolved tradeoffs in water allocation between different users have often caused strong degradation of ecosystems with severe consequences for the social-ecological system as a whole. The new realities of water management in the Amudarya River basin created by the recent ongoing political and economic changes have lead to the introduction of some bottom-up management elements such as water user associations into the otherwise top-down managed system (Yalcin and Mollinga 2006).

## THE MODEL

The social-ecological system in the delta area is represented by three subsystems: the social system, the irrigation system, and the aquatic ecosystem (Fig. 2). The available water resources support both the irrigation system and the aquatic ecosystem. The aquatic ecosystem is modeled by a lake inhabited by a commercially valuable fish species. Water availability in the system is determined by the highly variable monthly inflow to the delta. The water is used to produce crops, i.e., irrigation system, and to sustain viable fish populations in the lake. The latter depend on inflow of offspring with the water inflow to the lake from more suitable habitats upstream. The social system is composed of actors at different levels that interact with other actors, the irrigation system, and the ecological system, and take water allocation decisions to sustain their agricultural production system or the aquatic ecosystem. Actors engage in crop production and exploit the fish populations. The actors determine water and fish extraction levels and timing based on their targeted yields, expected water availability, their knowledge on the state and dynamics of the resources, their expectations on the behavior of other actors in the system, and their individual goals.

The subsystems are tightly linked through the exchange of resources, e.g., water, crops, and fish, mediated by the actors' decisions to use or allocate them. Withdrawal of water and fish resources by the actors establishes an indirect relation between the actors in the system because of their location relative to the water flow and their access to the fish resources (Fig. 3). An actor that comes to use the resource will find it influenced, i.e., less water, less fish, by the ones that have used it before in time or space (Anderies et al. 2004). The interactions between the social system and the resources represent the structure of management, i.e., the governance system, which will be varied and investigated with the model.

Figure 3 gives an overview of the general structure of the model and the distribution of the resources and agents in space. This spatial arrangement roughly corresponds to the irrigation system in the Amudarya delta. Actors are represented at different national and local organizational levels. They can be individuals such as farmers, or regulators such as a national authority. Agents at different levels have different goals and different information on resource availability. They make decisions on the amount of resource extraction and collect information on resources dynamics and other agents' behavior. On the local level farmers extract water to irrigate their fields according to their location along the river. They benefit from direct use of the water for irrigated agriculture and indirect use through the exploitation of the fish resources. The success of individual agents, the overall social system, as well as the state of the human-used ecosystem depends on local water availability.

In the following the representations of the water resources and three subsystems are explained in more detail.

**Fig. 1.** Map of the Amudarya River delta in Central Asia. The delta is located in the Republic of Uzbekistan, Turkmenistan, and the Autonomous Republic of Karakalpakstan (Uzbekistan). Water distribution in the delta region is largely determined by the Tyuyamuyun system of single-year reservoirs at the entrance to the delta. Water is diverted into a vast network of irrigation and drainage canals. The lakes in the northern part of the delta are intensively used for fishing. Source: modified from Aral Sea GIS (Micklin et al. 1998).

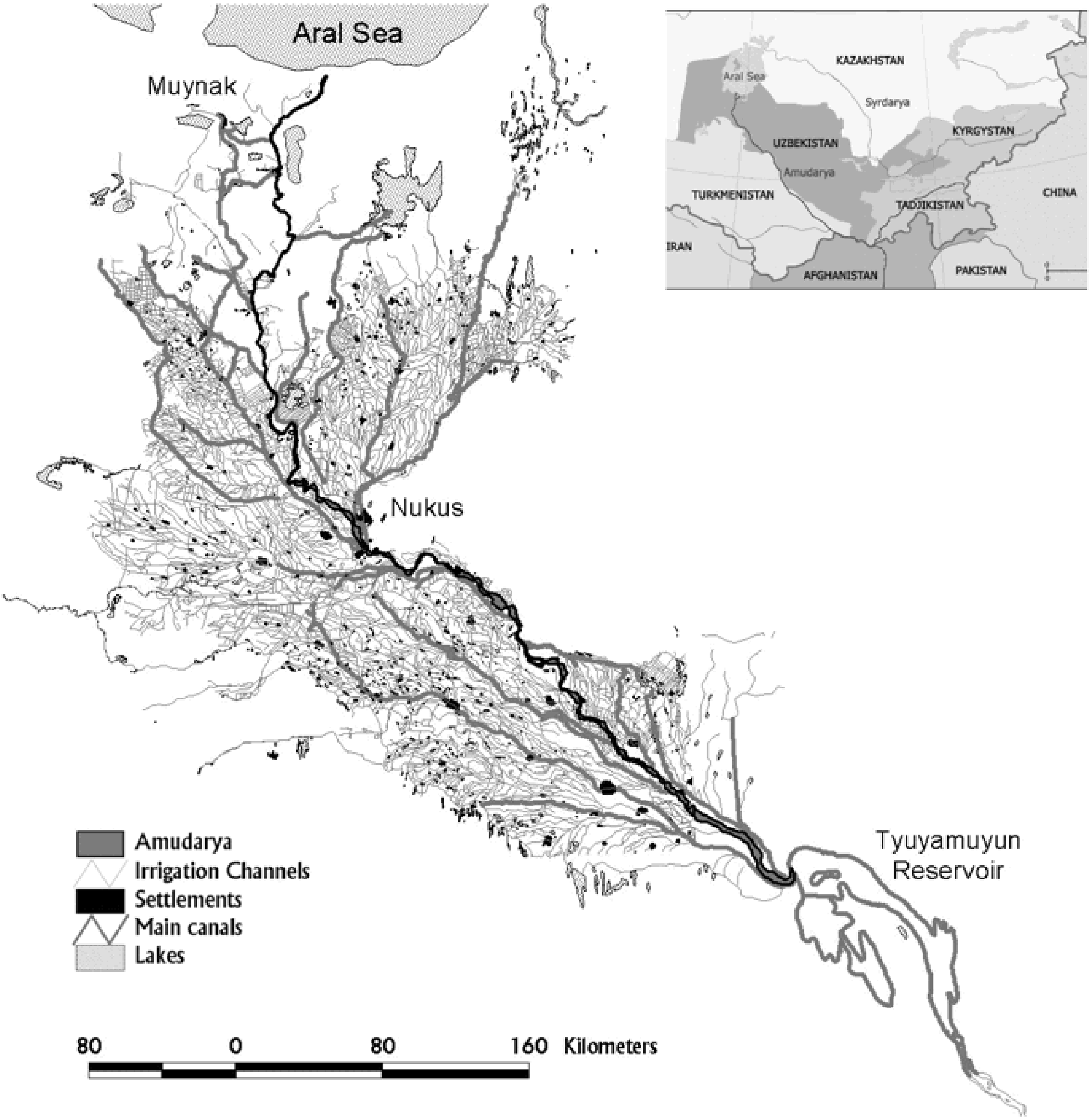
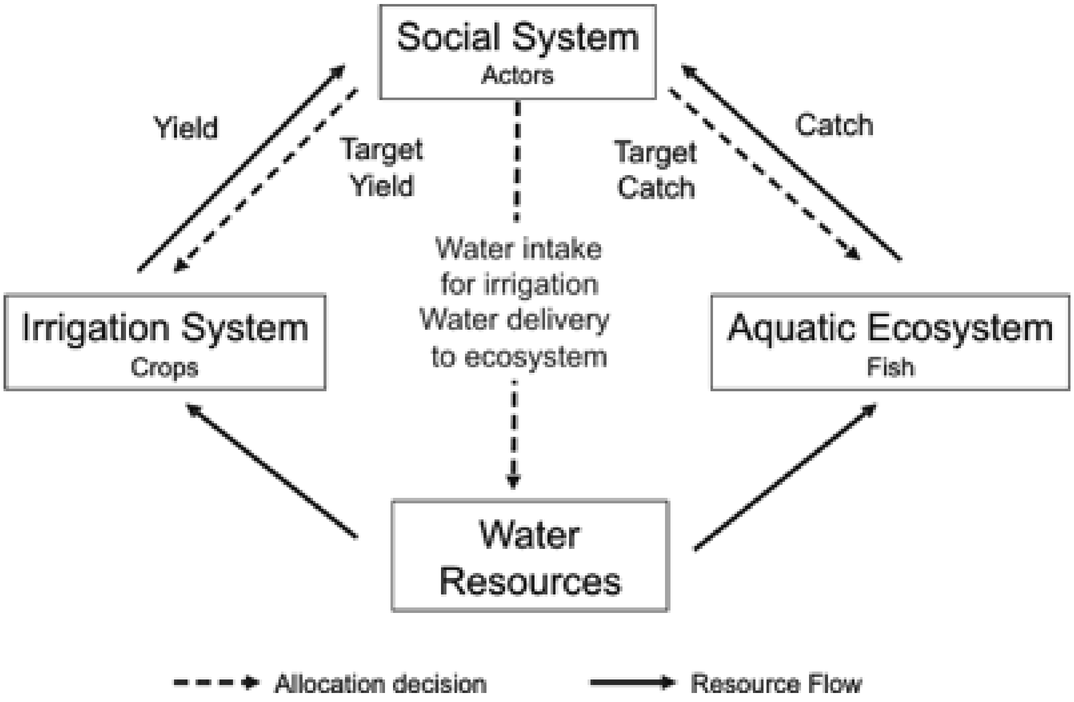


**Fig. 2.** Conceptual model of the social-ecological system in the river delta showing the major linkages between the water resources that supply the irrigation system and the aquatic ecosystem, which both support the social system.



