Using agent-based modeling to depict basin closure in the Naivasha basin, Kenya: a framework of analysis

P.R. Van Oel* A. Van der Veen

*University of Twente, PO Box 217, 7500 AE Enschede, The Netherlands

Abstract

A spatially-explicit agent-based modeling (ABM) approach is applied for depicting the processes leading to basin closure in the Naivasha basin by representing interdependencies between water availability and water use. Modeling the dynamics of water use and water availability yields patterns of their distribution over space and time. The approach allows for exploring the potential effectiveness of governance alternatives such as payment for environmental services (PES) schemes. This study shows that ABM is a promising approach for supporting water governance and can assist in increasing the understanding of the occurrence of basin closure.

Keywords: agent-based modeling (ABM); basin closure; water resources; environmental services
1. Introduction

There is a growing interest in understanding the effects of the complex interdependencies between economic development and environmental sustainability on different temporal and spatial scales in river basins. On the one hand human interference in natural systems affects indicators of environmental sustainability, while on the other hand changes in natural systems affect indicators of socioeconomic development. Moreover, relations between human systems and natural systems in a river basin are often reciprocal and may include both positive and negative feedback loops [1-2]. The more water stress is already experienced in water systems, the more relevant these feedback loops become. Thus, especially in closed and closing basins [3] there is a need for including human-environment interactions into policy modeling tools.

Policy alternatives for dealing with basin closure include payment for environmental services (PES) programs. PES programs generally involve voluntary transactions where a well-defined environmental service (or land use likely to secure that service) is being ‘bought’ by a service buyer from a service provider [4]. In a river basin context PES programs may include efforts to motivate upstream resource users/polluters to organize their activities in such a way that the negative externalities of their activities for downstream resource users are acceptable. With regard to water quantity, alternative land uses may lead to changes in runoff, for instance due to changes in land cover or water abstractions for irrigation. To depict the related processes and their effects a spatially-explicit agent-based modeling (ABM) approach may be applied.

An ABM approach comprises autonomous, interacting agents. Most ABMs involve agents and a spatiotemporal framework within which those agents perform actions. ABMs are flexible in representing dynamic and adaptive physical and human phenomena [5]. Agents are self-directed objects that have the ability to satisfy internal goals or objectives through actions and decisions based on a set of internal (nonlinear) rules (e.g. based on rationality, heuristics or learning). This distinguishes ABMs from mathematically continuous models [6]. Examples of applying ABM for water management problems include Berger et al. [7] and Schlüter and Pahl-Wostl [8].

In this paper a spatially-explicit ABM approach is presented in which the interactions between agricultural water users and the natural river basin system are modeled. The mutual relationship between water availability and land/water use is depicted by modeling the behavior of water users at the local level. Modeling the dynamics of water use and water availability yields patterns of the distribution of water use and availability over space and time.

2. The Naivasha basin, Kenya

The Naivasha Basin is located in Kenya (Figure 1). It covers around 3200 km² and its climate is semi-arid. The rainfall distribution has a bi-modal character, with long rains during April-June and short rains during October-November. The long-term spatial rain distribution varies from about 600 mm at Naivasha Town to some 1,700 mm in the uplands. The open water evaporation of Lake Naivasha is approximately 1,720 mm/year [9]. The basin has no outlet into the sea but discharges its runoff into Lake Naivasha of which the bottom is located at an altitude of around 1,880 meters above mean sea level. The lake is mainly fed by the inflow of two perennial rivers, the Malewa and the Gilgil Rivers.

The natural vegetation in the area consists of humid forest and bamboo in some parts while other parts are covered by tree-savannah and dry land forest and grassland. Cultivated land is covered by maize, vegetables, and fast growing tree species.
A stable inflow into the lake is important for both the ecological and economic value associated with the Naivasha basin and its population. Climate variability has caused lake levels to fluctuate heavily over the past ages [10], while water abstraction in the lake’s catchment over recent decades has significantly lowered freshwater reserves [11].

