IWMI
Research
Report

163

Demonstrating Complexity with a Role-playing Simulation: Investing in Water in the Indrawati Subbasin, Nepal

John Janmaat, Suzan Lapp, Ted Wannop, Luna Bharati and Fraser Sugden

1985
2015
30

IWMI
International Water Management Institute

CGIAR

RESEARCH PROGRAM ON
Climate Change, Agriculture and Food Security

CCAFS

Research Reports

The publications in this series cover a wide range of subjects—from computer modeling to experience with water user associations—and vary in content from directly applicable research to more basic studies, on which applied work ultimately depends. Some research reports are narrowly focused, analytical and detailed empirical studies; others are wide-ranging and synthetic overviews of generic problems.

Although most of the reports are published by IWMI staff and their collaborators, we welcome contributions from others. Each report is reviewed internally by IWMI staff, and by external reviewers. The reports are published and distributed both in hard copy and electronically (www.iwmi.org) and where possible all data and analyses will be available as separate downloadable files. Reports may be copied freely and cited with due acknowledgment.

About IWMI

IWMI's mission is to *provide evidence-based solutions to sustainably manage water and land resources for food security, people's livelihoods and the environment.* IWMI works in partnership with governments, civil society and the private sector to develop scalable agricultural water management solutions that have a tangible impact on poverty reduction, food security and ecosystem health.

IWMI Research Report 163

Demonstrating Complexity with a Role-playing Simulation: Investing in Water in the Indrawati Subbasin, Nepal

John Janmaat, Suzan Lapp, Ted Wannop, Luna Bharati and Fraser Sugden

International Water Management Institute (IWMI)
P O Box 2075, Colombo, Sri Lanka

The authors: John Janmaat is an Associate Professor of Economics at the University of British Columbia, Canada, and British Columbia Regional Innovation Chair (RIC) in Water Resources and Ecosystem Sustainability; Suzan Lapp is a Water Resources Specialist at Urban Systems Ltd., British Columbia, Canada, but was a freelance researcher at the time this research study was conducted; Tedd Wannop is an undergraduate Research Assistant in the Irving K. Barber School of Arts and Sciences, University of British Columbia, Canada; Luna Bharati is Senior Researcher - Hydrology and Water Resources, and Head of the International Water Management Institute (IWMI) office in Kathmandu, Nepal; and Fraser Sugden is Researcher – Social Science at IWMI, Kathmandu, Nepal.

Janmaat, J.; Lapp, S.; Wannop, T.; Bharati, L.; Sugden, F. 2015. *Demonstrating complexity with a role-playing simulation: investing in water in the Indrawati Subbasin, Nepal*. Colombo, Sri Lanka: International Water Management Institute (IWMI). 38p. (IWMI Research Report 163). doi: 10.5337/2015.212

/ water storage / calibration / river basins / watershed management / drinking water / households / economic aspects / income / budgets / investment / crop production / climate change / precipitation / labour productivity / social structure / rural communities / policy making / capacity building / education / sustainability / Nepal /

ISSN 1026-0862
ISBN 978-92-9090-819-7

Front cover photograph shows a concrete lined irrigation canal in Langarche village development committee (VDC), Sindhupalchowk District, Nepal (*Photo*: John Janmaat).

Please send inquiries and comments to IWMI-Publications@cgiar.org

Acknowledgements

The core part of this study was funded by the Department of Foreign Affairs, Trade and Development, Canada (formerly Canadian International Development Agency [CIDA]). Invaluable support was provided by Tashi Sherpa (former consultant, IWMI, Nepal) and Alexandra Skodyn (former student, research assistant) in data collection and analysis. The authors are grateful for the field support provided by local contacts in the study districts, and would like to thank staff at the Water and Energy Commission Secretariat (WECS), the Department of Irrigation, Kathmandu, Nepal, and all those who provided logistical advice and local expertise. The valuable feedback and comments provided by Vladimir Smakhtin (Theme Leader – Water Availability, Risk and Resilience, IWMI) and two anonymous reviewers are greatly appreciated.