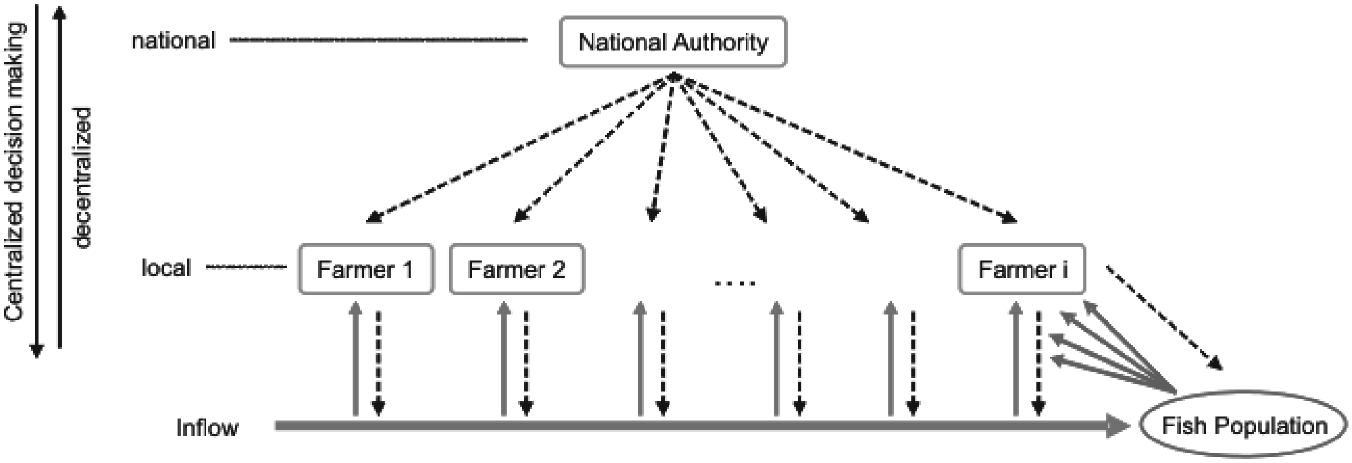
## Water resources

In the current version of the model the water resources are considered as a one-dimensional downstream flow of water that is tapped sequentially by each farmer. Inflow to the delta area is given by the river flow to the delta from upstream modeled by a 15–year characteristic historical monthly runoff time series (Schlüter et al. 2005, Schlüter et al. 2006). Water entering the delta directly reaches the first farmer. In this version there is no reservoir for water storage. The aquatic ecosystem in a lake that is located downstream of the irrigation area receives the flow left after all farmers extracted the amount of water allocated to them.

## Irrigation system and crop production

The water extracted from the river by the farmers is used to irrigate the number of fields determined by themselves or the national authority at the beginning of each season. During the vegetation season from April to September, farmers irrigate their fields every month. They withdraw water according to the allocation schemes determined at the beginning of the season. If the amount of water actually reaching the fields is less than the amount needed to irrigate the given number of fields, then water stress occurs. Water stress accumulates over the season and affects yields according to the following relationship (Eq. 1):

**Fig. 3.** The general structure of the model, which is then modified for each specific model implementation, e.g., the centralized and the decentralized models presented here. Agents take water allocation decisions at both global and local levels. Farmers extract water resources for irrigation sequentially according to their location along the river. All farmers can additionally access fish resources in the lake, however downstream farmers can access them prior to upstream farmers.



$$Y_{j,t} = Y_{\max} * N_{F,j} * \left(\sum_{m=4}^{9} \frac{V_{R,j,m}}{V_{D,j,m}} / 6\right) \quad (1)$$

where $Y_{j,t}$ = yield of farmer $j$ at time $t$; $Y_{max}$= maximum yield; $N_{F,j}$=number of fields of farmer $j$; $V_{R,m}$=received water volume in month $m$; and $V_{D,m}$ = demanded water volume in month $m$.

This linear relationship of water deficit to yield is an approximation that does not take into account that the plants are affected by water stress to different degrees depending on their development stage and the severity of water scarcity. For cotton, the decrease in yield with decrease in water supply is not totally linear, rather, it decreases slightly slower than the water supply. Thus, in the case of cotton, the model overestimates the effect of water stress on yield to some extent. For other crops, such as maize, it is the other way around.

## Aquatic ecosystem and fish populations

The fish population model is a discrete-time Leslie matrix model of an age-structured population. The zero age class contains fish born by the age classes 5–12 as well as larvae, which have migrated into the lake from upstream (Eq. 2). The reproduction rate is density dependent. Inflow of larvae from upstream can only take place if the river flow to the lake in May is above a certain threshold. Survival of the fish in the juvenile age classes 1–4 is density dependent because individuals compete for the same resources. Only adult fish from age class 5 onwards are harvested. All fish older than 12 yr die.

$$\begin{aligned} N_{0,t} &= I_t + \sum_{i=5}^{12} \alpha * e^{-\sigma \sum_{i=5}^{12} N_{i,t-1}} * N_{i,t-1} \\ N_{n,t} &= (1-\beta_{n-1}) N_{n-1,t-1} - \gamma_{juv} * \left(\sum_{i=0}^{4} N_{i,t-1}\right)^2 \quad \text{if } n \in (1,2,3,4) \\ N_{n,t} &= (1-\beta_{n-1}) N_{n-1,t-1} \quad \text{if } n \in (5,\ldots,12) \end{aligned} \quad (2)$$

where $N_{0,t}$=number of individuals in 0 age class at time $t$; $N_{n,t}$=number of individuals in $n$ age class at time t; $I_t$=immigration of offspring at time $t$; α=birth rate, σ=strength of density dependence; β= environmental mortality; γ=density dependent mortality.

The model was calibrated to reflect the current nonviable state of fish populations in the aquatic ecosystems of the northern delta. Due to severe changes in the hydrological regime and a massive loss of spawning habitats, fish populations in the deltaic lakes cannot produce sufficient offspring to sustain their populations. Hence, they are dependent on inflow of offspring from upstream (Joldasova et al. 2002). This natural stocking mechanism creates exploitable fish populations in the lakes (Joldasova et al. 2003). The fish model was thus parameterized such that population growth is dependent on sufficient inflow of larvae. The inflow of larvae is dependent on the water inflow to the lake in May, which is the month of reproduction. The number of larvae transported into the lake is proportional to the water volume after the flow has passed a threshold value. Flow velocity below the threshold is too low to ensure the survival of the eggs and larvae.

## Social system and agents

The choice of how to represent the behavior of human actors in an agent-based model has a strong influence on model results. Gintis (2000) highlighted the implications of increasingly relaxing assumptions of the rational actor paradigm on the outcome of strategic interactions. Hare and Pahl-Wostl (2001) analyzed the impact of different behavioral types on simulation outcomes in a model that investigated the effectiveness of policy measures in influencing farmer behavior. They showed that the sensitivity of model results to structural uncertainties in the social model largely exceeded the effect of parameter uncertainties in the natural system. In this paper we have chosen an approach that aims at representing the behavior of rational agents in what is generally considered a more realistic approach than the rational actor paradigm from neoclassical economics. It is assumed that actors behave boundedly rational (Simon 1957) and because of limited information processing capacity rely on heuristics or hypotheses to guide their behavior (Ostrom et al. 1994, Ostrom 1999). The individual actor’s heuristics are based on his past experience, knowledge of resources dynamics, expected water availability, and the expected behavior of other actors. Agents use a form of inductive reasoning (Deadman et al. 2000). They tend to stick to their past behavior and vary it only slightly as long as it produces satisfying results. Hence, agents are “satisficers” rather than optimizers. Individual farmers engage in a process of trial and error to determine their optimal harvest level or to reach harvest levels that satisfy their basic needs. Collective actors, i.e., national authority, aim to achieve global agricultural production goals. The heuristics have been developed based on empirical knowledge from the case study river basin and using theoretical approaches of bounded rationality (Gigerenzer and Selten 2001, Ebenhoeh and Pahl-Wostl 2007).