The horticultural industry around Naivasha has boosted the local economy and contributed to a rapidly growing population. The environmental impacts of the large water abstractions for irrigation and, changing land use among other factors have put the ecosystem under serious pressure [e.g. 9; 12]. Recent efforts to support a sustainable future of the basin include a water allocation plan [13] and a couple of small-scale Payment for Environmental Services programs [14].

3. Method

3.1. Agent-based modeling

The ABM approach for the Naivasha basin is designed to represent the interdependencies between human behavior (decision-making with regard to agricultural land use) and water availability in the Naivasha basin and its sub-basins. Its current version is developed in NetLogo [15]. The model represents feedback processes between water availability, land use and water use for irrigation. Topography, hydrological processes, possibilities of freshwater storage and water use for irrigation characterize the spatially-explicit model environment in which agents interact.

In the downstream part of the basin a lake is situated. Many individuals depend on the water of this ‘local’ resource. These lake area agents depend on each other’s actions to sustain the local resource. However, in the upstream parts of the basin several communities (some linked, some parallel) engage in land use practices that influence runoff and therefore inflow into the lake. Individual agents in these upstream communities may consider participating in PES-schemes. Their willingness to accept (WTA) a payment for a service that they could provide may involve taking into account experiences by other local individuals. Agents downstream may need to come to collective actions (‘collective’ willingness to pay) to persuade upstream agents to reduce the negative externalities of their actions. In Table 1 the main model characteristics are summarized according to the ODD protocol as described in Grimm et al. [16].
Table 1. ODD scheme for the Naivasha ABM approach

<table>
<thead>
<tr>
<th>Overview</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Purpose:</strong> Represent complex interdependencies between human behavior (land use decision-making) and spatiotemporal variations in water availability distribution over the Naivasha basin.</td>
</tr>
<tr>
<td><strong>State variables and scales:</strong> The spatial extent of the model is the Naivasha basin, covering around 3200km². The temporal scale may extend to several decades. The model uses a 1-day time-step for water-balance calculations. Water availability is represented in local resources: a lake or river branches and their alluvial aquifers. Water users operate at the local level. In the model farmer agents make land use decisions for managing their local plots which may be inspired by: actual and expected water availability in the local water sources (i.e. rivers, aquifers), actions &amp; achievements of other individuals in the (local) environment, stimuli by other agents or water managers (e.g. a PES scheme in which the willingness to accept (WTA) and the willingness-to-pay (WTP) of different users may play a role.).</td>
</tr>
<tr>
<td>Water management decisions may be influenced by physical indicators that emerge at the basin level (e.g. spatial water availability distribution, lake levels)</td>
</tr>
<tr>
<td><strong>Processes overview and scheduling:</strong> Agents represent farmers that are situated at geographical locations and make land-use decisions, followed by actions, affecting water availability in the environment. The modeling sequence is the following: (i) physical parameter update; (ii) biophysical dynamics; (iii) land use decisions and actions. In the physical parameter update rainfall and natural runoff are determined, in the biophysical dynamics evapotranspiration and irrigation in agricultural lands are updated. Decisions on land use are made by individual agents and a water management authority monitors the state of basin level indicators such as the Lake Naivasha water level. In the present version of the model a scheme for PES has not been implemented yet.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Design concepts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water availability in the modeled area is affected by water use and hydrological processes. Agent behavior influences water availability and in this way influences water available for use by agents at later dates. Both a water-using agent itself and agents located relatively downstream of a water-using agent may adapt to the resulting changes in water availability. Agents may also modify their behavior by what they observe in their environment (i.e. their willingness to accept can change when they perceive experiences of other agents). In this way water-scarcity patterns and the occurrence of basin closure may emerge as a collective result of the behavior by individual agents.</td>
</tr>
<tr>
<td>It is assumed that agents aim at achieving high economic revenue. Agents consider alternatives land uses and decide to go for the one they perceive as likely to be the most profitable alternative. Agents may predict the amount of rainfall based on experiences in recent years. Also they sense the local availability of water in alluvial aquifers. It is assumed that agents can sense the achieved economic performance by their neighboring agents. Agents may also interact by actually trading environmental services. The way this is done depends on the design of PES schemes.</td>
</tr>
<tr>
<td>Local or social groups of individuals may affect individual behavior by providing information or setting up programs. For the Naivasha basin the Water Resources Users Associations (WRUAs) appear to be an important collective forum for water users. In the present model the WRUA sub basins are used as spatial units at which agents decide collectively.</td>
</tr>
<tr>
<td>Several global and local indicators can be monitored and analyzed. Next to water balance parameters (spatiotemporal patterns of water use and water availability) the concept of downstreamness [17] is used to analyze the occurrence of basin closure. Although it is hard to tell when basin closure actually occurs the concept of downstreamness is helpful in depicting the phenomenon because it allows for monitoring the spatiotemporal development of water use and water availability on a basin scale.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initialization:</strong> Water users operate at the local level corresponding to plots that are obtained from land cover classifications performed by several students from the University of Twente - ITC. Runoff coefficients estimates are obtained from a Master thesis of Graham [18]. Although debatable, the following runoff coefficients have been chosen: cropland (10%), forest/woodland (8%), grass/shrubland (15%). The coefficients are used irrespective of rainfall intensity. This study does not aim for accurate hydrological modeling. The created environment serves as a platform to explore developments in a qualitative sense.</td>
</tr>
<tr>
<td><strong>Input:</strong> Daily rainfall data from a set 7 meteorological stations is used for the period 1960-1980. These data were obtained from the Ministry of Environment and Natural Resources (MENR), Government of Kenya.</td>
</tr>
</tbody>
</table>
4. Results