Collaborators

This research study was a collaboration of the following organizations:

International Water Management Institute (IWMI)

University of British Columbia, Canada

Donors

This research study was funded by the following:

Department of Foreign Affairs, Trade and Development, Canada (formerly Canadian International Development Agency [CIDA])

This work was undertaken as part of the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), which is a strategic partnership of CGIAR and Future Earth.

CGIAR is a global research partnership for a food-secure future. The views expressed in this document cannot be taken to reflect the official opinions of CGIAR or Future Earth.

Contents

Summary

Rural people in Nepal and other developing nations are part of complex social-ecological systems. Efforts to understand and provide assistance to rural people must integrate knowledge from a variety of perspectives. However, communicating diverse insights and emphasizing their interactions can be difficult. This report documents the use of a role-playing game, supported by an agent-based model, to demonstrate the interaction between migration, social capital and the effectiveness of water storage. The importance of these interactions was highlighted by fieldwork that took place at several sites in the Koshi River Basin. The model underlying the game was a stylized representation based on the Indrawati Subbasin northeast of Kathmandu, Nepal. The objectives of the game included enhancing the engagement of project supporters with the research results, and to foster networking that may facilitate greater future interaction.

Several broad themes emerged from the field studies. Rural households in the hill and mountain regions, in particular, often depend on post-monsoon rainfall to meet basic needs. Climate change promises to increase their vulnerability. Remittance income from family migrants is often an important means of managing local vulnerability. However, emigration and the resultant social instability in rural villages tend to reduce social cohesion. This, in turn, increases challenges with implementing and sustaining projects that serve the village as a whole. Consequently, interventions such as building water storage systems may have complex and unanticipated impacts.

Simulation models have long been used to explore the implications of interventions on social, economic and physical systems. Agent-based models have emerged as an effective way to incorporate the complex interactions of social-ecological systems. Coupling team-based role-playing games with agent-based simulation models can facilitate cooperation between people who otherwise seldom interact, and forces participants to actively engage with the management challenges inherent in a complex system.

An agent-based model was built to stylistically capture interactions between migration, social capital and the effectiveness of water storage. It was used in a role-play tournament conducted as part of the final meeting of a research partnership between the Department of Irrigation, Nepal, International Water Management Institute (IWMI), and the University of British Columbia. The tournament was effective in engaging participants with the research results built into the model, and at facilitating cooperation between people who otherwise have little time to work together. Further development of such tournaments, particularly focussed on people whose responsibilities are more closely connected to implementing interventions, was recommended. Improving model precision in both the physical and social dimensions was seen as critical, pointing to the importance of continuing work to understand how social forces interact to impact the effectiveness of development interventions. Finally, building the model with participation from village farmers to project managers will enhance its credibility, and make both building and use of the model an effective way to help identify interventions that best suit the local context. The tournament results also highlighted the important impacts that policy can have. The winning policy both encouraged migration of households with limited local opportunities and enhanced the situation of the remaining households. This reinforces the view that migration is one part of the agricultural transition that accompanies economic development, and plays an important role in enhancing the livelihoods of those who stay and those who leave.

Demonstrating Complexity with a Role-playing Simulation: Investing in Water in the Indrawati Subbasin, Nepal

John Janmaat, Suzan Lapp, Ted Wannop, Luna Bharati and Fraser Sugden

Introduction

Rural Nepali villages are embedded within social-ecological systems (Schlueter et al. 2012; Berkes et al. 2003). Social-ecological systems are complex and adaptive systems involving social actors, institutions and the ecosystems that they inhabit (Glaser et al. 2008). The impact of interventions, such as building water storage systems, must be assessed within the context of the complex system into which they are introduced. These assessments can be complicated and time consuming, and therefore may not occur. In this report, we describe the development and implementation of a role-playing game that engages experts with some aspects of these complex social-ecological systems.

This research is part of a larger study on water storage in the Koshi River Basin, which is carried out in collaboration with the Department of Foreign Affairs, Trade and Development, Canada (formerly Canadian International Development Agency [CIDA]), International Water Management Institute (IWMI), Department of Irrigation, Nepal, and the University of British Columbia, Canada. The larger study highlighted the complexity of the social-ecological system of the villages in the hill region. Results emphasized the interacting roles of different environmental, economic and sociopolitical drivers that determine how water storage interventions ultimately impact rural livelihoods. A competitive role-playing game, supported by an agent-based model, was seen as a vehicle to enhance the engagement of project partners and other experts with these complex interactions.