In the current water management regime farmers in the Amudarya River basin are informed by the authorities about how much water they will receive to irrigate the number of fields and crops that have been determined based on state cropping plans. The government makes predictions on water availability by comparing current flow patterns with flow patterns observed in the past. Farmers have only little information on expected water availability, which in combination with wrong planning of the government can lead to severe crop losses. The heuristics for the decision making of the government and the farmer agents have been based on those empirical observations as well as the assumptions that agents have only limited information processing capacities and might follow other goals besides profit maximization, e.g. maintenance of a certain income level.

In the following the functions for the estimation of water availability and the calculation of global and individual returns are given. The actors’ decision rules to choose the number of fields to irrigate are explained later when describing the different regimes.

## Estimation of water availability

Agents estimate water availability each season by evaluating the observed water flows from previous years during the peak month of July, i.e., either by the national authority at the inflow to the delta, i.e., a centralized regime, or by farmers along the irrigation network, i.e., a decentralized regime (Eq. 3). Because of different access to information or memory capacities of the agents, the number of past years included in the estimation of the current water availability can vary. These differences are incorporated into Eq. 3 through the coefficient delta raised to the power of the number of past years, representing the weight of preceding years. It decreases with distance from the current year. If delta = 1 the expected water availability is the arithmetic mean of the years up to the current year, and if delta << 1 water availability of the immediately preceding years dominate the prediction (Fig. 4). The smaller delta the more the estimates try to capture the fluctuations in the availability of the resource. Delta is a measure of the uncertainty the agents face in determining the amount of irrigated land and thus the agricultural investment for the current season.

$$V_E^7(t)=\frac{\sum_{i=0}^{t-1}\delta^i * V_R^7(t-1-i)}{\sum_{i=0}^{t-1}\delta^i} \qquad (3)$$

where $V^7_E$=expected water volume in month 7; $V^7_R$= received water volume in month 7; $\delta$=strength of memory of water availability in past years.

### Accumulation of financial capital: local and global returns

At the end of the season, each farmer determines his individual accumulated returns, i.e., local returns/ financial reserve of the farmer, which is the accumulated return from the previous year plus the current agricultural yield and fish catch reduced by the costs for irrigation and consumption in the current year as shown in Eq. 4. One unit of fish is equivalent to 10 units of agricultural yield (scaling factor $\lambda$ = 10), which reflects the empirical relationship of relative incomes from the two types of resources in the study area.

$$R_{j,t} = R_{j,t-1} + Y_{j,t} + \lambda * H_{j,t} - C_{I,j,t} - C_{C,j,t} \qquad (4)$$

where $R_{j,t}$=accumulated local returns of farmer j at time t; $Y_{j,t}$=yield of farmer j at time t; $\lambda$=scaling factor for income from fish catch; $H_{j,t}$=fish catch of farmer I at time t; $C_{I,j,t}$=irrigation costs of farmer I at time t; $C_{C,j,t}$=consumption costs of farmer j at time t.

The irrigation costs are fixed costs for the irrigation of a standard field with the standard crop, i.e., 5 units/field, multiplied by the number of fields irrigated. Consumption covers the annual expenses of a household independent of any agricultural or fishing activity. It is assumed constant and the same for each household, i.e., 40 units/yr. Consumption reflects the minimum amount of resources the household needs to survive. It thus cannot be reduced in low water years.

The global accumulated returns, i.e., financial reserves of the national authority, are determined as follows (Eq. 5). Note that income from fishing is not included in the global returns, because fishing activities are local subsistence activities and returns remain with the individual farmers. However, they enable the farmer to invest more into agriculture and thus indirectly influence global returns.

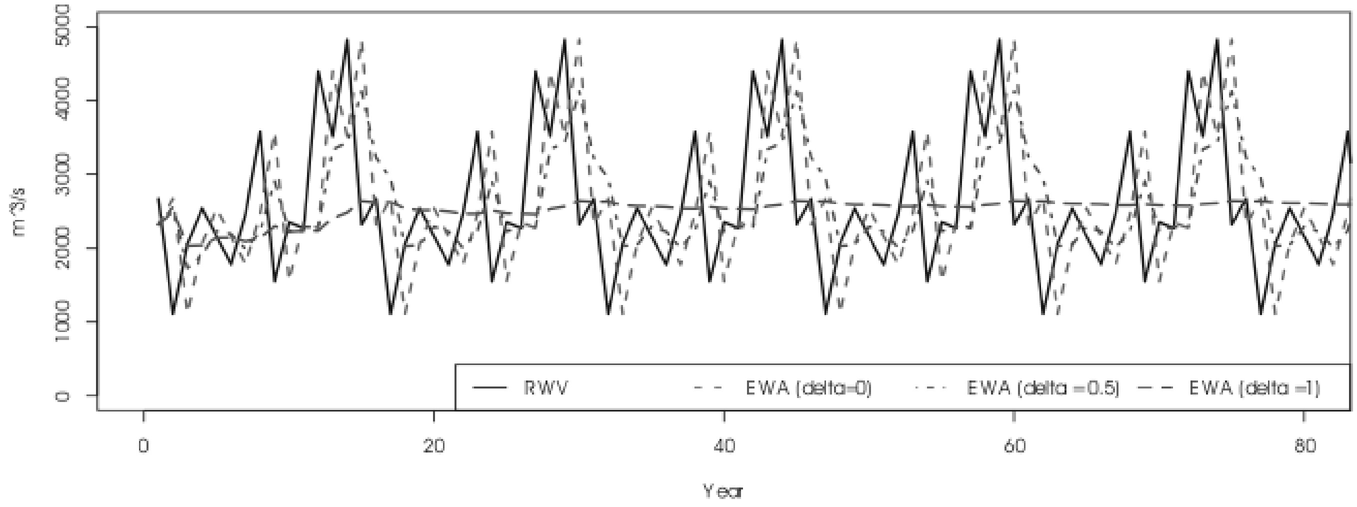
$$R_{total,t} = R_{total,t-1} + Y_{total,t} - C_{I,total,t} - C_{C,total,t} \qquad (5)$$

where $R_{total,t}$=global returns at time t; $C_{I,total}$=sum of irrigation costs of all farmers; $C_{C,total}$=sum of consumption of all farmers; $Y_{total}$=sum of yields of all farmers.

## APPLICATION

In the following section, implementations of simplified centralized and decentralized management regimes are presented. In a centralized, top-down water management regime, the national authority at the global level formulates an allocation strategy, which is motivated by the aim to maximize global agricultural production. Farmers execute the orders from the national authority and irrigate the assigned number of fields. The national authority does not consider fishing as an additional income source. Farmers are free to fish in their spare time; however, the returns from this activity remain with the farmer and are not available for farming investments of the national authority. This regime caricatures features of the current water management practices in the river basin. In a decentralized, bottom-up management regime, on the contrary, the individual farmers themselves determine their strategies of water extraction aimed at increasing their local agricultural production. In the simplest case of open access to the water resources the global water allocation scheme emerges from the actions of the individuals. Subsistence fishing contributes to the farmer’s individual income.

**Fig. 4.** Prediction of expected water availability with delta = 0, 0.5 and 1 compared to real water flows during the peak month, i.e., July of each year.



Both regimes are compared as to their local and global performance under different scenarios of information on water availability. A reference run in which the national authority has complete information on water availability in July was carried out for comparison. The quality of information on past water flows influences the quality of the prediction of expected water availability in the current year and thus the actor's response to variability in water availability and his success in irrigation. Uncertainty of water availability is a major challenge actors in the Amudarya River basin have to deal with. Scenarios run for 200 yr, and scenarios of both the centralized and decentralized models without fishing activities of the farmers will be presented to compare the effects of the different governance regimes on performance. An analysis of the effect of fishing follows.

