Describing human decisions in agent-based models - ODD+D, an extension of the ODD protocol

Birgit Müller[a,*], Friedrich Bohn[a], Gunnar Dreßler[a], Jürgen Groeneveld[a,f], Christian Klassert[c], Romina Martin[a], Maja Schlüter[d,e], Jule Schulze[a,b], Hanna Weise[a], Nina Schwarz[b]

Affiliations:
[a] Department of Ecological Modelling, UFZ - Helmholtz-Centre for Environmental Research UFZ Leipzig-Halle, Permoser Str. 15, 04318 Leipzig, Germany
[b] Department of Computational Landscape Ecology, UFZ - Helmholtz-Centre for Environmental Research UFZ Leipzig-Halle, Permoser Str. 15, 04318 Leipzig, Germany
[c] Department of Bioenergy, UFZ - Helmholtz-Centre for Environmental Research UFZ Leipzig-Halle, Permoser Str. 15, 04318 Leipzig, Germany
[d] Stockholm Resilience Centre, Stockholm University, Kräftriket 2B, 106 91 Stockholm, Sweden
[e] Department of Biology and Ecology of Fishes, Leibniz-Institute of Freshwater Ecology and Inland Fisheries, Müggelseedamm 310, 12587 Berlin, Germany
[f] School of Environment, University of Auckland, Private Bag 92019, Auckland, New Zealand

Email-addresses:

Birgit Müller	birgit.mueller@ufz.de
Friedrich Bohn	friedrich.bohn@ufz.de
Gunnar Dreßler	gunnar.dressler@ufz.de
Jürgen Groeneveld	juergen.groeneveld@ufz.de
Christian Klassert	christian.klassert@ufz.de
Romina Martin	romina.drees@ufz.de
Maja Schlüter	maja.schlueter@stockholmresilience.su.se
Jule Schulze	jule.schulze@ufz.de
Hanna Weise	hanna.weise@ufz.de
Nina Schwarz	nina.schwarz@ufz.de

*__Corresponding author:__ Birgit Müller, Phone: ++49- 341- 235 1708, Fax: ++49- 341- 235 1473

Preprint of:

Müller, B., F. Bohn, G. Dressler, J. Groeneveld, C. Klassert, R. Martin, M. Schlüter, J. Schulze, H. Weise, and N. Schwarz, 2013. Describing human decisions in agent-based models - ODD+D, an extension of the ODD protocol. Environmental Modelling & Software 48, 37-48.

Abstract

Representing human decisions is of fundamental importance in agent-based models. However, the rationale for choosing a particular human decision model is often not sufficiently empirically or theoretically substantiated in the model documentation. Furthermore, it is difficult to compare models because the model descriptions are often incomplete, not transparent and difficult to understand. Therefore, we expand and refine the 'ODD' (Overview, Design Concepts and Details) protocol to establish a standard for describing ABMs that includes human decision-making (ODD+D). Because the ODD protocol originates mainly from an ecological perspective, some adaptations are necessary to better capture human decision-making. We extended and rearranged the design concepts and related guiding questions to differentiate and describe decision-making, adaptation and learning of the agents in a comprehensive and clearly structured way. The ODD+D protocol also incorporates a section on 'Theoretical and Empirical Background' to encourage model designs and model assumptions that are more closely related to theory. The application of the ODD+D protocol is illustrated with a description of a social-ecological ABM on water use. Although the ODD+D protocol was developed on the basis of example implementations within the socio-ecological scientific community, we believe that the ODD+D protocol may prove helpful for describing ABMs in general when human decisions are included.

Keywords: adaptation; decision-making process; human behaviour; human-environmental interaction; learning; natural resource use; ODD model description; simulation model; standard protocol.

1 Introduction

It is widely acknowledged that process-based models, and in particular agent-based models (ABMs), can play an important role in fostering understanding of the dynamics of complex systems (see Matthews et al., 2007; Clifford, 2008; Polasky et al. 2011; Schlüter et al., 2012 with respect to coupled human-environmental systems). A number of studies have demonstrated that the appropriate inclusion of human decision-making in models is of fundamental importance (Parker et al., 2003; Bousquet and Le Page, 2004; Jager and Mosler, 2007; Parker et al., 2008b; Le et al., 2012). This is supported by the fact that, in many modelling studies, macro-level patterns are strongly influenced by the assumed human decisions and behaviour at the micro-level (Hare and Deadman, 2004; Rounsevell and Arneth, 2011). However, current modelling practice has two substantial shortcomings: (1) The reasoning behind the choice of a certain human decision model is often not well documented; insufficient empirical or theoretical foundations are given; or the decision model is only assumed on an ad-hoc basis (Feola and Binder, 2010). (2) Often the model is not described in a transparent manner (clear and complete) that would allow for reproducibility and facilitate the communication of the model and its results (Polhill et al., 2008). Consequently, model comparison and advancement is hampered to a large extent.

Referring to first shortcoming, one has to take into account that decision-making in ABMs can be based on various theories (for an introduction see Baron, 2000): A widely used approach for modelling decision-making in general, especially in economics, is rational-choice theory (Sen, 2008). However, rational-choice theory has been criticised for being overly simplistic (Camerer and Loewenstein, 2004). Various alternative theories of how decision-making is in reality based on a more bounded rationality have been proposed (Simon, 2008; Kahnemann, 2003; Gigerenzer and Selten, 2001). For implementation in ABMs, rational choice theory is often represented by an optimisation routine, whereas models based on bounded rationality rely on condition-action rules or on a combination of both approaches (Schreinemachers and Berger, 2006). New opportunities to model bounded rationality are considered to be one of the major advantages of using an ABM approach (Epstein, 2006, p. 6), and there are by now many examples of ABMs that make use of bounded rationality (Jager et al., 2000; Duffy, 2001; Pahl-Wostl and Ebenhöh, 2004).

Referring to the second shortcoming mentioned above, several attempts have been made in the social sciences and land-use sciences to develop frameworks, classification schemes or protocols to represent and communicate ABMs. Hare and Deadman (2004) presented a taxonomic structure to help modellers choose the appropriate model type based on three requirements for social-ecological ABMs: Different specifications for (1) the coupling of social and environmental models, (2) social interactions and (3) the intrinsic adaptation of the agents. Richiardi et al. (2006) criticised the lack of a methodological standard for social ABMs and proposed a three-stage process that could lead to the establishment of such standards in social and economic simulations. The proposed process was based on the development of a questionnaire that includes specific questions on the model structure (including decision-making mechanisms), model analysis and replicability. According to the authors, the evaluation of the questionnaire can then provide the input for a methodological protocol. The MR POTATOHEAD framework, "Model Representing Potential Objects That Appear in The Ontology of Human-Environmental Actions & Decisions", represents key elements of standard ABM and LUCC (Land Use and Cover Change) models in a structured and comprehensive way (Parker et al., 2008a). This “conceptual design pattern” aims first to facilitate a comparison of the structure and functioning of different models and second to assist scholars new to the field with designing their models. Certain facets of human decisions are discussed in all three of these classification schemes and frameworks. However, these studies differ in terms of purpose and none of them puts the main focus on human decisions or elaborates on this topic in a comprehensive way.

Modelling in general, not only the modelling of human decisions, has to address the challenge of providing transparent and complete model descriptions (Richiardi et al., 2006; Parker et al. 2008a). Standardised protocols for (agent-based) model descriptions and especially the ODD (Overview, Design Concepts and Details) protocol (Grimm et al. 2006, 2010) have been well received by the scientific community. The ODD protocol consists of three parts: First, it provides an ‘Overview’ on the purpose and main processes of the model. Second, in the ‘Design Concepts’ block, the general concepts underlying the model design are depicted and third, in the ‘Details’, all of the necessary information is given that would allow for a reimplementation of the model. However, the original ODD protocol focuses primarily on ecological dynamics (Grimm et al., 2006). The first revision of the ODD protocol has attempted to open the standard for all ABMs (Grimm et al., 2010). Nevertheless, a comprehensive description of the human decision process was not a focal point until now.

First attempts have been made to determine the usefulness of the ODD protocol for describing social-ecological models. Polhill et al. (2008) investigated to which extent the ODD protocol can be applied to LUCC models, considering three ABMs that include human agents as examples. They concluded that the ODD protocol could provide a useful standard to facilitate communication and model comparison. However, refinements are required concerning the definition of terms (such as entities, state variables and parameters). An (2012) took the same line and concluded in his review on modelling and understanding human decisions that the development of protocols similar to the ODD protocol for social-ecological models aimed at modelling human decisions must be put on the future research agenda.

We want to address this gap. The aim of this paper is to provide an extension of the ODD protocol, termed ODD+D (ODD + Decision) which facilitates a clear and comprehensive description of ABMs in a standardised way, with an emphasis on human decisions and which includes the empirical and theoretical foundations for the choice of decision model. The paper is structured as follows: In the next section, the main shortcomings of the ODD protocol, in particular with respect to describing human decisions, are summarised. Then, important terms are defined. The terms *decision-making*, *adaptation* and *learning* are clarified and distinguished. Furthermore, general structural changes in the ODD+D protocol (mainly in the Design Concepts block), as compared to the ODD protocol, are delineated and discussed. Afterwards, we present a detailed description of the revised and new design concepts with an emphasis on human decision-making. In Section 4, we illustrate the application of the extended protocol ODD+D by describing a social-ecological ABM on water use as an example. Given our background in social-ecological modelling, we refer for illustrative purposes in Sections 3 and 4 to examples from that domain, but we believe that the ODD+D protocol may prove to be a helpful protocol for describing ABMs that include human decisions in general. The discussion section focuses on the expected benefits and the efforts required while applying the protocol. The section closes with open challenges for the future. Online Appendix A provides a standardised form of the ODD+D protocol that can be used as template to fill in the necessary information about the model to support a transparent and complete model description.

2 Shortcomings of the ODD protocol for describing human decision-making

The ODD protocol is not fully suited to describe how human decision-making has been modelled for the following reasons: (1) Central aspects of modelling human decision-making are not explicitly addressed, such as decision algorithms, the formation of expectation, the temporal characteristics of decision-making and cultural values, amongst others. (2) The theoretical and empirical basis for the chosen decision submodel is not sufficiently emphasised. (3) The Design concepts section does not provide a suitable structure for describing human decision-making.