The role-playing game was built on a model that incorporates interactions between a few of the important drivers which emerged from the field research. Rural households are faced with an uncertain climate and therefore uncertain crop yields, while being embedded in an evolving economy and a changing village social structure. At the most fundamental level, households can choose to migrate or remain where they are. With institutions that enable remittances, there is an intermediate choice, which is to send some household members away and count on those remittances to boost household income. The model is built to incorporate this 'stay or go' decision and some aspects of the complicated way that this decision impacts on a rural village economy.

In what follows, we begin with a limited exploration of the literature studying migration and that exploring social capital – here referring to the reciprocal relationships, norms of behavior, and networks that facilitate collective action (Hayami 2009). In our case study, social capital is an important lubricant within the village economy, enabling easier and cheaper construction and maintenance of water storage systems. We also briefly survey some work examining games as tools for education and policy examination. Then, a more detailed description of the study site is provided. We briefly mention a few results from the initial explorations, and then describe some of the main results. This is followed by a general description of the model, and further details of the model can be found in the Appendix. We then discuss how the model was used in a role-playing tournament. Finally, we describe and discuss the results of the tournament, and some implications drawn from the model.

Background

The decisions made by villagers both impact and are impacted by the ecological processes in the village locale. For our model, and the resultant tournament, we focus on the interactions between three main features: water storage, migration and social capital.

Water Storage

Little needs to be said about the role water storage can play in enhancing rural livelihoods, all else being equal. Water storage flattens the hydrograph, moving water from the rainy season to the dry season. This enables greater crop yields in the dry season, which contribute directly to enhancing livelihoods. Where climate change promises to increase variation in precipitation, storage can play an important role in adapting to this change (McCartney and Smakhtin 2010) Our work departs from 'all else being equal', exploring how migration and changes in social capital impact on the effectiveness of investments in water storage.

Migration

Migration is a complex phenomenon. Early work (Todaro 1969; Harris and Todaro 1970) described migration as a response to an 'expected' urban wage being higher than the prevailing rural wage. So long as the probability of getting a job was high enough that the average earnings of all migrants (employed or not) was higher in the urban area, migration would continue. While consistent with some observed facts, this simple explanation was quickly seen to be lacking (Byerlee 1974). For many developing nations, migrants contribute remittances to those family members who remain behind. For Nepal, remittances account for as much as 20% of the gross domestic product (GDP) (Sapkota 2013). Remittances maintain a linkage between the migrant and the remaining family, where those who stay behind continue to be impacted after the migrant has left. Thus, in more recent analyses of migration in developing countries, the decision to have a family member migrate is seen as a household adaptation strategy rather than an individual choice (Moench and Dixit 2004; Hoermann and Kollmair 2009) .

Where wage differentials pull migrants, environmental factors can push them. Using the sustainable livelihoods framework as an organizing principle, de Sherbinin et al. (2008) surveyed previous work and concluded that environmental degradation is one factor. However, its effects are attenuated by household connections, having more marketable skills and having the resources to pay the migration costs. They also argue that migration cannot be disconnected from remittances, emphasizing the household level nature of the migration decision. For the Chitwan Valley in Nepal, Massey et al. (2010) found that environmental degradation is strongly related to local migration, but only weakly related to long-distance migration. Human capital and having a network (friends and relatives at the destination), in particular, were important for distant moves (see also Naivinit et al. 2010; World Bank 2011; UN RCHCO 2013). Migration is an important way for households to adapt to environmental change, but which households make use of this strategy and how they do depends on the household context. Fundamentally, there is a cost involved in this strategy with households investing in migration, where they expect the payoff to make it worthwhile.

Social Capital

Hayami (2009) described social capital as the reciprocal relationships, norms of behavior and networks that facilitate collective action. Out-migration seems to reduce the willingness to contribute both labor and funds to communal infrastructure, consistent with a reduction in social capital. Within Nepal, Lam (1999) compared 150 government- and farmer-managed irrigation systems and found that their success depended heavily on the social relations between farmers receiving water from the system. Social capital is easily eroded by undermining the sources of mutuality, and immigration and emigration (Ostrom 2001).