At present no results of the interactions between agents using a PES scheme can be presented. However, the relevance of the approach applied can be illustrated by showing the potential impact of agent behavior.

Three model runs have been done: a reference run with no irrigation in any part of the basin, a run where 25% of the agricultural land could be irrigated during the cropping season (wet season) and a run where 25% of the agricultural land was transformed into grass-/shrubland. This third scenario can be associated to a PES scheme in which service providers leave their land uncultivated. Some results of these three model runs are shown in Figures 4-6).

5. Discussion and future work

Rather than using a pattern-based approach for projecting the spatially-explicit developments with regard to adopting PES by individuals, a process-based model may be more helpful in understanding the process of adoption. In that case explorations of possible developments may also be more accurate. A way to test this would be to compare model outcomes to a pattern-based approach that uses spatial autocorrelation.

In cases of basin closure the effects of over-development are obviously most severe for downstream parts of basins. In the case of the Naivasha basin these include both economic and ecological effects, as the catchment residual flows accumulate into a freshwater lake system. In this paper only the effect of agent behavior on the spatial distribution of water quantities has been addressed. Future applications could also include socio-economic and ecological indicators. The preliminary results show that the impact of changing land use is limited with regard to runoff, but considerable with regard to water abstractions for

Figure 3. A 3D view of the Naivasha basin map in the NetLogo model.

Figure 4. Lake levels for the three scenarios.

Figure 5. Downstreamness of water availability (lake Naivasha and the alluvial aquifers together) for the three scenarios.

Figure 6. Annual storage changes relative to annual lake inflow for the scenario with 255 of the cropland irrigated.
irrigation. This suggests that PES should aim at limiting excessive irrigation rather than restoring natural vegetation as far as water quantity is concerned. However for water quality this may be completely different.

In the Naivasha basin small scale PES schemes are applied at two locations (Figure 1). This offers a good opportunity for validating our modeling approach. In this way the model can be helpful in exploring the potential of up scaling current efforts with regard to PES schemes.

6. Conclusion

In this study it was shown that the use of spatially-explicit ABM is a relevant tool for depicting the processes that lead to basin closure. It was shown that this tool is helpful in analyzing the effectiveness of implementing a PES scheme at the basin level.

Acknowledgements

NOW/WOTRO Integrated Programmes

References