## Allocation and fishing decision making in the centralized and decentralized regimes

Figures 5 and 6 show activity diagrams of the centralized (Fig. 5) and the decentralized (Fig 6.) models. The agents make their decisions on the number of fields to irrigate each season based on their assessment of water availability and the financial resources available to them. In the centralized regime (Fig. 5) the national authority determines how many fields can be irrigated with the expected amount of water, and given that it has enough financial reserves, equally distributes the amounts of water to withdraw for irrigation of the assigned number of fields to the farmers. If it is not sufficient, the national authority reduces the number of fields to the amount that can be financed. Contrary to the national authority farmers in the decentralized regime (Fig. 6) do not have information on real flows in the river and thus have to base their assessment of water availability on observations of the amounts of water they received in the past. In part this corresponds to reality since individual farmers do not have the possibility to measure water flows at the entrance to the delta, however, they most likely do observe real water availability at their location with simple means. Farmers try to determine their realistic limits to water withdrawal by trial and error. Besides assessing local water availability individual farmers also assess their personal income situation. If the past yield is below the minimum income requirements the farmer will increase the number of fields hoping that in the current year water availability will be higher again, but also risking of losing his investment to irrigate those fields. If his demands have not been met in the previous year but his income needs have been satisfied he will not risk and rather irrigate the number of fields suitable for the amount of water he expects. Again, the amount of fields irrigated is constrained by the financial reserves of the individual agent. Besides, there is an upper limit to the number of fields an individual farmer, in the decentralized version, or the total number of fields the national authority, in the centralized version, can irrigate.

All farmers can fish at no cost in their spare time without any effect on their agricultural activities. The last farmer downstream can access the fish resources first, because he is located closest to the lake. The other farmers access the lake in order of their distance from the lake. Each farmer tries to catch as many fish as given by the fixed target catch level, i.e., number of fish/yr*farmer. All farmers have the same target catch level. Fish are caught randomly from one of the adult age classes. If there are no fish left in the selected age class the farmer has an unsuccessful attempt to catch fish.

At the end of each season, farmers harvest the fields and in some scenarios they fish. The local and global returns are assessed and added to the financial reserve.

## Performance of the centralized and decentralized regimes without fishing

Figures 7a and 7b show the global accumulated returns at the end of the simulation for the different delta scenarios with changes in the maximum total number of fields, i.e., centralized, or maximum number of fields/farmer, i.e., decentralized. The maximum number of fields/farmer (maxfields) in the decentralized regime determines the maximum amount of water one farmer can withdraw for irrigation and thus the maximum returns he can receive. It can be seen that the global accumulated returns are higher for the centralized regime for most values of delta and maxnumfields. In both regimes the performance increases with an increase in quality of estimation of water availability (delta). However, although this is linear in the centralized case, highest performance in the decentralized case are with intermediate values of delta, except for high maxfield values. It can also be seen that with low deltas both regimes break down. Although in the centralized case the breakdown only occurs with delta <= 0.2, in the decentralized case breakdown happens with delta <= 0.4, depending on the maximum number of fields/farmer. The maximum global accumulated return in the centralized model with delta = 1 is 8045. This is still half as much as with perfect knowledge on water availability in July (16581).

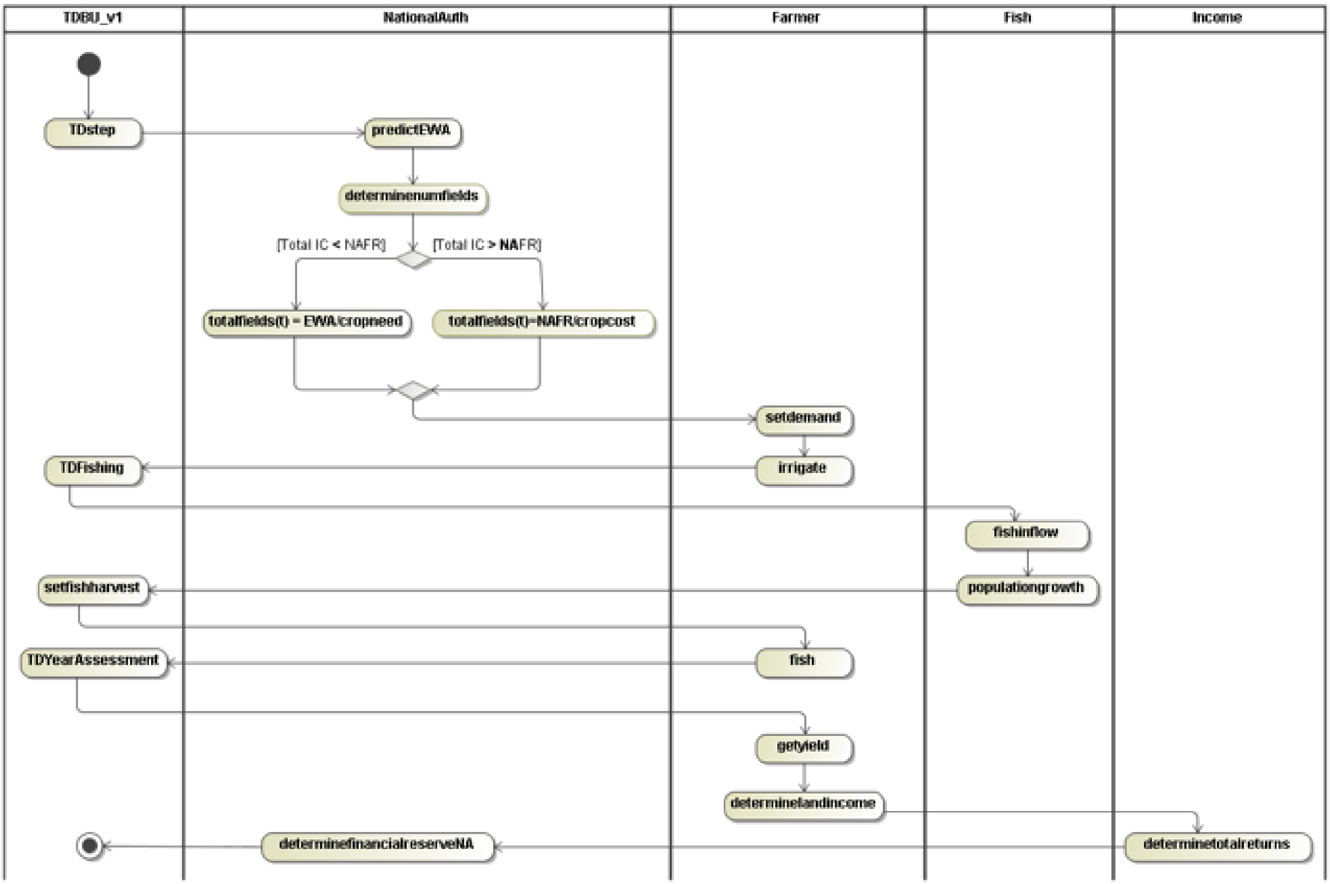
The increase in accumulated global returns with delta can be explained by the better estimation of number of fields to irrigate which increases returns on irrigation costs. Total yields remain almost equal for delta > 0.1 (centralized) and delta > 0.5 (decentralized). The breakdown in the low delta scenarios occurs because losses have reduced the individual or global financial reserves to an extent that there is no financial capital left to sustain consumption and provide investment for the next irrigation season.

The maximum number of fields that the national authority can irrigate does not have an effect on the outcome above a value of approximately 140 fields. A total of 72 fields that produce maximum yield are needed to compensate for consumption and irrigation costs/yr in both regimes. However, due to imprecise estimation of water availability maximum yield cannot be achieved on all fields. In the decentralized regime, the maximum number of fields each farmer can irrigate affects total returns up to a value of 70 fields/farmer. With high maximum numbers of fields/farmer, the system becomes more like a single user system, which is similar to a centralized regime, because the first few farmers upstream can use most of the water. With intermediate number of fields/farmer, e.g., 35 – 55 fields/farmer, and delta values between 0.3 and 0.6, the system performance is very low. In those cases the net losses in low water years are higher than the net gains in high water years, often because a farmer with intermediate income crossed a critical threshold to sustain his irrigation and went out of business. This causes the total performance to decrease.