Community management of watersheds and water systems has been popular of late (Pretty 2003). However, the sustainability of externally induced collective projects is questionable (Adhikari and Goldey 2010). Again, within Nepal, Lam (1996) showed that infrastructure interventions can erode the need for collective action, and consequently fail to achieve the expected results. In something of a corollary, Michelini (2013) found that the inability of settlers in a frontier agricultural region of Argentina to develop social capital contributed to low productivity. Bouma et al. (2008) used a trust experiment to measure social capital in a set of Indian villages. Villages where the average trust level was high were more likely to contribute to the operation and maintenance of infrastructure that reduced soil erosion. However, the level of trust was not related to the contribution of villagers to the construction of such infrastructure. Since villagers are often paid by nongovernmental organizations (NGOs) or the government for their contribution to constructing such infrastructure, this may have weakened their incentive to contribute.

Introducing interventions, such as water storage, into the village system may lead to surprising behavior. Several studies (Ostrom 2001; Lam and Ostrom 2010; Lam 1999) have shown the many ways in which Nepali communities have developed institutions and arrangements that enable them to solve difficult coordination problems and sustain livelihoods. They have also shown that well-intentioned interventions can lead to unintended consequences, sometimes even making the situation worse than it was prior to the intervention (e.g., Lam 1996). Interventions should not be made without considering the overall social context into which they will be introduced.

Agent-based Modelling

Exploring complex relationships, such as those between climate variability, water storage, social capital and migration, requires a technology that can represent multiple, independent interacting entities. Agent-based Models (ABMs) are well suited for this purpose. An ABM consists of a set of heterogeneous agents, an environment which the agents inhabit, and rules and institutions governing the interaction between agents and between agents and their environment (Railsback and Grimm 2011; Tesfatsion 2002). Agents can be people, households, animals, plants, etc. They are entities whose own behavior depends on, and affects, the behavior of other agents and the environment. ABMs can show emergence, where (sometimes unexpected) properties of the system emerge from the behavior and interactions of the component parts.

The well-known Artificial Anasazi model (Axtell et al. 2002) is a classic example of using an ABM to explore the interaction between environmental and societal evolution. Several other projects have focussed specifically on watershed management in developing nations. Lansing (Lansing 2009; Lansing and Kremer 1993) built a model where groups of farmers with irrigated plots are organized into clusters, locally known as *subak*s, mimic the choices of more successful neighboring *subaks*. This simple behavior, over the watershed, generates a staggered pattern of planting and fallowing that effectively shares water and reduces pest populations. Becu et al. (2003) explored the effect of different interactions between upstream and downstream water users in a small Thai catchment. Failure of coordination or water theft is found to exacerbate upstream/downstream differences and wealth inequality. Barreteau et al. (2004) developed a model of a Senegalese watershed and examined how different mechanisms of coordination between irrigators affect the long-term viability of the system. Schlüter and Pahl-Wostl (2007) compared centralized and decentralized management of a watershed with both a fishery and irrigated agriculture. They found that the presence of a fishery creates a reciprocal dependence – the order of access to fish is the opposite of the order of access to water – that increases the resilience of the decentralized solution. Some researchers have also built ABMs collaboratively with those being modelled, as a means of facilitating cooperation and resource sharing (Barnaud et al. 2007; Naivinit et al. 2010; Barnaud et al. 2006).

A number of ABMs have also been built to explore migration processes. Kniveton et al. (2011) built an ABM to explore migration in Burkina Faso, calibrated using data studied by Henry et al. (2004). The attitudes, norms and adaptive capacity of agents change through their experiences, interactions with other agents, and as influenced by climate and policy scenarios. Model results are consistent with the observations made by Henry et al. (2004), and suggest that climate affects long-term international migration. Berman et al. (2004) examined how a small arctic community may evolve in response to climate change and various policy scenarios, and found that migration is an important adaptation strategy.

