General Comments

Khan et al. present a manuscript on a coupled natural-human modeling framework that is applied in multiple river basins. They link a process-based, distributed hydrologic model, with an agent based model that characterizes variability in human decision making and cooperation. Although this is a very interesting modeling tool, additional methodological details and edits to presentation of results and discussion would improve the manuscript. The web-based tool is a great way to show users how agent behavior influences the system!

We thank the reviewer for their detailed comments that has helped us improve the quality of the manuscript significantly.

The use of empirical survey data to develop the behavior rules is particularly valuable, but details about the population sampled and relevant results from the IFPRI report would be useful to include so readers can follow along.

We have provided further explanation for the surveys that were performed, and their usage in the modeling framework in lines 144-153 (reproduced below). In addition, we have included a copy of the survey questionnaire in the supplemental material.

As part of this project, we conducted comprehensive electronic surveys across three transboundary river basins (Indus, Mekong and Niger) to identify water use preferences (Khan et al., 2017). A sample survey questionnaire is provided in the supplemental material. The surveys were developed to elicit the perceived importance of various ecosystem services in different parts of each basin under a variety of economic and hydrologic future conditions. The survey sample size ranged from 75-85 for each of the basins. One of the questions in the survey asked respondents to rank different ecosystem services in order of importance for each agent. These responses were then averaged across all the respondents for each agent to obtain a ranking of the importance of the different ecosystem services. These rankings were used in the decision algorithm for the case study models developed and presented in Sect. 4.

It would also be beneficial to clarify the working definition of "ecological hotspots" and how they were identified.

We have provided more details on what the ecological hotspots represent (paragraph beginning on line 196) and how they were identified in lines 291 and 376.

An important input to the ABM is identification of ecosystem hotspots. Ecosystem hotspots are specific regions in the river basin that are especially critical to or indicative of the health of the ecosystem in the entire basin. Ecosystem hotspots can be identified in a variety of ways including through a literature review of critical ecological concerns in a basin and/or input from local ecological experts. Fort his analysis, for each ecosystem hotspot, relevant Indicators of Hydrologic Alteration (IHA) and Environmental Flow Component (EFC) parameters are selected based on expert opinion to measure ecosystem health (Richter et al., 1997, 1996). Baseline values for relevant IHA and EFC parameters, which are streamflow based indicators, are calculated from daily streamflow of the calibrated SWAT model. The IHA and EFC parameters included for the case study application described in Sect. 4 include monthly median *flows, 7-day annual maximum flow, small and large flood event duration, timing and duration of extreme low flows etc.*

Creating an associated ODD (Overview, Design concepts and details – Grimm et al. 2010) document would be beneficial for transparency of how the ABM works (for example it is highlighted that the geographic scale of the agents in the ABM are larger than others).

This is a very useful suggestion. We have developed an associated ODD document and provide that in the supplemental material with the manuscript. The ODD protocol is also reproduced at the end of this document.

The discussion and conclusion largely reiterate the utility of dynamic coupled natural human systems modeling in regards to water resources management, but only one paragraph highlights take-homes from the two case studies (in the conclusions, with only limited discussion of third party impacts in the discussion). Specific findings from the case studies are discussed in their respective components of section 4 – perhaps this confusion could be resolved by clarifying that the discussion (section 5) is on the utility of this type of modeling framework in general, or having a "discussion" subsection within 4.1 and 4.2.

Thank you for the suggestion. We have modified the title for section 5 to clarify the purpose of the discussion. We have also expanded the discussion of the third party impacts in the discussion.

Specific Comments

80: is this speaking to open source hydro models or ABMs?

This refers to open-source hydrologic models. We have modified the sentence in the revised manuscript to make that clear.

83: why/how is the spatial modeling unit is important?

Thank you for the question. The spatial modeling unit is important to maintain consistency in the hydrologic and the agent-based model delineations. When the agent-based model is delineated following sub watershed boundaries (as done here for the case studies), we require a hydrologic model such as SWAT that simulates hydrologic processes at that same sub watershed level. Alternatively, if the agent-based model setup is in a grid format (e.g. cellular automata), hydrologic models that simulate hydrologic processes at each individual grid cell (e.g. Variable Infiltration Capacity (VIC) model) would be more appropriate. We have provided this further clarification in the revised manuscript.

126: what is this empirical data, how was it collected? Add at least sample size and citation.