(1) Central aspects of human decision-making are addressed in related frameworks: In their checklist-type summary, Richiardi et al. (2006) mention the type of agent behaviour (optimising, satisficing, …), the interaction structure, the coordination structure, the formation of expectations and learning with respect to decision-making. In their MR POTATOHEAD framework, Parker et al. (2008a) use the decision algorithm of the agents, their characteristics and cultural values, and the temporal aspects in decision-making and the like as general aspects of decision-making. While the ODD protocol includes some of these aspects (e.g. interaction), other aspects such as coordination, the temporal aspects in decision-making and cultural values are not explicitly mentioned (see Table 1 Section II.ii of ODD+D).

(2) Different scientific disciplines use a variety of approaches for conceptualising human decision-making. Even within a single discipline, different schools of thought have specific, often implicit assumptions about decision-making. Without knowing the exact theoretical or conceptual background, scholars from different disciplines or schools might interpret the same model description in a totally different way and come to different conclusions. Such

guessing might lead to metaphorical and theoretical plasticity (Hare and Deadman, 2004, p. 38) if the same implementation of a model can be explained and justified by the use of more than one metaphor or theory. In the ODD protocol, the basic principles ask for general concepts, theories, hypotheses, or modelling approaches that are underlying the design of a model. The guiding questions do not include the assumptions that underlie the decision-making in particular and the reasons for choosing a certain concept or theory. Apart from a theoretical basis, the choice of decision model may be based on empirical observations / data. This is crucial information for the reader of a model description and should be mentioned explicitly. This was not accounted for in the ODD section on basic principles.

(3) In part, the structure of the design concepts in the ODD protocol does not follow a logical order when it is used to describe human decision-making. For example, the ODD protocol foresees that prediction shall be explained before sensing, although agents usually sense their environment before they predict possible outcomes of their decision-making.

Finally, some minor aspects of the ODD protocol might be elaborated that could also be relevant for models that do not include human decision-making: (a) Stating the target group of a model makes its influence on model design transparent, but is not asked for in the ODD protocol. (b) In the ODD protocol, internal and environmental state variables are not clearly defined; thus, Polhill et al., 2008, suggested using the terms ‘endogenous’ and ‘exogenous’ instead. (c) Space is included in the ODD protocol, but its importance could be highlighted. (d) Heterogeneity, a very important issue for ABMs, was not discussed in a separate design concept. (e) The published attempts to replicate ABMs have shown that model results often cannot be reproduced or are based on assumptions that differ from the ones stated in the publication. Therefore, implementation details that are lacking in the ODD protocol, including where to find possibly available source code, need to be added.

3 The ODD+D Protocol: Adapting ODD for describing decisions in ABMs

3.1 Definitions of terms

The consideration of human decisions is a crucial aspect of agent-based complex models and an important issue in various disciplines. However, the definitions of terms vary widely. In this section, we specify our definitions of the most ambiguous terms.
Because we are considering ABMs, our first task is to clarify our definition of the term “agent”: Following the definition given in Tesfatsion (2006), we define an agent as “bundled data and behavioural methods representing an entity constituting part of a computationally constructed world”. This allows for the consideration of human beings, social groupings and institutions or biological and physical entities as agents (Tesfatsion, 2006). The ODD+D extension is designed for human decision-making. However, it may also be applied to non-human agents to describe their simulated actions in a detailed way without any limitations.

With “decision-making”, we refer to “the methods agents use to make decisions about their behaviour” (Dibble, 2006). Two important concepts are often confused: adaptation and learning. For “adaptation”, we adopt the definition given by Dibble, 2006: Adaptation “is generally distinguished from learning by being passive and biological rather than active and cognitive”. We operationalise this distinction in the following way: Agents’ decision rules are prone to adaptation, where the information used by the rules to generate a decision changes, and learning, where the rules themselves change over time.

Any confusion that resulted from the application of the original ODD protocol concerning the definition of the terms “entities” and “state variables” has already been addressed in the updated ODD protocol (Grimm et al., 2010). Here, we will follow the proposed definitions: “An entity is a distinct or separate object or actor that behaves as a unit and may interact with other entities or be affected by exogenous factors (drivers). Its current state is characterised by its state variables […]. A state variable […] is a variable that distinguishes an entity from other entities […], or traces how the entity changes over time”. Therefore, the above-defined agent is one specific type of entity. Furthermore, Polhill et al. (2008) criticise the lack of delineation between state variables and parameters. According to our understanding, state variables are the minimal set of variables that completely describe the system and are dynamic. Parameters are static but can vary between simulations, scenarios or agents.

A further lack of clarity refers to the understanding of internal and environmental state variables in the ODD protocol. Environmental variables could also be internal, e.g. rain depending on the evapotranspiration calculated within the model. Therefore, we follow the proposition of Polhill et al. (2008), and use the terms endogenous and exogenous instead. Variables that can be influenced by other variables of the model should be referred to as endogenous, whereas those that cannot be influenced by other variables should be referred to as exogenous. From our point of view, the usefulness of the ODD protocol for ABMs can be enlarged if these exogenous factors, also called drivers, are explicitly listed separately, which has not been the case up to now. In land-use science, a driver is defined as an exogenous variable that influences actors and/or changes in land use but is not influenced by them (see also Turner et al., 1995).

3.2 Structural changes between the ODD protocol and the ODD+D protocol

The main idea behind the ODD+D protocol is to preserve the basic structure of the ODD protocol to foster the establishment of the ODD protocol as a standard. Hence, changes were mainly made to the Design concepts block (cf. Figure 1). It is more difficult to standardise this block across different disciplines and Grimm et al. (2010) already anticipated that the list of design concepts may need to be enlarged. Note: “The block …“Design concepts” does not describe the model itself, but rather describes the general concepts underlying the design of the model” (Grimm et al., 2006).

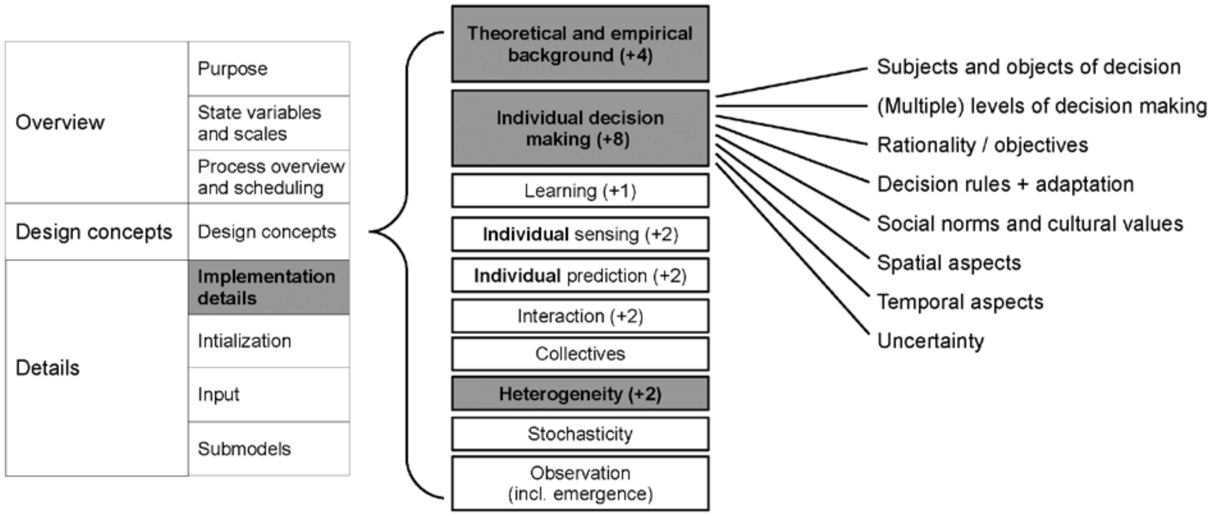

Figure 1 The structure of the ODD+D protocol. Grey boxes indicate new design concepts/categories compared to the ODD protocol. The numbers of new questions added are noted in parentheses. The different aspects of the new design concept “Individual decision-making” are displayed on the right.

The ODD protocol was structurally changed as follows for the ODD+D protocol: The design concept “Basic Principles” was renamed “Theoretical and Empirical Background” and expanded to emphasise the importance of information regarding the sources of the assumptions and data used in a model. The ODD design concept “Objectives” was merged into the new design concept “Individual decision-making”, which summarises the conceptual background of the decision model (see the right side of Figure 1). We deleted “Adaptation” as separate design concept because we see adaptation as part of “Individual decision-making” (see Section 3.1, Definition of terms). “Sensing” and “Prediction” were expanded, and their order was reversed to reflect the characteristics and timeline of human decision-making. For the same reason, “Interaction” was expanded. A new design concept, “Heterogeneity”, was introduced as it is a property that often distinguishes ABMs from other models, and can, therefore, provide crucial insights into their characteristics. Despite its undisputed importance for ABM modelling, the design concept “Emergence” was moved into “Observation” to reduce the risk that users might mistake it for a feature to be constructed rather than an outcome of the interplay of the model entities. By including “Emergence” in “Observation”, the forms of stochasticity that were put into the model and the patterns that emerge in the model’s results can be clearly distinguished. Finally, the category “Implementation Details” was included in the Details block because we believe that this information will improve comparability and reproducibility (see also Ince et al., 2012).

3.3 Usage of the ODD+D protocol

Beyond the requirements formulated in the ODD protocol (Grimm et al., 2006, 2010), we strongly encourage that all questions be answered to avoid an incomplete model description. If the model description is very long, we recommend the following: The complete ODD+D description including the submodels could be published in an Online Appendix using the template provided. Using the template makes the creation of an ODD+D description easier, since some categories can be answered by keywords such as “yes” or “no” instead of full sentences (see Online Appendices A and B). The use of this tabular form simplifies the comparison of models applied in different studies to a large extent. In the main text, the overview and the design concepts should be copied and, if necessary, shortened. One concern about the ODD protocol is the potential redundancy between the purpose, design concepts and the submodels description. This redundancy can be reduced by not repeating the details already given as design concepts in the submodel description (see Grimm et al., 2010). However, this drawback is outweighed by the benefits of a hierarchical model description that first gives an overview and afterwards provides the details with regard to comprehensibility and clarity.