Games and Education

Water management is inherently multi-disciplinary, and simulation games are being recognized as an effective way to enhance learning among water management professionals (Rusca et al. 2012; Hoekstra 2012). Games played by multi-disciplinary teams facilitate communication, exchange of viewpoints and perceptions, the creation of awareness about existing and/or looming challenges, and mutual learning across disciplinary boundaries. Partnering gaming and modelling can help unpack the 'black box' of the model, when those playing the game are connected to the entities being modelled. Rapidly advancing computer technologies are enabling a level of realism previously impossible, which can enhance the engagement and learning potential of educational gaming (Hatley 2013; Kapp 2012). Developing educational games is time consuming, and outcomes are not guaranteed. However, carefully designed and executed games are often found to enhance learning outcomes.

By simulating the interactions of collections of heterogeneous agents, ABMs can provide the realistic behavior required for effective engagement with water management experts. The realism is further enhanced, if the model is built using results of related fieldwork or even more by involving people directly in the model-building process. For example, Castella et al. (2005) used a role-playing game to identify the behavioral patterns for a sample of Vietnamese villagers. These patterns were then used to calibrate an ABM of watershed-scale land-use change. The villagers found the resultant model consistent with their beliefs about how land-use change is likely to evolve. However, higher level administrators did not see the model as being useful for policy formation. The authors of this report suggest that involving stakeholders from the village level to regional government level in the model-building process will be more effective by better integrating the realities of the policy process with the experience of local villagers. In later work, Castella et al. (2007) argued that better policy results can be achieved by integrating the results of modelling exercises at different scales. ABMs are able to model complex processes, and have the potential to demonstrate the implications of policy decisions in complex environments where other approaches are challenged (Lempert 2002). However, to date, engaging policymakers with the models in ways that clearly improve policy decisions has been difficult (Schlueter et al. 2012). The results presented here build on this earlier work, using an ABM to engage senior government and professional experts with the complex interactions observed during field research. This approach enhances engagement with the research results, and thereby increases the likelihood that these results will enter into future policy discussions.

The role-play tournament described in this report follows a similar tournament developed by the Science and Technology Branch (STB) of Agriculture and Agri-Food Canada (AAFC). The Invitational Drought Tournament (IDT) was envisioned as a way of engaging stakeholders and experts with the challenge of managing an artificial watershed, building bridges between the participants who otherwise may seldom interact (Hill et al. 2014). By implementing a realistic watershed model, the IDT provided an environment where potential knowledge gaps and vulnerabilities in current response plans can be identified and assist in making preparations for future climate extremes (Brislawn and Black 2012; AMEC Environment and Infrastructure 2012; Hill et al. 2014).

A tournament was normally a daylong workshop with diverse water resource experts/users as participants, such as representatives from farming communities, government officials from agriculture and environmental departments, fisheries biologists, academics, local government staff and local politicians. Confirmed participants were grouped into teams that mixed expertise and interests. Participants were given a workbook describing the biophysical and socioeconomic features of the model watershed, providing a list of policy options and outlining how the tournament would proceed.

Teams were competing to find the 'best' balance between environmental, social and economic performance of the watershed through a multi-year drought. They were provided climate and hydrologic information for the beginning of each cropping season. Within a specified budget, teams selected a portfolio from a list of policy options provided, where each option had an associated cost. Each team had to justify their chosen portfolio to all participants. Policies were implemented and the simulation was run to the end of the cropping season, and the results were provided to each team. This was repeated for several rounds, with the climate sequence reflecting a serious drought. During the later rounds, teams could also provide innovative strategies, provided they could convince a set of judges of both the practicality and affordability of the strategy. The winning team was selected through a combination of model-generated performance metrics, participant voting and scoring by the judges.

Pilot workshops of the IDT have been held in Calgary, Alberta (2011), Denver, Colorado (2012), Kelowna, British Columbia (2012), and Forestburg, Alberta (2012). The Forestburg tournament engaged decision makers, regional organizations and members of the public with draft drought policy advice and guidelines developed by the local watershed alliance. In all cases, tournament participants found the exercise to be both fun and educational. The tournament allowed them to learn about how people with different perspectives perceived the management challenge, and to appreciate the difficulty of choosing policies when individual interests differ. The pilot workshops also demonstrated the difficulty of identifying meaningful indicators of the environmental, economic and social status of the watershed, and using those to choose a winner.