Besides the maximum number of fields a farmer can irrigate, outcomes of the decentralized regime are sensitive to the minimum yield a farmer uses as a threshold for a decision to increase the number of irrigation fields. The minimum yield requirement is an indicator of the risk a farmer is willing to take and is discussed in more detail in the annex.

The distribution of yields of individual farmers strongly varies with delta as well as between the two regimes (Fig. 8). Generally, yields are more equally distributed among upstream and downstream

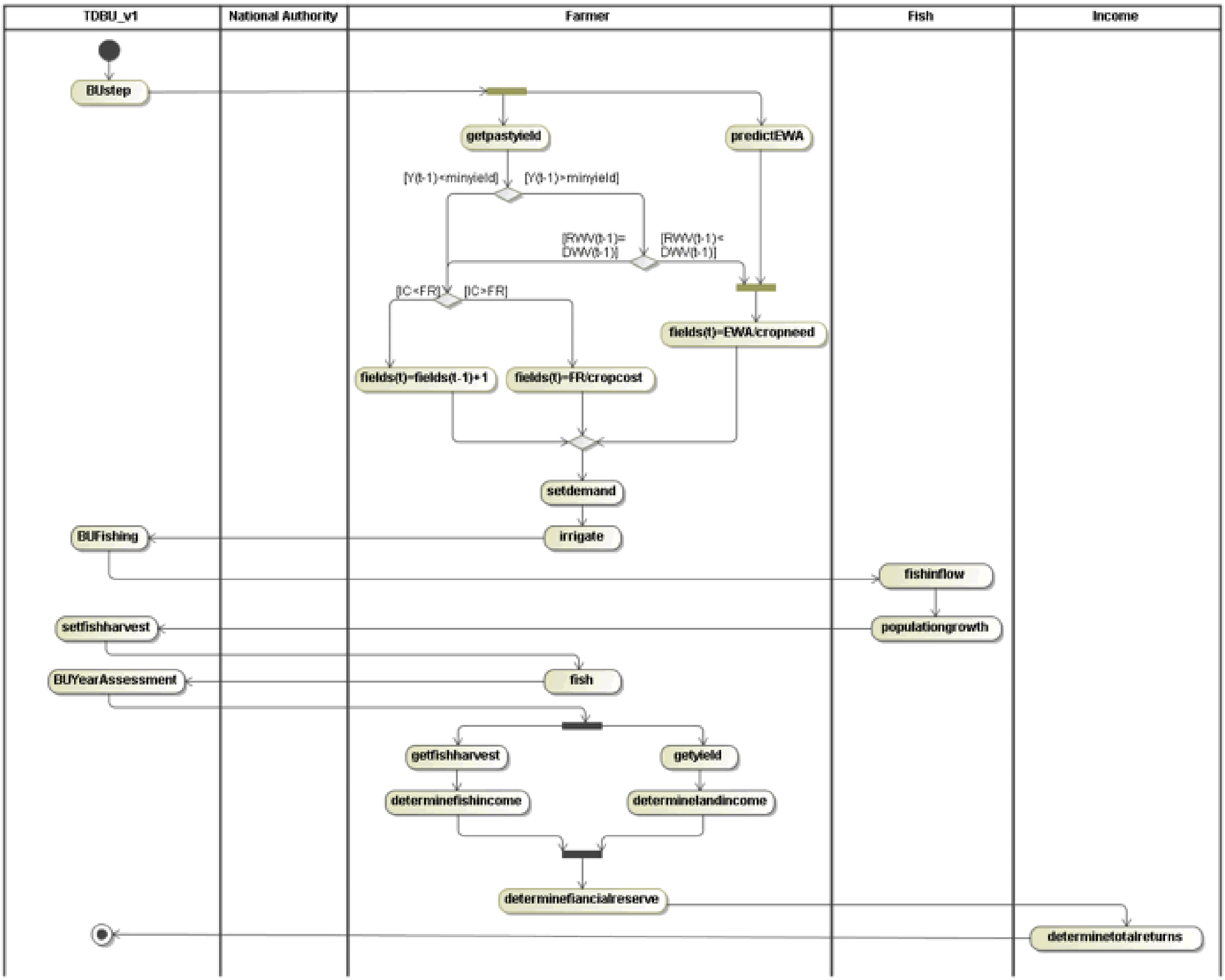
**Fig. 5.** Activity diagram of the centralized model. Sequence of activities within 1 yr (t). EWA(t)= expected water availability in mo 7 of yr t, RWV(t)= requested water volume in mo 7 of yr t, Total IC = total costs of irrigating the total amount of fields, NAFR = Financial Reserve of the National Authority, cropneed = water needed to irrigate one field of the respective crop, and cropcost = cost of cultivating the crop on one field.



farmers in the centralized regime. This is in the nature of the allocation mechanisms, which in the centralized regime allocates resources equally to all farmers. Nevertheless, inaccurate estimations of water availability by the national authority affect the downstream farmers first, lowering their individual performance and making it more variable. With the low quality assessment of water availability, i.e., delta = 0 and 0.1, farmers obtain yields only in single years, mainly during the beginning of the simulation. With delta = 1 the number of irrigated fields converges to an average value, which is lower and has stronger variations the further downstream a farmer is located. However, since farmers receive all capital they need to irrigate their fields from the national authority they can plant even if their individual financial reserves would be too low.

In the decentralized model, benefits from resource use are distributed very unevenly. The first three farmers can produce high yields no matter how good their estimation of water availability. Yields of the upstream farmers are much higher than the downstream ones and much higher, i.e., up to 3.5 times for farmer 1, than in the centralized model.

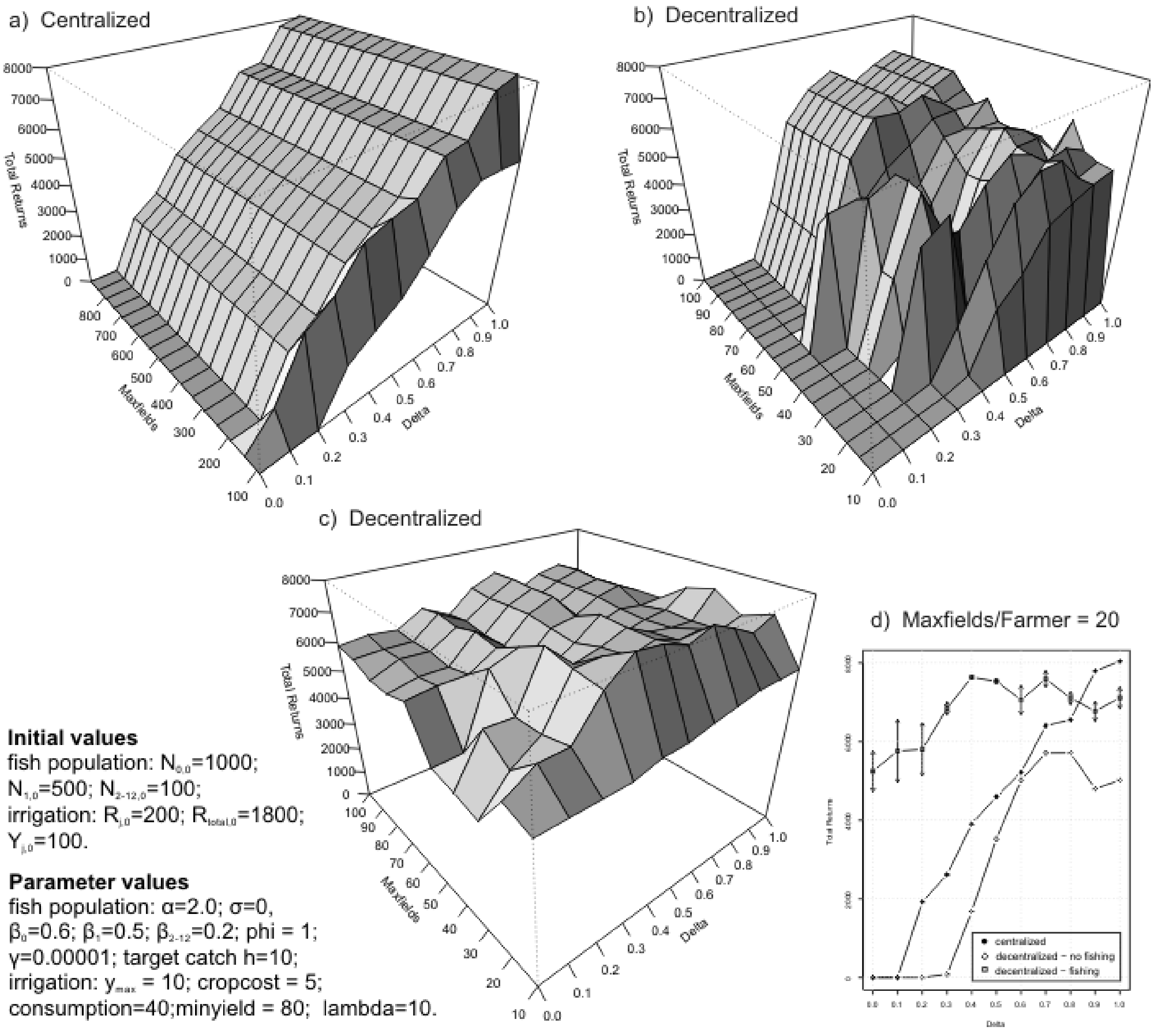
**Fig. 6.** Activity diagram of the decentralized model. Sequence of activities within 1 yr (t). EWA(t)= expected water availability in mo 7 of yr t, RWV(t)= requested water volume in mo 7 of yr t, DWV(t) = delivered water volume in mo 7 of yr t, Y(t) = yield in yr t, IC = costs of irrigating the total number of fields, FR = financial reserve, cropneed = water needed to irrigate one field of the respective crop, and cropcost = cost of cultivating the crop on one field.