We have modified the sentence in the revised manuscript and provide additional description of the empirical data collected from surveys in lines 145-153 (reproduced below).

As part of this project, we conducted comprehensive electronic surveys across three transboundary river basins (Indus, Mekong and Niger) to identify water use preferences (Khan et al., 2017). A sample survey questionnaire is provided in the supplemental material. The surveys were developed to elicit the perceived importance of various ecosystem services in different parts of each basin under a variety of economic and hydrologic future conditions. The survey sample size ranged from 75-85 for each of the basins. One of the questions in the survey asked respondents to rank different ecosystem services in order of importance for each agent. These responses were then averaged across all the respondents for each agent to obtain a ranking of the importance of the different ecosystem services. These rankings were used in the decision algorithm for the case study models developed and presented in Sect. 4.

Paragraph starting on 188: It's not clear how the ecosystem hotspots are determined.

In this methodology section, we present the generalized framework, so it does not refer to ecosystem hotspots in a specific location. Ecosystem hotspots can be identified in a variety of ways such as through literature reviews of critical ecological concerns in a basin and/or input from local ecological experts. For the case studies used in this paper, the ecosystem hotspots were identified by local ecology experts. The ecological hotspots in the Mekong Basin were identified by Eric Baran of WorldFish based on Baran et al. (2007). For Niger, the hotspots are obtained from the Niger River Basin Atlas prepared by the WWF and Wetlands International (Aboubacar, 2007). We have revised the manuscript to clarify this.

Aboubacar, A.: Niger River Basin Atlas, Niger Basin Authority, Niamey., 2007.

Baran, E., Chum, N., Fukushima, M., Hand, T., Hortle, K.G., Jutagate, T., Kang, B. (2012)

p. 149-164. In: Nakano, S. ; Yahara, T. ; Nakashizuka, T. The Biodiversity Observation Network in the Asia-Pacific Region: Toward Further Development of Monitoring. Ecological Research Monographs. Tokyo, Springer

205: The distinction between what the IHA and EFC parameters represent versus the actual components of the ecosystem isn't clear, could you add some details?

The IHA and EFC parameters are used as streamflow based indicators of ecological health. Ecosystem hotspots are specific regions in the river basin that are especially critical to or indicative of the health of the ecosystem in the entire basin. What we mean to say is that the response of ecosystem hotspots to changes in streamflow may not be well understood. In some cases, it is also possible that ecological concerns will not be directly related to streamflow. We have revised the explanation of ecosystem hotspots in the paragraph beginning at line 199 (reproduced below) to provide further clarification.

An important input to the ABM is identification of ecosystem hotspots. Ecosystem hotspots are specific regions in the river basin that are especially critical to or indicative of the health of the ecosystem in the entire basin. Ecosystem hotspots can be identified in a variety of ways including through a literature review of critical ecological concerns in a basin and/or input from local ecological experts. Fort his analysis, for each ecosystem hotspot, relevant Indicators of Hydrologic Alteration (IHA) and Environmental Flow Component (EFC) parameters are selected based on expert opinion to measure ecosystem health (Richter et al., 1997, 1996). Baseline values for relevant IHA and EFC parameters, which are streamflow based indicators, are calculated from daily streamflow of the calibrated SWAT model. The IHA and EFC parameters included for the case study application described in Sect. 4 include monthly median flows, 7-day annual maximum flow, small and large flood event duration, timing and duration of extreme low flows etc.

299: Consider starting the paragraph in such a way that you set up the discussion about importance of hydrologic variability versus agent preferences. This section is somewhat confusing, if Figure 4 and 5 are analogous examples of how preferences impact agriculture and hydropower perhaps you could make them into a two panel figure to highlight the differences.

This is a valuable suggestion by the reviewer. We have modified the paragraph beginning to setup the discussion on the importance of hydrologic variability. We agree with the reviewer that combining Fig 4 and Fig 5 in a two-panel figure would allow for an easier comparison, however, when combined, the dimensions of the figure are reduced and makes it difficult to note the differences, especially in Figure 5. Thus, we have kept the figures separate.

307: It is not clear which figure this refers to, if it is figure 5, how does it show that hydrology is more important when the only results presented are in relation to ranking of the importance of hydropower?

Thank you for the comment. This statement refers to figure 5. The fluctuations in HP generation from year to year are caused by the different hydrologic conditions, while the differences between the blue and red lines represent agent preferences regarding the importance of hydropower. We observe that the annual fluctuations in hydropower generation (due to hydrology) are significantly greater than the slight changes in generation stemming from modified reservoir operations. We have provided this further clarification in the revised manuscript.