3.4 The ODD+D protocol in detail: Guiding questions and examples for describing human decisions in models

Table 1 provides a complete list of the guiding questions for each element of the extended ODD+D protocol. A template for using the ODD+D protocol, including examples for possible answers to the guiding questions, is available at as Online Appendix A and on the website http://www.ufz.de/index.php?de=10464.
The questions that have been added are displayed in bold. In the following paragraphs, the questions are explained more in detail and examples and literature references are given. In the examples and literature references, emphasis is put on the new part for describing the decision model. In this part, the guiding questions are mentioned again to facilitate orientation.

Table 1: The ODD+D protocol including the guiding questions. (We provide both the original questions (Grimm et al. 2010) and the newly proposed questions (in bold print) to present a comprehensive model description.)

Structural elements		Guiding questions
I) Overview	I.i Purpose	I.i.a What is the purpose of the study?
		I.i.b For whom is the model designed?
	I.ii Entities, state variables and scales	I.ii.a What kinds of entities are in the model?
		I.ii.b By what attributes (i.e., state variables and parameters) are these entities characterised?
		I.ii.c What are the exogenous factors / drivers of the model?
		I.ii.d If applicable, how is space included in the model?
		I.ii.e What are the temporal and spatial resolutions and extents of the model?
	I.iii Process overview and scheduling	I.iii.a What entity does what, and in what order?
II) Design Concepts	**II.i Theoretical and Empirical Background**	II.i.a Which general concepts, theories or hypotheses are underlying the model's design at the system level or at the level**(s)** of the submodel**(s)** **(apart from the decision model)?** What is the link to complexity and the purpose of the model?
		II.i.b On what assumptions is/are the agents' decision model(s) based?
		II.i.c Why is /are certain decision model(s) chosen?
		II.i.d If the model / submodel (e.g., the decision model) is based on empirical data, where do the data come from?

		II.i.e At which level of aggregation were the data available?
	II.ii **Individual Decision-Making**	**II.ii.a What are the subjects and objects of the decision-making? On which level of aggregation is decision-making modelled? Are multiple levels of decision making included**?
		II.ii.b What is the basic rationality behind agent decision-making in the model? Do agents pursue an explicit objective or have other success criteria?
		II.ii.c How do agents make their decisions?
		II.ii.d Do the agents adapt their behaviour to changing endogenous and exogenous state variables? And if yes, how?
		II.ii.e Do social norms or cultural values play a role in the decision-making process?
		II.ii.f Do spatial aspects play a role in the decision process?
		II.ii.g Do temporal aspects play a role in the decision process?
		II.ii.h To which extent and how is uncertainty included in the agents' decision rules?
	II.iii **Learning**	II.iii.a Is individual learning included in the decision process? How do individuals change their decision rules over time as consequence of their experience?
		II.iii.b Is collective learning implemented in the model?
	II.iv **Individual** Sensing	II.iv.a What **endogenous** and **exogenous** state variables are individuals assumed to sense and consider in their decisions? **Is the sensing process erroneous?**
		II.iv.b What state variables of which other individuals can an individual perceive? **Is the sensing process erroneous?**
		II.iv.c What is the spatial scale of sensing?
		II.iv.d Are the mechanisms by which agents obtain information modelled explicitly, or are individuals simply assumed to know these variables?
		II.iv.e Are the costs for cognition and the costs for gathering information explicitly included in the model?
	II.v **Individual** Prediction	**II.v.a Which data do the agents use to predict future conditions?**
		II.v.b What internal models are agents assumed to use to estimate future conditions or consequences of their decisions?
		II.v.c Might agents be erroneous in the prediction process, and how is it implemented?
	II.vi Interaction	II.vi.a Are interactions among agents and entities assumed as direct or indirect?
		II.vi.b On what do the interactions depend?
		II.vi.c If the interactions involve communication, how are such communications represented?
		II.vi.d If a coordination network exists, how does it affect the agent behaviour? Is the structure of the network imposed or emergent?
	II.vii Collectives	II.vii.a Do the individuals form or belong to aggregations that affect and are affected by the individuals? Are these aggregations imposed by the modeller or do they emerge during the simulation?
		II.vii.b How are collectives represented?
	II.viii Heterogeneity	**II.viii.a Are the agents heterogeneous? If yes, which state variables and/or processes differ between the agents?**
		II.viii.b Are the agents heterogeneous in their decision-making? If yes, which decision models or decision objects differ between the agents?

	II.ix Stochasticity	II.ix.a What processes (including initialisation) are modelled by assuming they are random or partly random?
	II.x Observation	II.x.a What data are collected from the ABM for testing, understanding and analysing it, and how and when are they collected?
		II.x.b What key results, outputs or characteristics of the model are emerging from the individuals? (Emergence)
III) Details	**III.i Implementation Details**	**III.i.a How has the model been implemented?**
		III.i.b Is the model accessible, and if so where?
	III.ii Initialisation	III.ii.a What is the initial state of the model world, i.e. at time t = 0 of a simulation run?
		III.ii.b Is the initialisation always the same, or is it allowed to vary among simulations?
		III.ii.c Are the initial values chosen arbitrarily or based on data?
	III.iii Input Data	III.iii.a Does the model use input from external sources such as data files or other models to represent processes that change over time?
	III.iv Submodels	III.iv.a What, in detail, are the submodels that represent the processes listed in 'Process overview and scheduling'?
		III.iv.b What are the model parameters, their dimensions and reference values?
		III.iv.c How were the submodels designed or chosen, and how were they parameterised and then tested?

I Overview

The overview section consists of the subsections i) purpose, ii) state variables and scales, and iii) process overview and scheduling. In the following, we summarise the original description of the ODD protocol (see Grimm et al., 2010) and our extensions. The citations from the original ODD protocol are given in double quotes.

I.i Purpose

Grimm et al. (2010) state "… ODD starts with a concise summary of the overall objective(s) for which the model was developed. Do not describe anything about how the model works here…" We suggest adding to this subsection some meta information that will facilitate understanding of the study, particularly whether the study was mainly designed for hypothesis testing, theory development, quantitative predictions, management and decision support, or communication and learning (e.g. Simon and Etienne, 2010). For whom is the model developed: scientists, students/teachers, stakeholders, or decision-makers?

I.ii Entities, state variables and scales

The intention of this section is well summarised by the guiding questions: "What kinds of entities are in the model? By what attributes (i.e. state variables and parameters) are these entities characterised? What are the temporal and spatial resolutions and extents of the model?" In social-ecological models, the entities will mainly be agents (e.g. humans, households, institutions), spatial units (e.g. grid cells), environments and collectives (list of agents). The different types of agents should only be mentioned here, as the detailed description will follow in the context of the Design Concept "Heterogeneity". In addition to the mentioned state variables in Grimm et al. (2010), state variables such as land ownership and memory are frequently used in social-ecological ABMs. In addition to the original ODD protocol, we suggest the inclusion of the question 'If applicable, how is space included in the model?' at this point in the protocol. To avoid wrong expectations, the authors should explicitly mention if they do not consider space at all. We think it is of special interest whether space is represented in models implicitly or explicitly, and if explicitly, to specify by which spatial dynamics the landscape is linked and whether the modelled space is based on real landscapes (e.g. based on GIS data). Additionally, all exogenous factors/drivers should be listed in this section because this will inform the reader from the outset whether the factors/drivers (e.g. precipitation or prices) are influenced by processes or other state variables during a model run or whether they are assumed to be exogenous.

I.iii Process overview and scheduling

Invaluable information for reimplementing the described model is given in this subsection. Such a description may be substantially facilitated by a graphical representation or a pseudo-code representation of the scheduling (Richiardi et al., 2006). Self-explanatory names for the model's processes foster a clear and concise description of the process overview. The authors should also inform the reader as to how the update process is implemented in the model (e.g. synchronous vs. asynchronous updates).

II Design concepts

In the following section, we introduce ten design concepts that are partly based on the previous ODD protocol (Grimm et al., 2010), extended and ordered from general to detailed information. There is a gradient from the overall view (the theoretical and empirical background, individual decision-making and learning) to the details (e.g. individual sensing and prediction). The stochasticity and observation relate to more technical questions and were therefore placed at the end of the section. Details of the implementation, such as the underlying equations, should, however, not be mentioned here but should appear in the submodels section. We provide guiding questions that should be answered by the model description and examples that help writers to give precise answers. This will give readers of the description a more profound understanding of the simulated decision-making process.

II.i Theoretical and empirical background

II.i.a The aim of this section is to describe the general concepts, theories or hypotheses that underlie the model's design. The answer should provide more precise information on the underlying theories; for example, the population dynamics theory and resilience thinking in Schlüter and Pahl-Wostl (2007), see the example description below. In contrast to Grimm et al. (2006), we do not ask for the modelling approach because the focus of the ODD+D protocol is only ABM.

II.i.b To compare the different models regarding the assumptions on which their representation of decision-making is based, it is important to note whether specific behavioural theories (such as profit maximisation, bounded rationality, cognitive models, social psychology approaches and mental models) real-world observations (mechanistic or process-based explanation, statistical regression methods and heuristics), ad-hoc rules (dummy rules and assumptions) or their combinations were used (see Johnson and Busemeyer, 2010 for a recent review of the theoretical approaches for modelling decision-making under risk and uncertainty).

II.i.c There may be many reasons behind the motivation for choosing a certain decision model, e.g. data (non)availability, reference to previous studies, theoretical reasons, or pattern-oriented modelling (Grimm et al., 2005). We believe that the choice of the decision model is often not only based on theory but is (co)determined by such practical factors. While these reasons should be dealt with in more detail in the discussions section of a paper, this question ensures that not only the choice for a certain decision model but also the practical constraints under which it was made can be compared.

II.i.d This section does not ask for the data input into the model in general, but specifically for the empirical data on which the decision submodel within the model is based (e.g. with regards to parameterisation, heuristics used, etc.). Such empirical data may stem from participatory approaches (role playing games, e.g. Castella et al., 2005), household surveys, interviews, direct observations, statistical census, archives, field or lab experiments, GIS products (see Smajgl et al., 2011, for an overview of empirical methods to parameterise ABMs).

II.i.e Information on the level of aggregation of the empirical data would be helpful for comparing the model with other models in terms of the data. Data levels might, for example, be at the individual, household or group level or there may be different resolutions of input data.