With better estimations, more farmers can irrigate, but in all scenarios, farmers 6 to 9 eventually go out of business.

The abundance of fish in the adult age classes in the centralized regime without fishing is similar in all but the delta = 0.8 and 0.9 scenarios where it is approximately 35% higher (Fig. 9a). Here, inflow to the lake crosses the threshold in more years then in the other scenarios, thus creating a larger inflow of larvae into the lake. The inflow of larvae is significantly higher with delta = 0 and 0.1, because in these scenarios less water is used in agriculture and instead reaches the lake (Figure 9b). However, due to the very high inflow density regulation prevents the adult age classes from growing

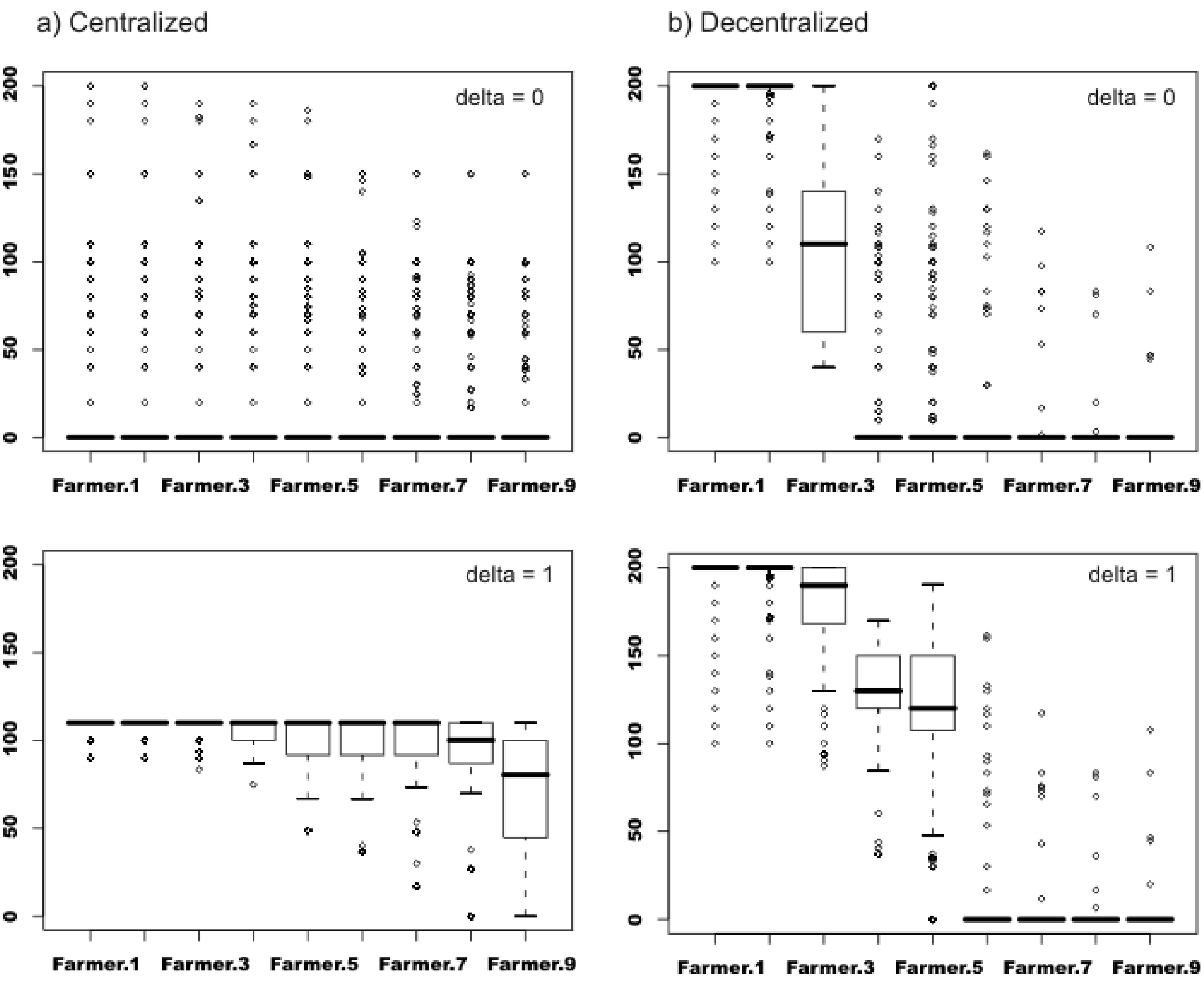
**Fig. 7.** Total accumulated global returns at the end of the simulation period (yr 200) with change in the maximum total number of fields (centralized) or maximum number of fields/farmer (decentralized) for the a) centralized and b) decentralized models without fishing, and c) decentralized with fishing. D) Comparison of the total accumulated global returns at the end of the simulation period of the centralized, decentralized without fishing and decentralized with fishing for a run with maximum number of fields/ farmer = 20.



**Initial values**
fish population: $N_{0,0}$=1000; $N_{1,0}$=500; $N_{2\text{-}12,0}$=100;
irrigation: $R_{j,0}$=200; $R_{total,0}$=1800;
$Y_{j,0}$=100.

**Parameter values**
fish population: α=2.0; σ=0,
$\beta_0$=0.6; $\beta_1$=0.5; $\beta_{2\text{-}12}$=0.2; phi = 1;
γ=0.00001; target catch h=10;
irrigation: $y_{max}$ = 10; cropcost = 5;
consumption=40;minyield = 80; lambda=10.

**Fig. 8.** Annual yields/farmer for delta = 0 and delta = 1 for the a) centralized and b) decentralized models without fishing. Parameter values are the same as in Fig. 6, i.e., max. number of fields–centralized: 180, maximum number of fields/farmer–decentralized: 20.