The IDT approach departs from companion modelling style approaches, where the model is built through an interactive process involving the stakeholders that the model represents (Barnaud et al. 2007; Gurung et al. 2006; Naivinit et al. 2010; Naivinit et al. 2008; Hoanh et al. 2008). Companion modelling exercises are typically undertaken to facilitate shared learning and enhance cooperation that can address existing conflicts. The model underlying the IDT was purpose-built to support the tournament, integrating prior research into watershed processes. The resulting model provides a high level of detail, which meant teams had to decide which information to focus on when making their decisions. Tournament participants were not involved in any stage of model development. Our approach lies between these two. Similar to the companion modelling approach, our model abstracts away from many physical details to emphasize key themes from the previous field research. As with the IDT, our participants are technical and policy experts rather than stakeholders who are represented in the model, and we therefore use a tournament as a means of increasing the engagement of participants with the research results represented in the model.

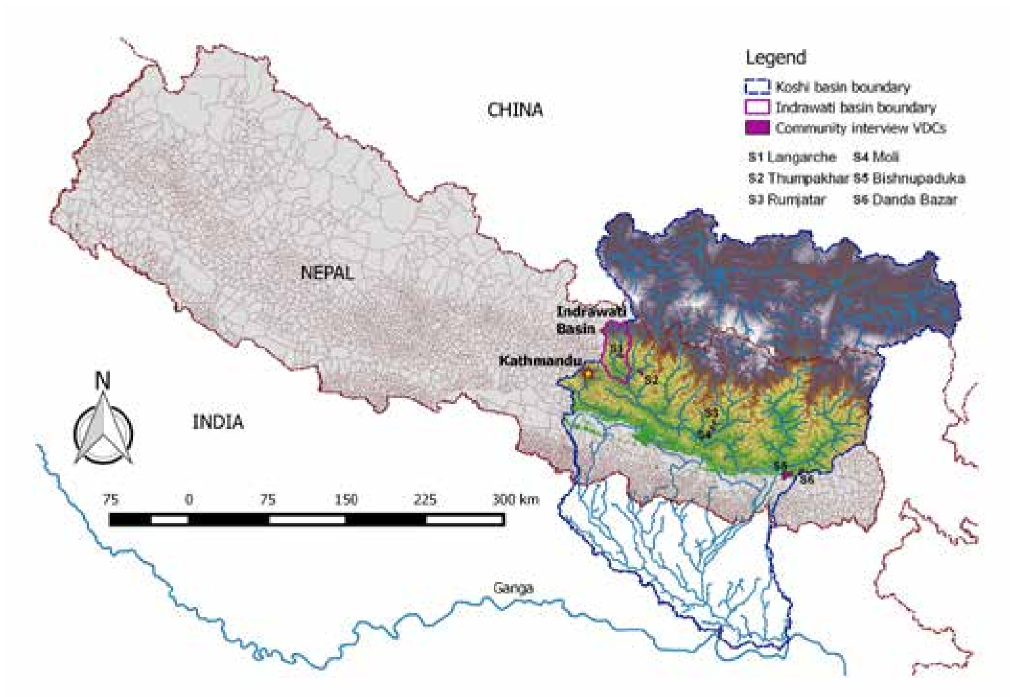
Study Area

The larger project focussed on the international Koshi River Basin (crossing China, Nepal and India), which is the largest river basin in Nepal (Figure 1). Much of the fieldwork was concentrated in two smaller subbasins of the Koshi River Basin - the Indrawati and Pankhu subbasins. The Indrawati Subbasin is situated northeast of Kathmandu in the transition zone between the hills and mountains. It covers an area of around 1,230 square kilometers (km^2), and the elevation ranges between 589 and 6,124 meters (m) above mean sea level (amsl). Above 2,500 m amsl, the only settlements found are seasonal herders' camps. The lower slopes are very fertile and densely populated. The Pankhu Subbasin is situated in the Okhaldhunga District east of Kathmandu. It is much smaller and more remote than the Indrawati Subbasin. Elevations range from 300 to 2,300 m amsl, with most of the population living between 600 and 1,800 m amsl.