330: if the ecological indicators do not account for the issues of biggest concern (Fish migration and sediment), how could agent preferences have a significant impact on ecological violations?

The ecological indicators included in this study are streamflow-based and identified by local ecologists familiar with the study sites. Agent preferences do have an impact on the ecological performance for the metrics that were included. The streamflow-based indicators (IHA and EFC) cannot directly measure the impact on fish migration patterns and sediment transport, even though they are important concerns in the Mekong Basin. Addressing ecological concerns such as these would require a more sophistical ecological model that is beyond the scope of this work, but could be a promising extension to this work.

445: Reiterate what third party impacts are here and reference findings from the case studies.

We reiterate the definition of third party impacts and reference the case study findings as suggested by the reviewer.

Overview, Design concepts, Details (ODD) protocol

1. Purpose

The coupled modeling framework is used to simulate the impacts of water resources management decisions on the food-water-energy-environment nexus (FWEE) at the watershed scale. Novel advancements offered in this framework are 1) the ability of agents to directly interact by requesting assistance from other agents based on their level of cooperation (LOC); 2) representing the "environment" by coupling with a process-based model.

2. Entities, state variables, and scales

This model is composed of different agents. The river basin is divided into politically and hydrologically similar sub-regions, where water management is primarily carried under the ambit of a single administrative unit, which represents an autonomous agent. The coupled modeling framework consists of a hydrologic model and an agent-based model.

The hydrologic model operates on a daily time step, for a period of approximately 25 years for each case study presented. The spatial resolution for the hydrologic model is the HRU level for each sub-basin in a larger river basin. Each sub-basin is delineated into eight HRUs. The agent-based model operates on an annual time step, with the spatial scale dependent on the area of the country-basin that the agent represents.

The state variables in the model include streamflow at each sub-basin's outlet, the irrigated area for each crop in each sub-basin, the reservoir storage and releases.

3. Process overview and scheduling

The model begins by initializing the daily hydrologic model and running it for a four-year spin-up period. The state variables from the hydrologic model on the last day of year 4 (streamflow at each sub-basin outlet, crop area and crop yields, and reservoir storage and release) are fed into the agent-based model. The agents make decisions on water management (based on preferences and level of cooperation) on an annual time step, through

i) a change in the operation of the reservoirs in its domain, or
ii) a change in the amount of irrigated area in a sub-basin in its domain

State variables for the ABM are updated on an annual time step. The decisions of the agents are fed back into the hydrologic model (implemented simultaneously in the next time step). Time is modeled as discrete time steps in both the models. A visual representation for the modeling process overview is provided below.