II.ii Individual decision-making

The following questions represent an important part of the extension of the ODD protocol with regards to the representation of decision-making in a model, as they explicitly address the basic design concepts behind it.

II.ii.a The documentation of the decision-making processes included in a model requires, first of all, that the subjects and objects of these processes are made explicit. The subjects are necessarily agents according to the definition above (see Section 3.1) and might belong to several different types, whereas the objects might be other elements of the model or may also be agents. As an example, farm household agents (subjects) might decide about the land-use state of land parcels they own (objects). The questions regarding multiple levels address models in which the decisions made on one level affect decisions made on higher or lower levels of aggregation; for example, farmer and government agents (Schlüter and Pahl-Wostl, 2007).

II.ii.b In this section, we focus the more general “Objectives” block from the ODD model on the specific characteristics of human decision-making. The rationality behind decision-making is crucial for understanding the role of decision-making in a model. It includes, for example, whether agents optimise according to an explicit objective, whether they have other types of success criteria, such as meeting aspiration thresholds, or whether they have no explicit objectives at all, as might be the case when decision-making heuristics are used. If agents have some type of success criterion, it should also be mentioned, whether they pursue it in a perfectly rational manner or whether their rationality is in some respects bounded, for example by limited information, limited cognitive capabilities, or limited decision-making time.

II.ii.c The question on how agents make their decisions refers to the way in which the rationality behind decision-making is translated into specific decision-making rules. For example, the pursuit of an objective might be implemented through the optimisation of an objective function via mathematical programming, whereas decision-making heuristics might be represented in a decision tree (Schreinemachers and Berger, 2006).

II.ii.d In this section, information shall be given on how agents adapt their behaviour to changing state variables, both endogenous and exogenous. Examples of agents adapting their behaviour is the adaptation of the number of irrigated fields to budget constraints and water inflow (see the example in Section 3) and of the mobility pattern of pastoralists to multiple stressors such as climate and policies (Boone et al., 2011). Because there is no universal agreement in the relevant literature on how to distinguish adaptation from learning, we have decided to use the one provided above in the “Definitions of terms” section (Section 3.1). According to this definition, adaptation occurs within given decision rules, whereas learning changes those rules.

II.ii.e Because real-world decision-making often takes place in relation to an individual’s social environment, it can be argued that social norms or cultural values should be reflected in models of decision-making (Van den Bergh et al., 2000). For example, trust between agents can be a basis for cooperation (Janssen et al., 2006), or traditional perspectives can represent an alternative strategy to purely economic profit maximisation (Millington et al., 2008).

II.ii.f Space plays a role in an agent’s decision-making process if the decision is influenced by the absolute or relative position of the agent or another entity in the model space. McAllister et al. (2006) investigated the role of spatial (and temporal) variations on the efficiency of the agistment networks in Australia using an ABM. Further examples can be found in An (2012).

II.ii.g Temporal aspects enter the decision process if agents’ decision-making takes into account past experiences or expectations for the future. Past experiences might be incorporated in some representation of the agent’s memory, which might also be related to agent learning (see Section II.iii below). The formation of expectations about the future depends on the ability of the agents to make predictions (see Section II.v below).

II.ii.h The information that the agents obtain may be characterised by uncertainty because, for example, agents have limited knowledge about future developments in the model. Thus, this section asks for a summary of the reactions to this uncertainty used in the model, which might enter the agents’ decision-making process at different points. Uncertainty might, for example, be included in different learning processes (see Section II.iii below), such as Bayesian learning, which seeks to gradually reduce uncertainty, or it might be directly manifested in the decision-making process, e.g. in the form of a satisficing rule (Gotts et al., 2003) or in the form of risk aversion (Quaas et al., 2007).

II.iii Learning

II.iii.a Learning is defined on the level of the individual by changes in each one’s decision-making rules. This is the part of the model documentation where different types of established learning representations can be cited (Brenner, 2006) or where the general idea behind the learning model can be described, e.g. reinforcement learning or belief-based learning.

II.iii.b Learning does not only take place on an individual level but also takes place on a collective level, when agents are able to exchange information. For example, different types of evolutionary algorithms can be used to represent how land-owner agents collectively “learn to interact, cooperate, and compromise” to decide about the use of common resources

(Bennett and Tang, 2009) or how researchers collectively learn to improve their publication practices (Watts and Gilbert, 2011).

II.iv Individual sensing

Compared to ecological sensing, where organisms or populations perceive their local environment, sensing becomes more complex in the context of human decision-making. Using societal structures, information may be transported on the global level. The following questions help to reflect on what information is exactly available before an agent has to decide. Thereby, all sensing processes may be erroneous.

II.iv.a In this section, the endogenous and exogenous state variables that agents are assumed to sense and consider in their decisions are summarised. Land managers may perceive the availability of (multiple) resources which include working power, monetary resources and different sources of income (e.g. Smajgl and Bohensky, 2012). Further, they may perceive the behaviour and actions of other agents (as opposed to the characteristics of other agents, see the following question) or market conditions. Additionally, the observation of the state of the natural resources can be erroneous (cf. Milner-Gulland, 2011, for a modelling study applying the management strategy evaluation approach).

II.iv.b This question refers to direct or indirect contact between agents that enables them to exchange information on their individual state. Signals may be sent between agents intentionally (e.g. Matthews, 2006) or unintentionally. Furthermore, it is asked whether the sensing process is erroneous.

II.iv.c The spatial scale of information flow may be local, global or via a network in the model space.

II.iv.d Sensing may be implemented via mechanisms by which agents obtain information explicitly, or via the assumption that agents simply know these variables. In the former case, signals or messages may be sent between agents (e.g. Matthews, 2006), which takes a certain amount of time within the model space so that information may not be available at once in every time step and may not be available to every agent.

II.iv.e This section asks whether the costs for cognition and costs for gathering information are included in the model. If the resources for gathering information are limited, it may be useful to include costs for different types of information acquisition, as e.g. motivated by the critique of rational choice (Simon, 1957).

II.v Individual prediction

The first question asks for data used by the agents for prediction, the second for their internal model and the last for their prediction error. The information used by the agent can be based on actual (spatial) observation, on experience or on a mixture of both. The agents' internal model describes how the agent processes the collected data to get predictions. This could be influenced by mental models such as a pessimistic versus optimistic view of the agents (e.g. Lux and Marchesi, 1999). The prediction error can, for instance, result from limited information processing capabilities of the agents or from unknown consequences of interactions with other resource users (e.g. unknown water extraction of upstream agents in Schlüter and Pahl-Wostl, 2007).

II.vi Interaction

We explicitly add the interactions between agents and entities in addition to the interactions among agents. Both can be mediated by the environment (Schlüter and Pahl-Wostl, 2007), by markets (Deadman et al., 2004) or auctions (Schreinemachers and Berger, 2011). The interaction itself depends on conditions (e.g. spatial distance, access to a resource). Additionally, we introduce a question about whether a (de)centralised or group-based coordination structure of the agents exists.

II.vii Collectives

Agents can belong to aggregations such as social groups, human networks or other organisations. These collectives can either emerge during the simulation or be defined by the modeller.

II.viii Heterogeneity

Agent heterogeneity is one of the characteristic features of ABMs. Agents may differ in parameters (e.g. managerial abilities, Happe et al., 2006; or preferences, Filatova et al., 2011). They can also be heterogeneous in their decision-making in terms of the different decision models (e.g. Jager et al., 2000, applied in Acosta-Michlik and Espaldon, 2008 and in Murray-Rust et al., 2011) or in their decision objects. If agents only differ in their state variables e.g. the location in space or financial budget, but are the same otherwise, we do not consider this population to be heterogeneous because exchanging an agent at the beginning of the simulation would not change the outputs of the simulation.

II.ix Stochasticity

To understand the model, it is crucial to know which processes include randomisation. Examples for coincidence in models can be the random initialisation of the values of agents' state variables (e.g. Balmann, 1997; Matthews, 2006), location of households on a map (e.g. Castella et al., 2005) or market-prices that influence agent decisions (e.g. Janssen et al., 2000).

II.x Observation

The questions asked in this paragraph aim to clarify which model output is collected at what time point in the simulation. It should also be stated which of the model results are a result of emergence.

III Details

The technical information that is needed to replicate the model and the experiments should be provided in this block (Grimm et al., 2006). This includes information on model implementation, availability of the model's source code, model input data and a detailed (mathematical) description of the submodels.

III.i Implementation Details

Information on the model implementation should be delivered in this section. This includes stating the programming language or modelling platform in which the model was implemented. For a list of further important implementation details, we refer to the "Guide for Authors" of the journal Environmental Modelling and Software and/or the data availability section (cf. EMS, 2012). Authors are encouraged to make the model code accessible (Janssen, 2009; Ince et al., 2012). If the model code was published, for example, in an open model library such as openabm.org, please state where it can be downloaded.

III.ii Initialisation

III.iii Input data

III.iv Submodels

We adopted the initialisation, input data and submodels elements almost as-given by Grimm et al. (2010). However, in the element 'Initialisation', we added the case that the data could be based on stakeholder choice.

4 Sample application of ODD+D

We present a sample application of the ODD+D protocol for describing an ABM of water use (Schlüter and Pahl-Wostl, 2007). The model has been used to compare the performance and resilience of a centralised and decentralised water governance system with single or multi-purpose water use in the face of uncertain water flows. The centralised version is a stylised representation of water management in the Amudarya river basin in Central Asia.

I Overview

I.i Purpose

The purpose of the model is to understand how different governance structures (centralised versus decentralised) and diversity of water use affect the resilience of a farming community to variable and uncertain water flows. The model has been designed for scientists, particularly those interested in natural resource governance and resilience, with the aim of testing hypotheses about resilience mechanisms.

I.ii Entities, state variables and scales

The model consists of two types of human agents, individual farmers and a regulator such as a national government authority, and one animal agent, an age-structured fish population. A fourth entity is the water resource. Water is modelled as the units of water that enter the river stretch upstream and are then distributed downstream along the river onto the fields and into a terminal fishing lake. Farmers are characterised by their location along the river and hence the distance to the water inflow and the fishing lake, the number of fields they irrigate, their individual expectation of the water available each season, their memory of past water deliveries, the yield they receive from cultivating their fields, the catch from fishing, and the financial budget that is determined by their net returns from agriculture and fishing activities. The national authority is characterised by the total number of fields irrigated in the area, its expectation of water availability each season, its memory of past water flows and a budget that is the sum of all of the farmers' net incomes from irrigation.