Nepal has a monsoon climate with most of the annual precipitation falling between June and September. Rural households, especially those in the hill regions of Nepal, are particularly vulnerable to drought (Ghimire et al. 2010; Shively et al. 2011). Within the Koshi River Basin, climate change is projected to increase temperatures by 0.7 to 0.9 °C, while reducing precipitation throughout the basin in both the wet and dry seasons, except for the transmountain region (China) during the dry season (Bharati et al. 2012). These changes promise to exacerbate the challenges faced by rural villagers, with increased water storage as one method to mitigate these challenges.

Background information was collected from a set of community interviews and consultations with the Department of Irrigation (DoI), Nepal. The communities interviewed were chosen to represent a variety of locations around the Koshi River Basin, where water projects had

FIGURE 1. Location of the Koshi River Basin, Indrawati Subbasin, and village development committees (VDCs) where community interviews were held. Moli VDC is closely coincident with the Pankhu watershed.



been implemented. The interviews explored a range of issues around water storage and water supply, as well as gathering information about the nature of the village and its economy. Table 1 provides a list of the projects, their locations and briefly summarizes their status. The most successful project, in terms of factors such as achieving project objectives, state of repair, etc., was the Moli Ponds. This project, and the village where it is located, had extensive external support from the World Wide Fund for Nature (WWF) for environmental remediation and community building, as well as some strong political connections that brought in funds and support to the village. It was also the most remote site visited, providing few nearby opportunities for employment outside the village. The least successful project, the Bishnupaduka Small Storage Project, was located in a village accessible by an easy short trip from Dharan, a rapidly growing city with many employment opportunities. In this village, community members were unwilling to contribute funds or labor to the water storage project, leaving it uncompleted for years. The remaining projects are based in communities where access to outside employment and the strength of the community lies between the noted extremes. The performance of the projects also lies between that of the two noted extremes.

A sample of households in the Indrawati and Pankhu subbasins were surveyed in detail about the value of enhanced water storage (Price et al. 2014). Interviewees were positive about enhanced water storage. However, households are not homogeneous in their perceptions of the value that enhanced water storage can bring. Those households that are more affluent, with a younger and better educated head, place the highest value on storage that increases irrigation opportunities. Less affluent households, where the head tends to be older and less educated, place a relatively higher value on storage that provides enhanced drinking water supplies. This suggests that, without due care, investments that enhance water storage may aggravate existing inequalities within the village.

Further interviews in the study area highlighted the fact that enhancing water storage addresses only one of the many challenges that rural households face (Sugden et al. 2014). Chief among these is out-migration opportunities, particularly for men, which reduces their incentive to invest in agricultural activities. This out-migration also leaves women with more agricultural tasks in addition to family and household responsibilities. Management institutions, often with little space for female voices, are less able to motivate the collective effort necessary to maintain communal infrastructure. Migration and the general social changes resulting from modernization tend to exacerbate the impact of inequalities in wealth and status that exist in rural villages. Evidence gathered in the study area emphasizes that the impact of enhancing water storage depends very much on how that storage affects the village social-ecological system.

TABLE 1. Community interviews and system background.

Project	Location	Status
Birauta Khola Irrigation Project	Langarche VDC, Sindhupalchowk	Functioning, revenue collection low. Equity concerns.
Sanopakhar Pond	Thumpakhar VDC, Sindhupalchowk	Functioning, not used as designed, productivity low. Absentee landlords and out-migration issues.
Moli Ponds	Moli VDC, Okhaldhunga	Functioning, fish farming and agriculture. Long transportation. Extensive external support.
Rumjatar Pond	Rumjatar VDC, Okhaldhunga	Under construction (2011). For the cultivation of oranges for sale to major centers.
Dhoje Danda Fog Water Project	Danda Bazar VDC, Dhankuta	Failed. Complex technology, little interest in learning.
Bishnupaduka Small Storage Project	Bishnupaduka VDC, Sunsari	Under construction (2011), limited commitment by local people. Employment opportunities nearby.

The Village Economy Model – An Agent-based Model

The literature reviewed and the field research conducted helped to identify a number of important features of the social-ecological system of rural villages, which decision makers should take into consideration.