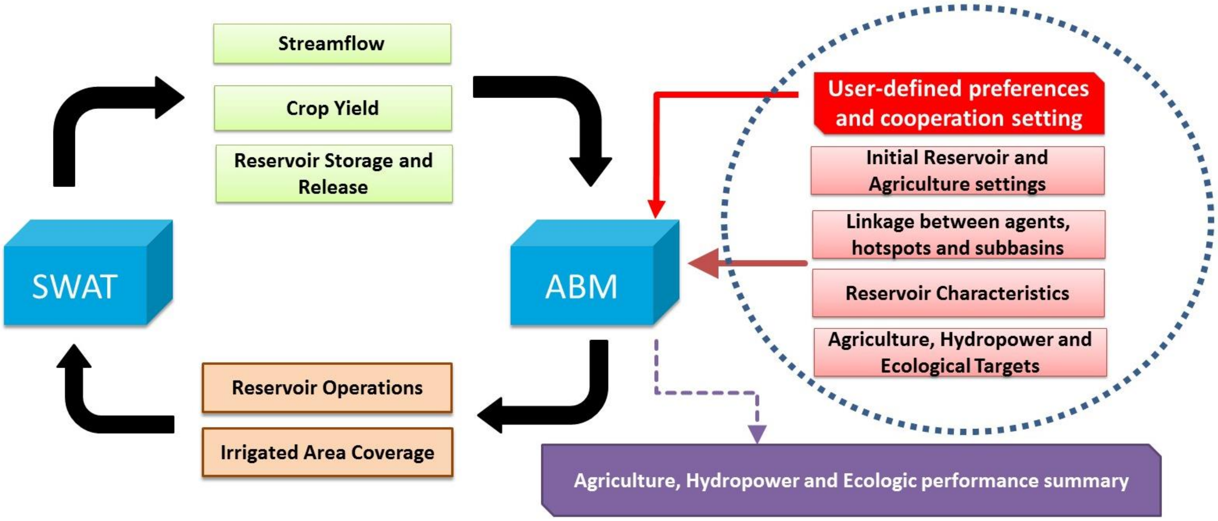

Figure 1: Overview of the modeling framework coupling ABM with SWAT

4. Design concepts

Basic principles

The agents are following rule-based simulation principles in which pre-defined rules are setup to guide agent's behavior. The environment is following basic hydrologic principles, such as rainfall-runoff process, surface water and groundwater interaction and water balance. These two principles interact when an agent's decision affects and/or is affected by the hydrologic cycle.

Emergence

The key outputs from the model include crop production, hydropower generation and ecological health for each agent. The preferences that agents have for different water uses influence the outcome for the particular water use. The willingness to cooperate of agents also affects the annual benefits derived by agents, in terms of direct and indirect (third party) impacts. These outcomes vary in a complex and stochastic manner depending on the agent characteristics.

Adaptation

Our algorithm models the interaction between the ABM and the hydrologic model and the process through which various agents make their water management decisions, in two distinct parts. In the first part, the agent's water management decision is made based on its preferences of water use, while in the second part the decisions are made based on its willingness to cooperate. In the first part, the algorithm uses the water use preferences for each agent, and compares the target value with the output from the SWAT model for each of the water uses to make the water management decision for each agent. Under the current setting, the agent is allowed to only make one water management decision every year.

For instance, consider an agent that ranks agricultural production higher than other water uses. In this case, the ABM checks to see whether crop production meets the target crop production. If crop production is significantly lower than the target crop production, then the agent decides to increase the irrigated area. If crop production meets the target production, then the ABM checks to see if hydropower generation for the current time step meets the hydropower generation target. If the hydropower generation target is not met, the agent decides to decrease the number of days to reach target storage. This allows for greater releases and increased hydropower generation. If the hydropower generation target has also been satisfied, then the ABM moves to the second part of the decision-making algorithm.

For each ecosystem hot spot, relevant Indicators of Hydrologic Alteration (IHA) and Environmental Flow Component (EFC) parameters are selected based on expert opinion to measure ecosystem health (Richter et al., 1997, 1996). Baseline values for relevant IHA and EFC are calculated from daily streamflow of the calibrated SWAT model. We use ± 10 % from the baseline value as a decision threshold in the ABM as recommended by research consortium partner WorldFish. This means the modeled IHA and EFC values deviating from the baseline value by more than 10% would require an agent to take action. In the absence of detailed information on ecological needs, we incorporate ecosystem hotspot management in the model by creating a "flag" when the timing and magnitude of relevant IHA and EFC deviates from the target values in each hotspot. Thus, while the agents do not actively consider ecosystem hotspots in their decisions, they recognize when violations (deviation from target values) occur. We use these violations to constrain the agent's decision, so that if any of the ecologic targets have been violated and ecologic needs are ranked highest, no action can be undertaken for agricultural production or hydropower generation.

In the second part of the decision-making algorithm, the agents decide whether to alter their water management actions based on requests by downstream agents. This feature aims to represent the possibility of cooperative water management in a transboundary river basin. A downstream agent can request an upstream agent to change its reservoir operations to alleviate prolonged water scarcity (at least two time steps). For instance, if a downstream agent has been unable to meet its agricultural production target for two years, then it can request an upstream agent to increase releases. Wherever available, one upstream reservoir is identified for each agent.

Once a request is made by a downstream agent, the upstream agent first checks to see if it has surplus storage, after accounting for its own needs, to consider releasing additional water. If the available storage is not sufficiently higher than the target storage, then the upstream agent declines the request and does not change its reservoir operations. If the upstream reservoir has sufficient storage, then it decides whether to respond favorably to the downstream request based on its willingness to cooperate. In this modeling framework, the LOC represents the probability (from 0 to 1) of the agent to respond favorably to a downstream request and incorporates human decision making uncertainty, making the second part of the decision-making algorithm stochastic to mimic human decision uncertainty. In any given time step, an upstream reservoir can only respond to one request. Once the second part of the algorithm is executed, the water management decisions are made and relevant information is then fed back the SWAT model as inputs for the next time step.