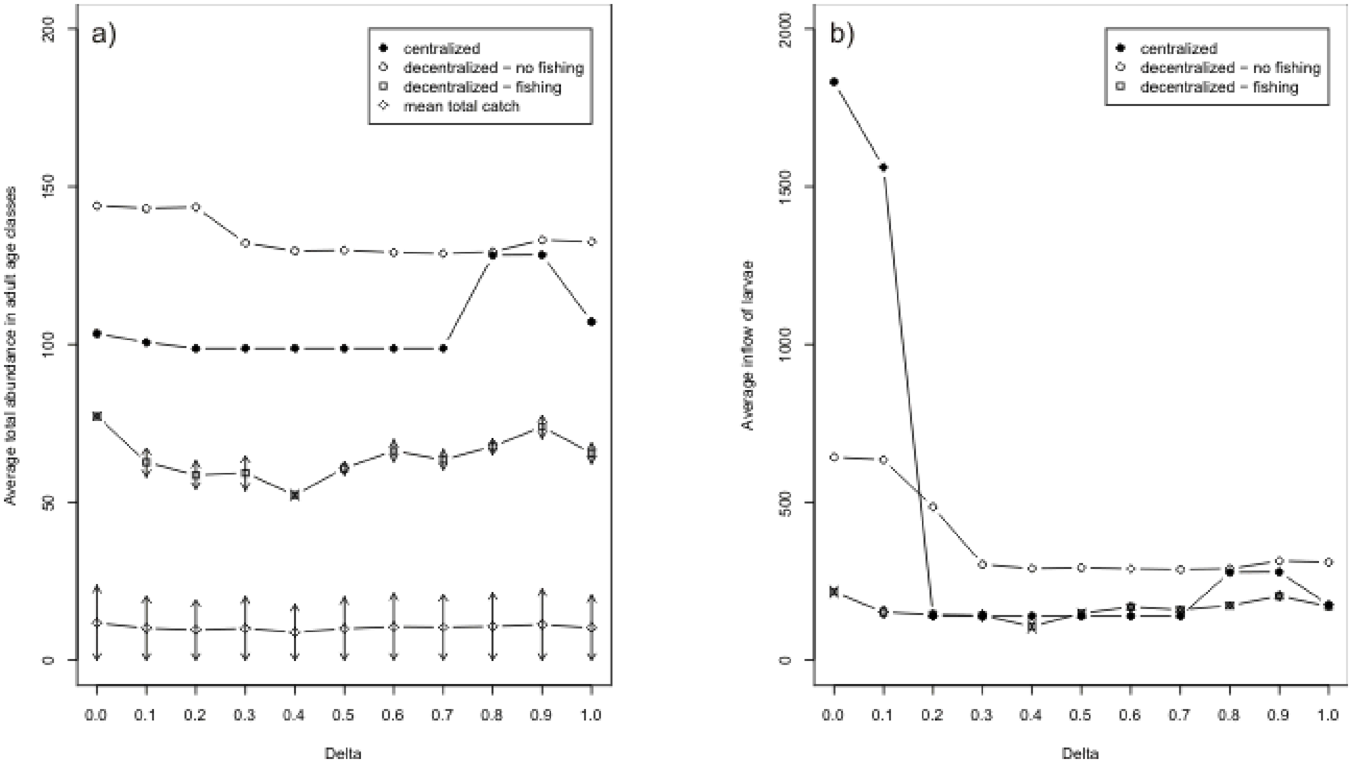


equivalently. In the decentralized model without fishing abundances in the adult age classes are higher because fewer active farmers use less water in agriculture, which leads to a higher inflow of larvae into the lake. Fishing decreases fish abundance but also the inflow to the lake because with the additional income from fishing, farmers perform better in agriculture and use more of the available water. Fish catch is almost identical in all delta scenarios.

## Diversification of resources use: the impact of fishing

When farmers additionally engage in fishing activities the yields and the local and global accumulated returns change; some of them significantly. Here, only the impact of fishing on the global accumulated returns (Fig. 7c) and the individual returns of the last farmer (Fig. 10) in the decentralized regime can be presented. Note that the

**Fig. 9.**. A) Total mean abundance in adult age classes of the fish population with different deltas for the centralized, decentralized without fishing, and decentralized with fishing models. Mean catch for the decentralized model with fishing. B) Mean inflow of larvae into the fish population with different delta for the centralized, decentralized without fishing, and decentralized with fishing models. Parameter values are the same as in Fig. 6.

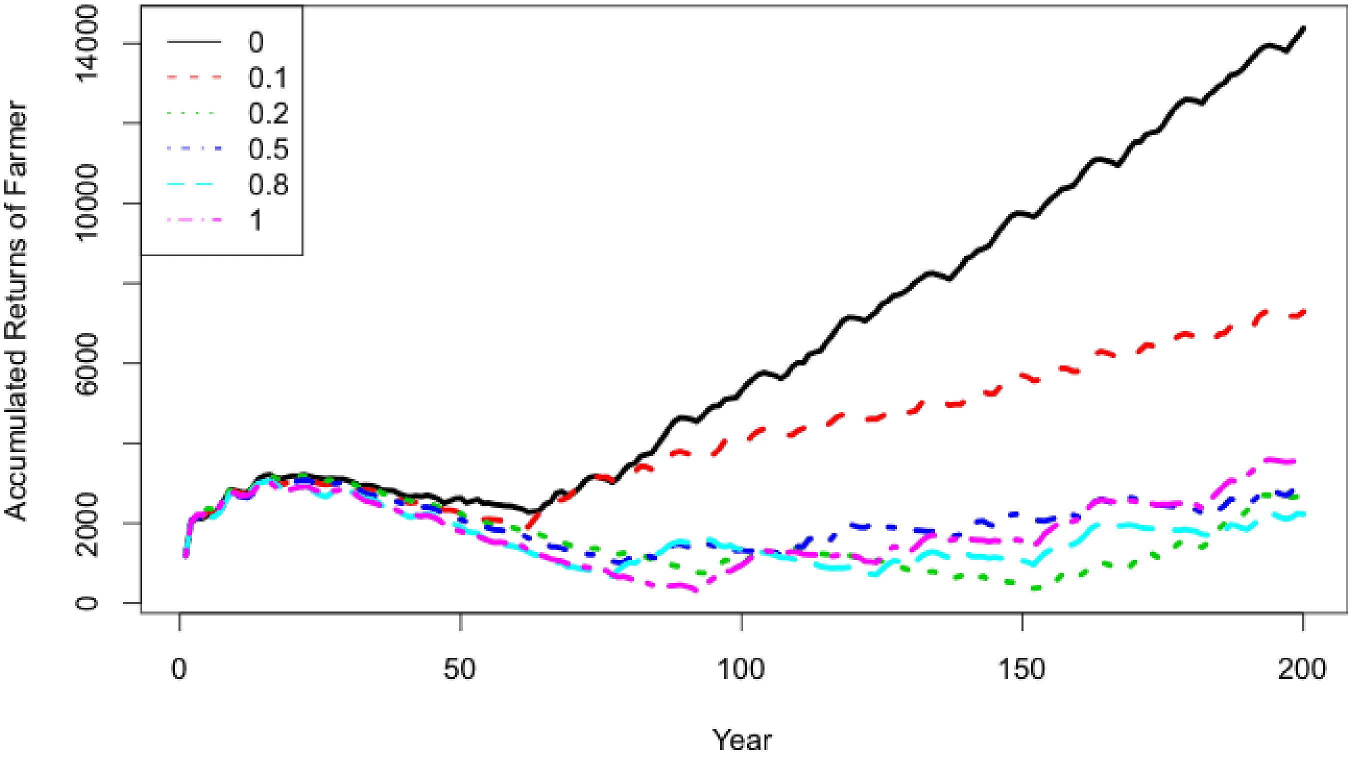


global accumulated returns in the scenarios with fishing summarize only the returns from crop production, not fishing, so that all scenarios can be compared directly. The increase in global returns is caused by the indirect compensatory effect of fishing on the individual level in low water years. The individual returns that each farmer can generate by fishing depend on the state of the fish population, which is a function of water inflow, his access to them, and the target catch level. With low target catch levels, all farmers can succeed in catching fish, and with higher levels, the first farmers accessing the lake deplete the resources (see also sensitivity analysis in Appendix).

Results show that the income from fishing activities create a buffer in low water years that prevents the farmer from going out of business and allows him to retain sufficient financial resources to invest in agriculture in the next year. This effect is especially pronounced in the low delta scenarios (0–0.4), where high uncertainty in water availability has caused the system without fishing to break down. Moreover, differences in returns between the different delta scenarios are much smaller. The performance of the decentralized regime is better than without fishing (Fig. 7d) and compares well with the centralized regime with high delta values and performs better in the low delta range. The decrease in differences between the performance of the centralized and decentralized regime also holds when the returns from fishing are included into the global returns of both regimes.

The maximum number of fields a farmer can irrigate (maxfields) influence outcomes for low delta values

**Fig. 10.** Individual returns over time of farmer 9 for delta 0, 0.1, 0.2, ...., 1. Parameter values are the same as in Fig. 6, except for target catch level h=100.



(0–0.2). However the impact is not as strong as without fishing. Fishing activities prevent the decline for intermediate values as in the scenario without fishing. Outcomes of the decentralized model are sensitive to the fish population growth, and the scaling factor for income of fishing, especially for low delta values and low values of the respective parameters (see sensitivity analysis in Appendix).