The fish population is composed of 12 age classes. Age 0 is larvae that are born in the lake or migrate to the lake from upstream, ages 1-4 are juveniles and ages 5-12 are adult. Each age group is characterised by specific density-dependent and density-independent mortalities, birth and reproductive rates and, in the case of the age 0 class, a migration rate. The water entity is characterised by a unidirectional flow that is reduced by irrigation uptakes by the farmers. The remaining water at the downstream end of the river stretch enters the lake where the fish population is located. Water inflow into the river stretch from upstream is an exogenous variable. The parameters of the model are given in Table 2 of Online Appendix B.

The governance structure is represented by two different model structures, a centralised and a decentralised version, that differ in terms of which type of agent (farmer or national authority) makes the decisions on the number of fields to irrigate in a season and hence the amount of water to withdraw from the river.

Space is implicitly included through the location of each farm along the river stretch, which determines the farm's access to water and to the fish resources as well as the information each farmer has on the water flows. There are nine farms along the river. The model runs with monthly time steps over a period of 200 years. Decisions about the number of fields to irrigate in a season are taken at the beginning of a season.

I.iii Process overview and scheduling

Within each year, a sequence of activities takes place in the following order. In the centralised version at the beginning of the season (April), the national authority predicts the expected water inflow to the river stretch and decides on the number of fields to irrigate. The farmers calculate their water demand and irrigate the fields each month with the water actually available. Crops experience water stress when they do not receive the required amount of water. The remaining water after all fields have been irrigated, if any, flows into the lake. At the end of the year, the fish population grows, the farmers fish and harvest, and the national authority calculates its budget.

In the decentralised version, all farmers make their individual prediction of the expected water availability at their location along the river stretch at the beginning of the season, and decide on the number of fields to irrigate. They calculate the water needed to irrigate their fields each month. They irrigate the fields each month with the actually available water. Crops experience water stress when they do not receive the required amount of water. The water remaining after all fields have been irrigated, if any, flows into the lake. At the end of the year, the fish population grows and the farmers fish, harvest and calculate their individual budgets. Each agent is updated in the sequence determined by its location along the river stretch.

II Design concepts

II.i Theoretical and empirical background

The hypothesis that this model was designed to test was informed by resilience thinking (Folke et al., 2010). The modelling of the fish population growth is based on population dynamics theory, in particular, the Ricker model (Ricker, 1954). The water distribution and the impact of water stress on crop yield are modelled based on standard hydrological and agricultural approaches. The agents' decision model is based on the assumption that their information processing capacity is limited and that they have only partial information on water availability, hence they are boundedly rational (Simon, 1957). The agents use a form of inductive reasoning (Deadman et al., 2000) and rely on heuristics that guide their behaviour (Ostrom et al., 1994). They have no foresight. They are satisficers who, once they are above a certain minimum income threshold, engage in a process of trial and error to determine their best irrigation strategy based on their experience with past strategies. It is also assumed that the agents have different memory strengths with respect to past water flows. The memory strength affects their prediction of future water availability. The decision model of the national authority is based on real-world heuristics of water allocation. It is a simplified caricature of decision-making in the case study.

The ad-hoc decision model for the decentralised version was chosen because a decentralised setting does not exist in the case study and hence there are no data. The calculation of the expected water availability is based on the assumption that agents have different memories of past events and value this past experience differently. The method is based on a discounting approach used before in models of agent past memory (e.g. Satake et al., 2007). A 15-year runoff time series for a gauging station at the entrance to the Amudarya river has been used to determine the exogenous inflow to the river stretch (Schlüter et al., 2005).

II.ii Individual decision-making

Decision-making is modelled on two different levels, the national and the local. In the centralised version, the national authority decides the number of fields to be irrigated by the farmers along the entire river stretch. Farmers only execute the decisions. In the decentralised version, each individual farmer decides on the number of fields to irrigate on the farm. The number of fields determines the amount of water diverted to the farm (if available).

The agents pursue the objective of finding the number of fields they can irrigate with the uncertain water supply and a limited budget. They try to find the best strategy by adapting the number of fields based on an evaluation of their past performance. They do so by adapting their behaviour to changes in expected water availability, experienced water flows, yields and budget. The heuristics the agents use to make a decision on how many fields to irrigate are represented in a decision tree.

Social norms or cultural values and spatial aspects do not play a role in decision-making; however, the latter influence the outcome of the decision. The decision on how many fields to irrigate is influenced by the memory of past water availability. Agents can have different memory strengths, i.e. they weigh the experience from past years more or less strongly. Note, however, that within a simulation run, the agents do not differ in their memory strength.

Uncertainty is not explicitly included in the agent’s decision rule; however, agents try to address the uncertainty of water flows by taking past flows as a predictor of future ones. The willingness of individual farmers to change their irrigation strategy and hence take the risk of losing their investment depends on their past income level. If the level is below a minimum value, the farmers take more risks.

II.iii Learning

No individual or collective learning is included in the decision process.

II.iv Individual sensing

The national authority knows about the realised water flows into the river stretch (note that this happens after the decision on the number of fields to prepare for irrigation has been made), the total agricultural budget available and the total irrigation costs. The farmers know in hindsight the amount of water delivered to their fields, their own budget, the costs of irrigation and the crop yields. Hence for the national authority, the spatial scale of sensing is global; for the farmers, the spatial scale is local. The agents receive this information for the on-going year without error. Farmers do not know any of the state variables for other farmers, but the national authority knows the net returns from irrigation of each farmer in the centralised version. In the model implementation, agents are assumed to simply know the values of the relevant variables, i.e. they do not carry out any activities to receive this information. The costs for cognition or for gathering information are also not explicitly included.

II.v Individual prediction

The national authority uses the information on past inflow to the river stretch to predict future water flows; the farmers use the information about past water deliveries to their fields to assess how much water they can expect in the next year. The agents make their prediction based on their memory of those past water flows. The prediction process is implemented through a weighted average of past water flows, where the weights are determined by the memory strength. The prediction is erroneous because of the variability of water inflows between years that is not known to the agents and the loss of memory of the agents. The downstream agents also do not know the water extraction of the upstream agents.

II.vi Interaction

Interactions among agents are indirect through their water and fish extraction (the resource extracted by one agent is no longer available for the other agents); the interactions are thus a consequence of the resources being common pool resources. The interactions depend on the location of the agent in relation to the water flow and distance from the fishing lake. In the centralised version, the national agency coordinates water use. Here, coordination affects the water extraction decision of each agent. In the decentralised scenario, no coordination mechanism exists.

II.vii Collectives

Agents do not belong to or form any collectives.

II.viii Heterogeneity

There is no heterogeneity of agents. Agents are not heterogeneous in their decision-making.

II.ix Stochasticity

Within the catchable age classes of the fish population, the actual age class from which a fish is caught is modelled randomly.

II.x Observation

The annual yields and catch of each farmer, accumulated total returns and abundance of the fish population are collected at the end of each year to compare the two model versions and the different scenarios of memory capacity and diversity of water use and for sensitivity analysis. A distinct pattern of distribution of yields along the upstream-downstream gradient emerges.

III Details

The model was implemented in Java using the Repast platform. The source code can be made available upon request.

The model world is initialised with nine farmers that all have the same initial budget, number of irrigated fields, yields and memory capacity but differ in their location along the river. The national authority in the centralised scenario has an initial budget, an initial number of fields and a memory capacity. The initial values for the agents and the fish population have been determined through calibration. The initial number of fields is varied among simulations to reflect scenarios with a strong focus on agriculture or fisheries. The inflow to the river stretch is provided by a data file of the observed characteristic runoff time series for the Amudarya River.

The model has a main part that models the actions of the two types of agents (the farmers and the national agency) and two submodels that represent the two resources (water and fish). The model parameters, their dimensions and default values are given in Table B.2 of Online Appendix B.

The remaining details section is described in Online-Appendix B. There, the completed template for the ODD+D protocol for this example can also be found.

5 Discussion

The documentations of ABMs that include human decision-making often do not describe the details that are needed to understand and replicate the decision-making part, particularly with respect to the underlying assumptions and theories on which the agent's decision making is based. Using standardised protocols can help to provide model descriptions that meet this need. The ODD protocol is now widely used for describing agent- or individual-based models in general, but lacks the details relating to decision-making. Therefore, we have introduced an extension for the ODD protocol to describe human decision-making in ABMs: ODD+D.

5.1 Expected benefits from ODD+D

Using standardised protocols to describe simulation models offers many advantages (see also Grimm et al., 2010): The experienced scientific audience can understand the models described with a standardised protocol more easily, and meta-analyses on existing models is facilitated. Our protocol also eases the use of the taxonomy of ABMs suggested by Hare and Deadman (2004): The three taxonomy levels (coupling social and environmental model, social interaction and intrinsic adaptation) are covered in Sections I.ii, II.vi and II.ii.d of the ODD+D protocol, respectively. Referees of scientific articles may find it easier to review a manuscript that draws upon such a protocol. Modellers do not have to decide upon the structure of their model description, as the structure is already given by the protocol. And finally, modellers-to-be seeking guidance on and thinking about what aspects of a model have to be conceptualised before implementing the model, might use the ODD+D protocol as a checklist for the model development process.

5.2 The added value of the ODD+D protocol compared to the ODD protocol

The ODD+D protocol enhances the original ODD protocol in three ways: First, it incorporates the central aspects of human decision-making into the design concepts section resulting in a considerable re-organization of this section. New components on individual decision-making and heterogeneity were added, and numerous questions regarding concepts that are missing in the ODD protocol were included, i.e. coordination, temporal aspects in decision-making, cultural values and the like. Second, greater emphasis has been placed on the theoretical and empirical basis by renaming the "basic principles" section and adding more detailed questions regarding the background of the model in general and the decision-making algorithms in particular. Third, the design concepts were organised (including a reversed order) in a hierarchical fashion. Finally, minor aspects have been revised, such as adding questions regarding target groups, exogenous factors, space and implementation details.