Objectives

Agents make water management decisions, on an annual time step, for agricultural production, hydropower generation and ecological management relative to targets set using long-term historical data. Targets are defined for each of the three water uses based on historical flow conditions. The model algorithm compares the target value with the simulated values for each of the water uses and makes the management decision based on the water use preferences for each agent.

Learning

While the model structure allows for agents' preferences to vary, the current framework operates under constant agent preferences that do not change with time.

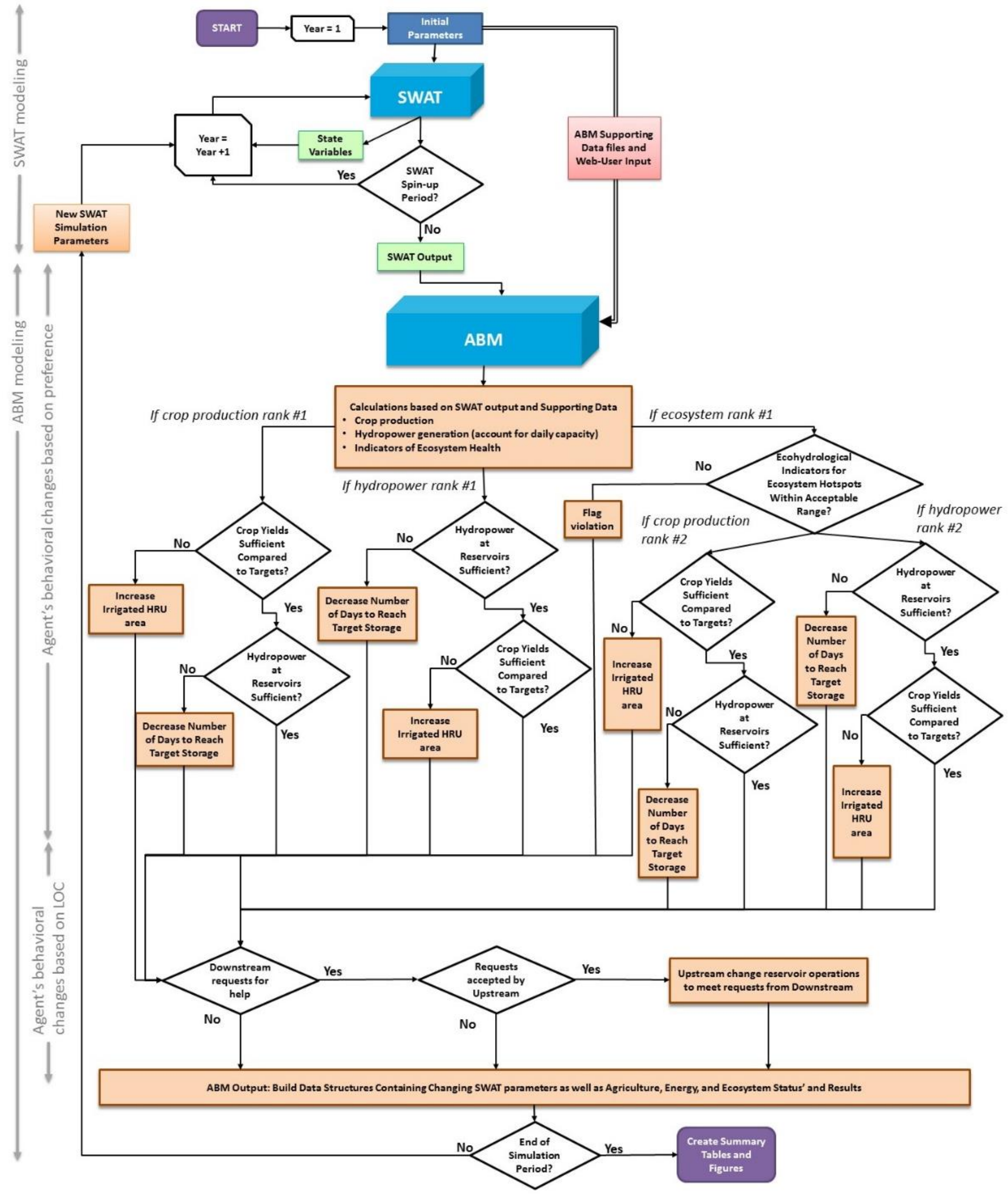

Figure 2: Modelling workflow including the two-part algorithm through which agents make water management decisions

Prediction

Agents are assumed to be myopic, where they make water management decisions to satisfy the targets for the current time step. For instance, if needed the agent alters its reservoir operation to increase releases to increase hydropower generation in the current time step. However, this reduces the reservoir volume for the next time step and may lead to reduced production in the next time step. The agent does not consider these future impacts in its decision-making.