Fishing activities reduce the fluctuations in the individual returns of each farmer, especially the downstream ones. The lower the potential income from agriculture for the downstream farmers in the decentralized model, the higher their fish catch has to be to achieve income levels that enable the farmer to invest in agriculture. It also takes significant time until fish population dynamics and catches are stabilized and the downstream farmers can increase their individual returns (Fig. 10). There is thus a trade-off between decrease in agricultural returns and increase in fishing returns with increasing distance down the river. If farmers go out of business water use for agriculture is reduced, which improves the state of the fish population.

## DISCUSSION

The two regimes presented in the example caricaturize a centralized and a decentralized regime of water allocation decision making. The structural differences between the two regimes are manifested in the level at which information on past water flows is generated, at which allocation decisions are taken and returns are accumulated. While the centralized regime has access to information of total water flows into the region, and takes allocation decisions that aim to optimize return at the global level using global financial resources, the decentralized regime has information on flows received at a certain location along the river, and takes allocation decisions that aim to increase individual returns using the available individual financial resources.

Both regimes are exposed to disturbances in the form of regularly recurring low water years. In the modeling exercise two mechanisms that might affect the resilience of both regimes are tested: (1) the potential to estimate the state of the resource to reduce the uncertainty of water availability and (2) diversification of water use.

Both mechanisms have an effect on the performance and thus resilience of both regimes. The quality of the prediction of water flows (delta), which is influenced by the memory capacity of each agent, determines its adaptive response to changes in water availability. With the given regularly fluctuating flow pattern the centralized regime performs better with increasing delta. Highest returns are achieved when the national authority uses the approximated mean water availability as a predictor, thus neglecting annual fluctuations. In the decentralized regime, however, an increase of delta can improve performance only to a certain extent with returns decreasing again when delta approaches 1. An interesting extension for future simulations will be to test the effect of heterogeneous agents that have different deltas, or can adjust their delta through learning.

Diversification of water use increases the resilience of both regimes to low water years and forecasting errors. Fishing activities act as a linkage between upstream and downstream water use, because the order of access to the fish resources is opposite to the access to water resources. This can increase the performance of the decentralized system with high fishing levels even beyond that of the centralized one because water resources can be used more efficiently. The contribution of this alternative water use to the individual returns could even be increased if the water and thus larvae inflow to the ecosystem would be actively managed. Understanding the resolution of the trade-off between different water uses is one question we intend to address using the model.

In the given version the centralized regime performs better because decisions taken by the national authority equalize access for all farmers to sufficient levels of water and financial resources for cropping. The regime can thus make better use of high water years, which increases returns. However, when performance is too low to sustain all individuals the centralized system completely breaks down, while in the decentralized case the upstream farmers can still survive. In such a case the complete independence of the individual agents proves to be an advantage. Otherwise, in the decentralized regime the lack of institutions that regulate access to the resources and/or of coordination among agents forces downstream farmers out of business in low water years. They cannot resume agricultural activities because of insufficient financial resources. Abundant water resources in high water years can thus not be used for irrigation any longer. By subsidizing the downstream farmers the centralized regime can use the water resources more efficiently.

Interestingly, the situation of unequal water distribution seen to emerge in the decentralized model without fishing has been observed in the Amudarya river basin during the severe drought years 2000 and 2001. During the drought the downstream users often received less than half the allotment of “normal” mean water availability years, which the upstream users continued to receive even at historically low river flows. Thus, although the centralized regime was intended to mimic the structure of the current water management regime, the current regime shows behavior closer to that of the decentralized one. In the reality of water management in the Amudarya River basin, regional and local level authorities often do not comply with the orders from the national government and manage the resources according to their own rules (R. Yalcin, *personal communication*).

Excessive use of water for irrigation combined with heavy fishing can reduce the fish population to very small numbers. However, fish populations can rebound when a decrease in agricultural activities increases the inflow of offspring. This may happen when the downstream farmers go out of business and only rely on fishing. The resilience of the virtual fish population is thus a function of the inflow of offspring, which might be an over-simplification of the actual ecological dynamics.

Model outputs suggest that the governance structure expressed in the two regimes has a significant effect on the resilience of the coupled system. Model runs without diversification and other institutions to regulate resource access indicate that the participation of more, especially local, actors in the decision does not enhance the system’s resilience, contrary to some empirical studies (Ostrom 1990, Tang 1992). Moreover, increasing the number of agents taking individual decisions increases the inequality among agents (see also Janssen 2007).

However, these results should be interpreted with caution given the simplistic implementation of the decentralized regime, which neglects communication and collective action among the individual actors or the emergence of a market for land or water. Besides, the superiority of the centralized regime, which in the best scenario has a 40% higher return than in the decentralized regime, might decrease or vanish once aspects of noncompliance with the rules from the national authority and nonregular fluctuations in water availability are taken into account. Noncompliance and free riding are fundamental problems in common-pool resource management, which affect both types of regimes. Empirical evidence suggests that in some situations self-governance is better capable of coping with them (Ostrom 1990, Tang 1992).

The model structure proved useful first as a vehicle to formalize our ideas about the core differences in structural and functional characteristics of agent-resource interactions between centralized and decentralized regimes. Second, contrasting the outputs of different regimes was valuable to investigate the impact of these characteristics and related uncertainties in resources availability on the resilience of the coupled system. We have chosen these simplified representations in order to allow for a systematic testing of the effects of structural characteristics on resilience. However, the use of an agent-based approach gives us the opportunity to test the resilience of alternative regimes that differ in human factors and behaviors such as cooperation and collective action. To further investigate those characteristics the decision making structure and interactions between agents and resources will be systematically varied. In the next modeling steps we want to carry out an exploration of what individual behaviors and simple rules can improve the performance of the bottom-up regime (see also Anderies 2000 for an example of traditional societies). This includes increasing the possibilities for agents to adapt their strategies based on the experiences they gain, addressing issues of noncompliance of agents, heterogeneity of agent behavior and in particular institutions for collective action. Further, the impact of the buffering capacity of a water storage reservoir or the fish population will be investigated. Another interesting question is how information availability and transfer as well as the level of strategic planning influences the capacity of the agents and the system to adapt. In the current regimes in the Amudarya River basin there is little strategic planning because the government today is mainly concerned with day-to-day operational management (I. Abdullaev, *personal communication*).

Limitations of agent-based approaches lie in the restricted possibilities for formal verification and validation. The sensitivity analysis of the decentralized regime confirms that when information on water flows is very limited, i.e., low delta values, the tradeoff between water use for irrigation and water use for fish production strongly determines the performance of the system. In those scenarios outcomes are sensitive to changes in any of the determining parameters for fish population growth and agricultural production. This tradeoff will be the subject of further investigations with the model in the future. Moreover, more analyses have to be carried out to further test whether management strategies are robust under various equally plausible assumptions on agent behavior and to analyze the coupling of the social and ecological systems. In this respect, an advantage of a heuristics-based approach to model agent decision making is the possibility to validate rules with stakeholders on the ground or through field work that may include stakeholder analysis and knowledge elicitation in interviews, questionnaires and role-playing games (Barreteau et al. 2001).

## CONCLUSION

The models presented here are a first attempt to develop simple models to systematically test structural and functional mechanisms that influence the response to disturbances of a coupled social-ecological system in a river basin. Such models can be valuable tools to identify potential mechanisms of resilience of specific social-ecological systems, e.g. in a common pool resource management situation. The two examples of a simple centralized and a decentralized regime show that under the given conditions the centralized system performed better as long as there is only one type of water use, e.g., irrigation, and variability in water availability is predictable. However, relaxing some of the strong assumptions on resources and agent behavior might reveal that a well designed decentralized regime performs better, as is already the case in the simple examples with high fishing activities. Careful analysis of such models can reveal robust structural features and rule sets that are little sensitive to the assumptions about agent behavior and learning.

We want to emphasize the need to study the dynamics of coupled social-ecological systems, especially their capacity to cope with change, as a theoretical basis for ecosystem and resource management. The given approach uses a real world example as context to explore theoretical issues such as implications of structural organization for the functioning of the system. Better understanding of system dynamics and the source and role of change in adaptive systems will assist identification, design and evaluation of management interventions and can inform an adaptive management process. In a river basin that historically has been conservatively managed from the top down, it is difficult to imagine how innovations at local and national levels might interact to affect water use, economy and society or, ultimately, their resilience to various sources of uncertainty and change. The model so far has shown potential for analysis of different policy options and their implications.

*Responses to this article can be read online at:*
*http://www.ecologyandsociety.org/vol12/iss2/art4/responses/*

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**Appendix 1.** Results of sensitivity analysis

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