By implementing these alterations, the ODD+D protocol allows for a concise and well-structured documentation of human decision-making in a more straightforward way than the original ODD protocol. In the example description, the ODD+D protocol helped to make the theoretical foundations of the decision-making algorithms more explicit, which would not have been possible with the ODD protocol. This makes it easier to link the model results to the results of other models that are based on similar assumptions about the decision-making process. It also facilitates the assessment of model results in view of the underlying assumptions and thus promotes a better understanding of the robustness and scope of the results. The ODD+D protocol also provides for the specification of the empirical data used as input to the model, which would not have been mentioned in the ODD protocol. This allows for a better understanding of how the model relates to a real-world setting. Finally, the questions about individual decision-making specify the details of the decision making process that would not be revealed in the ODD protocol but are relevant for assessing model outcomes, e.g. how the memory of past water flows affects the performance of individual farmers and the overall system in the face of inflow uncertainty.

5.3 The effort required to use the ODD+D protocol

The ODD+D protocol requires answering a variety of questions, which is inevitably time consuming. Compared to the ODD protocol, the ODD+D protocol, especially the Design concepts section, includes more questions and thus leads to a more lengthy documentation. Therefore, we provide a template that guides the user through the questions. Some of the questions can be answered simply using keywords instead of full-length descriptions. Thus, we think that the additional effort required when using the ODD+D compared to ODD is negligible. The wide usage of the ODD protocol shows that a detailed protocol is currently well received by the scientific community. We believe that the ODD+D protocol will make the documentation of human decision-making easier.

For users who have not described their simulation model before, applying the ODD+D protocol definitely requires effort to answer all of the questions. However, the structure provided in the ODD+D protocol will very likely facilitate the whole documentation process, as users do not have to decide upon the structure of their description. Users who already have a model description in the ODD protocol need to consider the additions made by the ODD+D protocol (see Figure 1 and Table 1 for a comparison of the ODD and ODD+D protocols). In sum, they need to (1) describe the spatial aspects in the overview section, (2) re-arrange the design concepts section into the ODD+D structure and answer the supplemented guiding questions of the copied design concepts, (3) add (3a) the theoretical and empirical background, (3b) individual decision-making and (3c) heterogeneity in the Design Concepts section and finally (4) provide implementation details in the Details section.

5.4 Future work

This first version of the ODD+D protocol was developed based on experiences gained in the social-ecological scientific community. We believe that the ODD+D protocol may prove to be helpful for describing ABMs in general. However, describing models with other thematic foci such as economic, sociological or political research questions might reveal blind spots in the ODD+D protocol. Furthermore, a wider application will show if the current structure of the ODD+D protocol constrains modellers and if model descriptions become very lengthy. Such issues should be addressed in updates of the protocol. This first version is meant as a starting point for a participatory discourse on describing ABMs including human decision-making. The scientific community is invited to try out the ODD+D protocol and participate in discussions on the protocol by contacting the authors of this article. Updates to the ODD+D protocol will be published on the website mentioned in Section 3.4.

A further challenge is the development of a ΔODD protocol to describe different model variants (Polhill et al., 2008) and its usage in the ODD+D protocol. This is especially relevant for describing human decisions, as testing the influence of different decision algorithms in a single overall model is often a part of ABM studies. Apart from that, the usability of the ODD+D protocol in the model development part of the TRACE modelling process documentation (Schmolke et al., 2010) still has to be tested. Finally, the current version of the ODD+D protocol draws solely on written text for describing the model concept and implementation. It might be useful to also provide templates for visualising individual aspects of the model, for instance using UML or the Web Ontology Language (Polhill and Gotts, 2009).

In sum, the ODD+D protocol shall foster the explicit description of the theoretical background of ABMs incorporating human decisions and important details of the model implementation. This enables the scientific community to reproduce simulation results and to further develop already existing models. As the ODD+D protocol also explicitly asks for the underlying theories, the ability of a theory or hypothesis to replicate patterns found in the real world can be assessed more easily. Furthermore, widespread usage of a protocol such as ODD+D would clearly facilitate model comparisons focused on human decisions. The ODD+D protocol might address the “particular need for research that compares these decision making models to extant theory, practice, and observation of the real world” (Parker et al., 2003) by facilitating model comparisons related to specific theories.

6 Online – Appendix A

The template for the ODD+D protocol, including guiding questions, examples and an empty column for the reader’s own model description.

7 Online – Appendix B

The completed template for the example and descriptions of the submodels.

Acknowledgements

We thank Nils Bunnefeld, Kornelia Fischer, Volker Grimm, Ryan McAllister, James Millington, Janos Sebestyen and participants of the workshop on human decisions in agent-based models during the iEMSs conference 2012 in Leipzig for very helpful comments on earlier versions of the manuscript. Financial support from the DFG (German Research Foundation) in the framework of the Collaborative Research Centre 586 "Difference and Integration: Interaction between nomadic and settled forms of life in the civilisations of the old world" (Universities of Leipzig and Halle) is gratefully acknowledged. MS acknowledges funding by the German Ministry for Education and Research within the project Besatzfisch in the Program for Social-Ecological Research (Grant 01UU0907) and the European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013)/ERC grant agreement no. 283950 SES-LINK. We thank three anonymous referees for their comments that greatly improved our manuscript and Anne Carney for scanning this paper from a grammatical point of view.

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Figure caption:

Figure 1: The structure of the ODD+D protocol. Grey boxes indicate new design concepts/categories compared to the ODD protocol. The numbers of added new questions are noted in parentheses. The different aspects of the new design concept "Individual decision-making" are displayed on the right.

Online Appendix A:

Table A.1. Template for ODD+D including guiding questions, examples and empty column for own model description, bold font denotes newly developed parts compared to Grimm et al., 2010.

Outline (→ template)		Guiding questions	Examples	Own ODD+D Model description
I) Overview	I.i Purpose	I.i.a What is the purpose of the study?	Research question incl. test of hypothesis, **system understanding, theory development, quantitative predictions, management or decision support, communication and learning (participatory modeling)**	
		I.ii.b For whom is the model designed?	**Scientists, students/teachers, decision makers, stakeholders**	
	I.ii Entities, state variables, and scales	I.ii.a What kinds of entities are in the model?	Agents / individuals (humans, institutions): types and subtypes, spatial units (grid cells), environment, collectives (groups of agents)	
		I.ii.b By what attributes (i.e. state variables and parameters) are these entities characterized?	Of Agents: identity number, age, sex, maximum age, memory, location, level of resources, **ownership of land,** (political) opinion, occupation, **decision model (only mention the name of the strategy, which is explained later on), one agent represents one individual / one household / one farm / all individuals of one specific type**, of spatial units: location, a list of agents in a cell, **land owned by farmer**, descriptor of environmental conditions (elevation, vegetation cover, soil type), current land use of collectives: list of agents, specific actions Units of measurement	
		I.ii.c What are the exogenous factors / drivers of the model?	**Disease, climate, lake water level, land cover change, tectonic disturbances, invasive species, legislation**	
		I.ii.d If applicable, how is space included in the model?	**Not included, spatial implicit, spatial explicit, georeferenced (GIS)**	
		I.ii.e What are the temporal and spatial resolutions and extents of the model?	One time step represents one year and the simulations were run for 100 years, one grid cell represents 1 ha and the model landscape comprises 1000 x 1000 ha	
	I.iii Process overview and scheduling	I.iii.a What entity does what, and in what order?	Self-explanatory names of the model's processes, **including decision making processes,** pseudo-code of the schedule, synchronous / asynchronous update	

II) Design Concepts	**II.i Theoretical and Empirical Background**	II.i.a Which general concepts, theories or hypotheses are underlying the model's design at the system level or at the level(s) of the submodel**(s) (apart from the decision model)?** What is the link to complexity and the purpose of the model?		
		II.i.b On what assumptions is/are the agents' decision model(s) based?	**Established theories (micro-economic models: homo oeconomicus, full / bounded rationality; cognitive models: social psychology, mental models; space-theory based models)** **real-world observations (mechanistic explanations / process-based understanding available; black-box, use of heuristics, statistical regression methods)** **ad-hoc rules (dummy rules, e.g. constancy assumption)** **combinations of theory and observations**	
		II.i.c Why is a/are certain decision model(s) chosen?	**Data (non-) availability, pattern-oriented modeling, reference to other studies, theoretical considerations**	
		II.i.d If the model / a submodel (e.g. the decision model) is based on empirical data, where does the data come from?	**Participatory approaches (role playing games), household surveys, interviews, direct observations, statistical census, archives, GIS, field or lab experiments**	
		II.i.e At which level of aggregation were the data available?	**Household / individual level, group level**	
	II.ii Individual Decision Making	**II.ii.a What are the subjects and objects of decision-making? On which level of aggregation is decision-making modeled? Are multiple levels of decision making included?**	**Name subjects (individuals agents / households, on communal level, top down decision maker) and objects of decisions, e.g.: Form of land use, distribution of labor, choices of buying and selling**	
		II.ii.b What is the basic rationality behind agents' decision-making in the model? Do agents pursue an explicit objective or have other success criteria?	**Rational choice (classical optimization approach, utility maximization), bounded rationality (satisficing approach), no objectives (routine based, trial and error)**	
		II.ii.c How do agents make their decisions?	**Decision tree, utility function, random choice**	
		II.ii.d Do the agents adapt their behavior to changing endogenous and exogenous state variables? And if yes, how?	**Adaption of resource extraction level in dependence of ecological state of resource**	
		II.ii.e Do social norms or cultural values play a role in the decision-making process?	**Cultural norms, trust**	