Sensing
The level of cooperation (LOC) signal is intentionally sent from downstream to upstream agents. Upstream agent will take this signal into their decisions and the structure is imposed. The environmental state valuables that each agent will sense for their decisions are last year's local crop production, hydropower generation and ecosystem health violation.

Interaction
Agents interact both directly and indirectly. Agents interact indirectly through their water usage decisions. Agents interact directly through the level of cooperation parameter, where they can request an agent to change its water management decision to benefit downstream neighbors.

Stochasticity
Stochasticity is included in the agent-based model in terms of the agent's response to a request by another agent to change its reservoir operation. The model includes a parameter call level of cooperation (LOC) which represents the probability (from 0 to 1) of the agent to respond favorably to a downstream request and incorporates human decision making uncertainty.

Collectives
In the river basins used as case studies for this modeling framework, each individual agent is a member of the River Basin Authority (e.g. for the Mekong, this would be the Mekong River Commission). In some cases, it is also possible for two or more agents to belong to the same country. Collectives in the model are represented by agents' preferences for water usage that are based on surveys of water practitioners in that region. As such, it is an emergent property of the individuals within an agent. The modeling framework allows the user to define the collective behavior as they see appropriate.

Observation
For each agent, the level of crop production, reservoir storage and releases and indicators of ecological health for critical regions are saved and analyzed. All the output data following the hydrologic model spin-up period is used.

5. Initialization

At t = 0, the hydrologic model is initialized using historical climate and land cover data. The model is run for 4 time steps, as a spin-up period. The state variables from the hydrologic model at the end of t = 4 are input into the agent-based model. The number of agents in the model remains the same throughout the simulation period. The initialization is always the same among all simulations. The state variables are set based on long-term averages corresponding to the period of analysis (e.g. crop yields). Sources for these datasets are provided below in Table 1 below.

SWAT is a semi-distributed model. In model setup, the Mekong River Basin is partitioned into 289 subbasins (Fig. S1(a)), and the Niger River Basin is divided into 178 subbasins (Fig. S1(b)). Hydrological response units (HRUs) were defined within subbasins to reflect the spatial variability of land use/land cover and soil. For this study, we defined crop HRUs for rainfed and irrigated upland crops and rice. The initial size of crop HRUs was estimated using cropping area data from International Food Policy Research Institute (IFPRI)'s SPAM database (You et al., 2014), which disaggregates national/sub-national crop production stations to a 5 arc minute grid.

Table 1: Data for SWAT model setup

Category	**Data**
Elevation	HydroSHEDS[1]
Land use/land cover	GLC2000[2] & SPAM 2005[3]
Soil	Soil Map of the World[4]
Precipitation	Mekong: APHRODITE[5] Niger: NCEP-CFSR[6] (monthly totals were corrected using monthly precipitation data in CRU TS v. 4.00[7])
Temperatures/solar radiation/relative humidity/wind speed	NCEP-CFSR

1. Source: The SHuttle Elevation Derivatives at multiple Scales (HydroSHEDS) database http://www.hydrosheds.org/
2. Source: Global Land Cover (GLC) 2000 database. European Commission, Joint Research Centre. http://forobs.jrc.ec.europa.eu/products/glc2000/glc2000.php
3. Source: Spatial Production Allocation Model (SPAM) database for 2005, IFPRI. http://mapspam.info/
4. Source: FAO/UNESCO. http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/
5. Source: Asian Precipitation-Highly Resolved Observational Data Integration Towards the Evaluation of Water Resources (APHRODITE) project. http://www.chikyu.ac.jp/precip/english/conditions.html
6. Source: National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR); downloaded via global weather database for SWAT https://globalweather.tamu.edu/
7. Source: Climatic Research Unit - University of East Anglia. http://www.cru.uea.ac.uk/data

6. Input data

The input data for this coupled model includes agent preferences of water use and level of cooperation. These agent specific values remain constant throughout the modeling run. Another input are the threshold values based on which agent's determine whether an outcome for water use is acceptable.

7. Submodels

We do not have submodels in this ABM.