		II.ii.f Do spatial aspects play a role in the decision process?	**Space-theory based models**	
		II.ii.g Do temporal aspects play a role in the decision process?	**Discounting, memory**	
		II.ii.h To which extent and how is uncertainty included in the agents' decision rules?	**Not at all / stochastic elements mimic uncertainties in agents' behavior / agents explicitly consider uncertain situations or risk**	
	II.iii Learning	II.iii.a Is individual learning included in the decision process? How do individuals change their decision rules over time as consequence of their experience?	**Change of aspiration levels depending on past experiences**	
		II.iii.b Is collective learning implemented in the model?	**Evolution, genetic algorithms**	
	II.iv Individual Sensing	II.iv.a What **endogenous** and **exogenous** state variables are individuals assumed to sense and consider in their decisions? **Is the sensing process erroneous?**		
		II.iv.b What state variables of which other individuals can an individual perceive? **Is the sensing process erroneous?**	**(Multiple) resources (including working power, monetary resources, other income resources) and behavior of other agents**	
		II.iv.c What is the spatial scale of sensing?	Local, network, global (whole model space)	
		II.iv.d Are the mechanisms by which agents obtain information modeled explicitly, or are individuals simply assumed to know these variables?	Sensing is often assumed to be local, but can happen through networks or can even be assumed to be global.	
		II.iv.e Are costs for cognition and costs for gathering information inclu-ded in the model?		
	II.v Individual Prediction	**II.v.a Which data uses the agent to predict future conditions?**	**Extrapolation from experience, from spatial observations**	
		II.v.b What internal models are agents assumed to use to estimate future conditions or consequences of their decisions?		
		II.v.c Might agents be erroneous in the prediction process, and how is it implemented?	**(External) uncertainty, (internal) capability of the agent**	
	II.vi Interaction	II.vi.a Are interactions among agents and entities assumed as direct or indirect?	Direct interactions, indirect interactions (mediated by the environment / **the market, auction)**	
		II.vi.b On what do the interactions depend?	**Spatial distances (neighborhood), networks, type of agent**	

		II.vi.c If the interactions involve communication, how are such communications represented?	**Explicit messages (Matthews et al., 2007)**	
		II.vi.d If a coordination network exists, how does it affect the agent behaviour? Is the structure of the network imposed or emergent?	Centralized vs. decentralized, group based tasks	
	II.vii Collectives	II.vii.a Do the individuals form or belong to aggregations that affect, and are affected by, the individuals? Are these aggregations imposed by the modeller or do they emerge during the simulation?	Social groups, human networks and organizations	
		II.vii.b How are collectives represented?	Collective as emergent property vs. as a definition by the modeler (separate kind of entity with its own state variables and traits)	
	II.viii Heterogeneity	**II.viii.a Are the agents heterogeneous? If yes, which state variables and/or processes differ between the agents?**	**Would an exchange of one agent with another at the beginning have an effect on the simulation?**	
		II.viii.b Are the agents heterogeneous in their decision-making? If yes, which decision models or decision objects differ between the agents?		
	II.ix Stochasticity	II.ix.a What processes (including initialization) are modeled by assuming they are random or partly random?		
	II.x Observation	II.x.a What data are collected from the ABM for testing, understanding, and analyzing it, and how and when are they collected?		
		II.x.b What key results, outputs or characteristics of the model are emerging from the individuals? (Emergence)		
III) Details	**II.i Implementation Details**	**III.i.a How has the model been implemented?**	**Computer system, programming language / simulation platform, simulation runtime, development time**	
		III.i.b Is the model accessible and if so where?	**Homepage?(link)**	
	III.ii Initialization	III.ii.a What is the initial state of the model world, i.e. at time t=0 of a simulation run?	Types and numbers of entities including the agents themselves, values / random distribution of their state variables	
		III.ii.b Is initialization always the same, or is it allowed to vary among simulations?		
		III.ii.c Are the initial values chosen arbitrarily or based on data?	References to data if any, **stakeholder choice**	

	III.iii Input Data	III.iii.a Does the model use input from external sources such as data files or other models to represent processes that change over time?	Observed time series e.g. annual rainfall, time series generated by other models, not: parameter values, initial values of state variables	
	III.iv Submodels	III.iv.a What, in detail, are the submodels that represent the processes listed in 'Process overview and scheduling'?	Equations, algorithms, additional information	
		III.iv.b What are the model parameters, their dimensions and reference values?	Tables of parameters	
		III.iv.c How were submodels designed or chosen, and how were they parameterized and then tested?	Justifications, references to literature, independent implementation, testing, calibration, analysis of submodels	

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Online Appendix B:

Table B.1: ODD+D protocol for the example of an ABM of water use (Schlüter and Pahl-Wostl, 2007). CV = centralised version, DV = decentralised version

		Guiding questions	Example (Schlüter and Pahl-Wostl, 2007)
I. Overview	I.i Purpose	I.i.a What is the purpose of the study?	To understand how different governance structures (centralised versus decentralised) and diversity of water use affect the resilience of a farmer community to variable and uncertain water flows.
		I.i.b For whom is the model designed?	For scientists, particularly those interested in natural resource governance and resilience.
	I.ii Entities, state variables and scales	I.ii.a What kinds of entities are in the model?	• two types of human agents - individual farmers and a regulator such as a national government authority • one biological entity that is an age-structured fish population • the water resource, as a bio-physical entity
		I.ii.b By what attributes (i.e. state variables and parameters) are these entities characterised?	Farmer: location along the river (determines distance to the water inflow and the fishing lake), number of irrigated fields, expectations of water availability, memory of past water deliveries, yield, fish catch, budget National authority: number of irrigated fields, expectations of water availability, memory of past water flows, budget Fish population: 12 age classes, in-migration rate, density-dependent and density-independent mortalities per age class, birth and reproductive rates Water: flow
		I.ii.c What are the exogenous factors / drivers of the model?	Water inflow into the river stretch from upstream.
		I.ii.d If applicable, how is space included in the model?	Implicitly through the location of each farm along the river stretch which determines its access to water and to the fish resources as well as the information each farmer has on water flows.
		I.ii.e What are the temporal and spatial resolutions and extents of the model?	Monthly time steps, 200 years, irrigation decisions are taken at the beginning of a season, i.e. once a year. Nine farms along the river and one lake at the end.
	I.iii Process overview and scheduling	I.iii.a What entity does what, and in what order?	CV, beginning of season (April): national authority predicts water inflow to the river stretch, decides about the number of fields to irrigate, farmers calculate water demand. CV, each month: farmers irrigate, water flows onto the fields and into the lake. CV, end of the year: fish population grows, farmers harvest, national authority calculates budget. DV, beginning of season (April): each farmer predicts water availability at his location along the river, decides on the number of fields to irrigate, calculates water demands. DV, each month: farmers irrigate, water flows onto the fields and into the lake. DV, end of the year: fish population grows, farmers harvest, calculate individual budgets. Each agent is updated in the sequence determined by its location along the river stretch.
II. Design Concepts	II.i Theoretical and Empirical Background	II.i.a Which general concepts, theories or hypotheses are underlying the model's design at the system level or at the level(s) of the submodel(s) (apart from the decision model)? What is the link to complexity and the purpose of the model?	Resilience thinking, population dynamics theory (Ricker, 1954), standard hydrological and agricultural approaches. For the fish population an age-structured model was used in order to represent the differential effect of water inflows on the zero age class (inflow of larvae into the population).
		II.i.b On what assumptions is/are the agents' decision model(s) based?	Agents are bounded rational (Simon, 1957), use a form of inductive reasoning (Deadman et al., 2000) and rely on heuristics (Ostrom et al., 1994). They have no foresight. Once they are above a certain minimum income threshold they engage in a process of trial and error to determine their

			best irrigation strategy based on their experience with past strategies.
		II.i.c Why is /are certain decision model(s) chosen?	The decision model of the national authority is based on real-world heuristics of water allocation in the case study. The ad-hoc decision model of the farmers was chosen because a decentralised setting does not exist in the case study and hence there are no data.
		II.i.d If the model / submodel (e.g. the decision model) is based on empirical data, where do the data come from?	A runoff time series for a gauging station at the entrance to the Amudarya river has been used to determine the exogenous inflow to the river stretch.
		II.i.e At which level of aggregation were the data available?	Monthly.
	II.ii Individual Decision Making	II.ii.a What are the subjects and objects of the decision-making? On which level of aggregation is decision-making modelled? Are multiple levels of decision making included?	Two levels, however in different model versions. In CV the national authority decides about the number of irrigated fields and the farmers follow. In DV the farmers decide about the number of irrigated fields themselves.
		II.ii.b What is the basic rationality behind agent decision-making in the model? Do agents pursue an explicit objective or have other success criteria?	Agents pursue the objective of finding the optimal number of fields they can irrigate with an uncertain water supply and a limited budget.
		II.ii.c How do agents make their decisions?	They compare their past yields with their minimum income level, assess past water flows and their current budget to select a strategy for the next season.
		II.ii.d Do the agents adapt their behaviour to changing endogenous and exogenous state variables? And if yes, how?	Yes, they use basic balance calculations or a simple heuristic to adapt the number of irrigated fields to the expected water availability, experienced water flows, past yields and budget.
		II.ii.e Do social norms or cultural values play a role in the decision-making process?	No.
		II.ii.f Do spatial aspects play a role in the decision process?	No, but the location of an agent influences the outcome of his decisions.
		II.ii.g Do temporal aspects play a role in the decision process?	Yes – agents have a memory of past water availability. The memory strength varies between different scenarios.
		II.ii.h To which extent and how is uncertainty included in the agents' decision rules?	Uncertainty is not explicitly included in the agent's decision rule; however, agents try to deal with the uncertainty of water flows by taking past flows as a predictor of future ones.
	II.iii Learning	II.iii.a Is individual learning included in the decision process? How do individuals change their decision rules over time as consequence of their experience?	No.
		II.iii.b Is collective learning implemented in the model?	No.
	II.iv Individual Sensing	II.iv.a What endogenous and exogenous state variables are individuals assumed to sense and consider in their decisions? Is the sensing process erroneous?	Individuals sense water flows, irrigation costs, yields and their budget. The sensing of water flows is erroneous because it is an estimation based on past water flows. Irrigation costs, yields and budget are known without error.
		II.iv.b What state variables of which other individuals can an individual perceive? Is the sensing process erroneous?	The national authority knows the net return from irrigation of all farmers without error.
		II.iv.c What is the spatial scale of sensing?	Global (national authority), local (farmers).
		II.iv.d Are the mechanisms by which agents obtain information modelled explicitly, or are individuals simply	The calculation of expected water availability is modelled explicitly (as a weighted average of past water flows). All other variables are just known by the agents.

		assumed to know these variables?	
		II.iv.e Are the costs for cognition and the costs for gathering information explicitly included in the model?	No.
	II.v Individual Prediction	II.v.a Which data do the agents use to predict future conditions?	Data on past water flows at its location.
		II.v.b What internal models are agents assumed to use to estimate future conditions or consequences of their decisions?	No specific models.
		II.v.c Might agents be erroneous in the prediction process, and how is it implemented?	Agents' predictions are erroneous because of unknown variability of water inflows and the loss of memory of past water flows. Downstream agents also do not know the water extraction of upstream agents. Agents estimate water availability using a weighted average of past water flows where the weights are determined by their memory capacity.
	II.vi Interaction	II.vi.a Are interactions among agents and entities assumed as direct or indirect?	Indirect through water and fish extraction (common pool resources).
		II.vi.b On what do the interactions depend?	Location of the agents along the river stretch.
		II.vi.c If the interactions involve communication, how are such communications represented?	N/A.
		II.vi.d If a coordination network exists, how does it affect the agent behaviour? Is the structure of the network imposed or emergent?	CV: the national authority is a coordination structure that coordinates water use by determining the amount of water for each farmer (equally distributed). There is no coordination network. The actors implement the decisions of the national authority without errors. DV: no coordination exists.
	II.vii Collectives	II.vii.a Do the individuals form or belong to aggregations that affect and are affected by the individuals? Are these aggregations imposed by the modeller or do they emerge during the simulation?	No.
		II.vii.b How are collectives represented?	N/A.
	II.viii Heteroge-neity	II.viii.a Are the agents heterogeneous? If yes, which state variables and/or processes differ between the agents?	No.
		II.viii.b Are the agents heterogeneous in their decision-making? If yes, which decision models or decision objects differ between the agents?	The agents are not heterogeneous in their decision-making.
	II.ix Stochasticity	II.ix.a What processes (including initialisation) are modelled by assuming they are random or partly random?	Vulnerability of the different age classes is modelled random (i.e. the age class from which a fish is taken by fishing).
	II.x Observation	II.x.a What data are collected from the ABM for testing, understanding and analysing it, and how and when are they collected?	Annual yields and catch of each farmer, accumulated total returns, abundance of the fish population are collected at the end of each year.

		II.x.b What key results, outputs or characteristics of the model are emerging from the individuals? (Emergence)	A distinct pattern of distribution of yields along the upstream-downstream gradient emerges depending on governance type (centralised or decentralised), diversity of water use, and the memory capacity of agents.
III. Details	III.i Implementation Details	III.i.a. How has the model been implemented?	In Java using the Repast platform.
		III.i.b Is the model accessible, and if so where?	Can be made available upon request.
	III.ii Initialisation	III.ii.a What is the initial state of the model world, i.e. at time t=0 of a simulation run?	Nine farmers with equal initial budget, number of irrigated fields, yields, and memory capacity. National authority with an initial budget, an initial number of fields and a memory capacity.
		III.ii.b Is the initialisation always the same, or is it allowed to vary among simulations?	The initial number of irrigated fields is varied.
		III.ii.c Are the initial values chosen arbitrarily or based on data?	The initial values for the agents and the fish population have been determined through calibration. The inflow to the river stretch is provided by a data file with an observed characteristic runoff time series for the Amudarya river.
	III.iii Input Data	III.iii.a Does the model use input from external sources such as data files or other models to represent processes that change over time?	A 15-year time series of river runoff is provided as input from a data file.
	III.iv Submodels	III.iv.a What, in detail, are the submodels that represent the processes listed in 'Process overview and scheduling'?	Water flow prediction Water allocation planning Irrigation Fishing Fish Population Growth Water Flow Budget calculation
		III.iv.b What are the model parameters, their dimensions and reference values?	See Appendix 2, Table 2
		III.iv.c How were the submodels designed or chosen, and how were they parameterised and then tested?	See text below.

Submodels

Water flow prediction: The agents predict water flows for the upcoming year by evaluating the observed water flows of previous years during the peak month of July. In the centralised version, the national authority bases its prediction on past flows into the river stretch. In the decentralised version, each farmer bases his prediction on the observed water flows at his location along the river stretch. Both the national authority and farmers have a memory capacity, δ, that determines the strength with which past years affect the current year's estimate. This is modelled with the following relationship:

$$V_{7,E,t} = \frac{\sum_{i=0}^{t-1} \delta^i * V_{7,R}(t-1-i)}{\sum_{i=0}^{t-1} \delta^i}$$

Where $V_{7,E}$ = expected water flow in month 7, $V_{7,R}$ = received water flow in month 7, δ = memory capacity.

The smaller delta is, the stronger an agent weighs the most recent years' experiences and the more the estimates try to capture the fluctuations in water availability.

Water allocation planning: The agents base their decision on the number of fields to irrigate each season on their prediction of water flows and the available budget. In the centralised version, the national authority determines the number of fields that can be irrigated with the expected amount of water and the available budget and distributes the water resources equally to all farmers. If the budget is not sufficient, the national authority reduces the number of irrigated fields to the amount that can be cropped. In the decentralised version, each farmer first assesses his income situation. If the income in the past year was below a critical threshold the farmer will risk and increase the number of irrigated fields by one independent of the water flow predictions, hoping that more water will be available in the current year. If his income is above the threshold but his water demands have not been met in the previous year, the farmer will not risk losing his investment but rather irrigate the number of fields suitable for the amount of water he/she expects in the current year. If the farmer received the demanded amount of water in the past year and has the necessary financial resources, he/she will increase the number of fields by one to test whether he/she can receive more water in the future. In all cases, the number of irrigated fields is limited by the farmer's available budget and the maximum number of fields of the farm.

Irrigation: During the vegetation season, farmers irrigate their fields every month. Water stress occurs when the amount of water delivered is less than the amount needed to irrigate all of the planned fields. Water stress accumulates over the season and affects yields according to the following relationship:

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

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.

Fishing: The farmers access the fishing lake in the order of their distance from the lake, i.e. the downstream farmers can access the lake first. Each farmer tries to catch the amount of fish given by a fixed target catch level. Fishing is not costly to the farmer and does not affect agricultural activities. Fish are caught randomly from one of the adult age classes.

Fish population growth: The fish population is modelled with an age-structured Leslie type matrix model with 12 age classes. The age 0 class is composed of fish born by all mature age classes (age 5-12) as well as larvae that migrate into the lake from upstream. Migration depends on the amount of water inflow into the lake during reproduction in May, which has to be above a certain threshold so that the larvae can survive. The number of larvae transported into the lake is proportional to the water volume once the threshold value is passed. Survival of the fish in the juvenile age classes 1-4 is density dependent, while adult fish are only subject to density-independent natural mortality. Only adult fish from age class 5 and onwards are harvested, and fish older than 12 years die.

$$N_{0,t} = I_t + \sum_{i=5}^{12} \alpha * e^{-\sigma \sum_{i=5}^{12} N_{i,t-1}} * N_{i,t-1}$$

$$N_{n,t} = (1 - \beta_{n-1}) N_{n-1,t-1} - \gamma_{juv} (\sum_{i=0}^{4} N_{i,t-1})^2 \qquad if\ n \in (1,2,3,4)$$

$$N_{n,t} = (1 - \beta_{n-1}) N_{n-1,t-1} \qquad if\ n \in (5, \dots, 12)$$

Where $N_{0,t}$ = number of individuals in age class 0 at time t, $N_{n,t}$ = number of individuals in n age class at time t, I = immigration of larvae at time t, α = birth rate, σ = strength of density dependence, β = natural mortality, γ = density dependent mortality.

The model was calibrated to reflect the current, non-viable state of the fish populations in the aquatic ecosystems in the delta that can only survive through the regular inflow of larvae and offspring from more suitable habitats further upstream (Joldasova et al., 2002).

WaterFlow: The water resource is modelled as a one-dimensional flow from upstream to downstream. The inflow of water into the river stretch is taken from a 15-year characteristic monthly runoff time series of inflow to the Amudarya river delta, which reflects the variability of water flows in this river basin (Schlüter et al., 2005). The water flow directly reaches the first farmer. Each farmer withdraws water sequentially according to his needs for irrigation. The remaining water flows downstream into the fishing lake.
Budget calculations: In the centralised version, the national authority calculates its budget as the accumulated sum of net returns from crop production of all farmers minus the costs for irrigation and the consumption needs of the farmers:

$$R_{total,t} = R_{total,t-1} + Y_{total,t} - C_{I,total,t} - C_{c,total,t}$$

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.
Note that in the centralised version, the returns from fishing remain with the individual farmers, as fishing is a subsistence activity that enables the farmers to cover his consumptive needs or provide for investment in agriculture.
The budget of each farmer in the decentralised version is the sum of the returns from agriculture and fishing minus the costs for irrigation and consumption.

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

Where $R_{j,t}$ = accumulated local returns of farmer j at time t, $Y_{j,t}$ = yields of farmer j at time t, λ = scaling factor for income from fish catch, $H_{j,t}$ = fish catch of farmer j at time t, $C_{I,j,t}$ = irrigation costs of famer j at time t, $C_{C,j,t}$ = consumption costs of farmer j at time t.

Table B.2: Parameters for Schlüter & Pahl-Wostl 2007 - Example

Parameter	**Explanation**	**Default value/ scenario range**
F	Number of farmers	9
A	Number of age classes of fish population	13
Water flow prediction		
δ	Memory capacity (forgetting rate)	0-1
Water allocation planning		
$f_{\mathrm{Na,max}}$	Maximum number of irrigated fields in the centralized model	180
$f_{\mathrm{j,max}}$	Maximum number of fields of farmer j in decentralized model	20
Y_{min}	Minimum yield threshold	80
Irrigation		
Y_{max}	Maximum yield	10
Fishing		
h	Target catch	10/100
Fish population growth		
α	Birth rate	2.0
σ	Strength of density dependence	0
β_0	Natural mortality of age class 0	0.6
β_1	Natural mortality of age class 1	0.5
β_{2-12}	Natural mortality of age classes 2-12	0.2
ϕ	scaling factor for amount of larvae inflow in water volume to lake	1
γ	Density dependent mortality	0.00001
ψ	Inflow threshold for migration of larvae into lake	2000 m^3/s
Budget calculations		
$c_{I,f}$	irrigation cost/field	5
$c_{C,j}$	Consumption costs of farmer j	40
λ	Scaling factor for fishing income	10

Initial values

Fish population

N_0	Number of individuals in age class 0	1000
N_1	Number of individuals in age class 1	500
N_{2-12}	Number of individuals in age class 2-12	100

Budget

R_j	Initial budget of farmer j in decentralized model	200
R_{total}	Initial total budget of national authority in centralized model	1800

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