- Rainfall variability has important impacts on households, which they may find difficult to adapt to.
- Water storage can smooth out the hydrograph, enabling households to sustain themselves better in the face of climate variability.
- Social capital plays an important role in facilitating the construction and maintenance of water storage infrastructure.
- Migration is an important strategic livelihood response to uncertainty. Entire households may migrate, or households may have members that migrate and send remittances to those left behind.
- Migration, particularly a constant, visible level of out-migration, reduces social capital.
- Expanding inequities between households within a village reduces social capital.

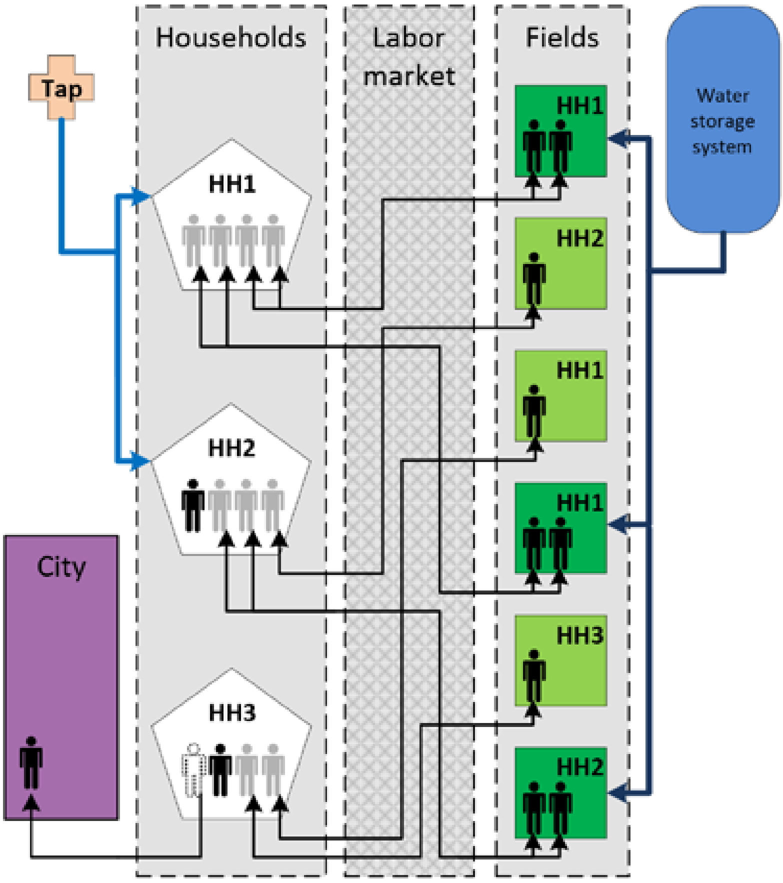
The purpose of our model development is to incorporate these features into an ABM, and design a method of engaging experts with the model. The goal was not to design a decision support system that provides predictions, but a model that would serve as a foundation of a process for engaging the expert participants with the complexity that affects the impacts of interventions.

The model was implemented in NetLogo (http://ccl.northwestern.edu/netlogo/). It was based loosely on the sustainable livelihoods framework (Scoones 1998; Chambers and Conway 1992), where households have multiple capital assets which they use to support their livelihood strategies. Figure 2 shows most of the model entities and the more direct physical relationships between them. Table 2 provides a brief description of the seven model entities.

Each village is a collection of households, people, fields, taps and water storage systems. Households own fields. Households contain people, the family. People work on the fields or migrate to a distant city, from which they send remittances to those left behind. We ignore seasonal migrants who are able to return to help with crop production. All else being equal, the priority for household labor is to work in the fields owned by the household. All costs except for labor are assumed to be proportional to yield and factored into the price. The net revenue (yield × price) earned on a field is split as one-third for the workers and the remainder to the household that owns the field. The entire net revenue is retained by the household when a member works on the field. The income earned by workers contributes to household income, which pays the subsistence costs of those members who live in the village. Households that are connected to a tap have access to high-quality drinking water, which reduces subsistence costs, and increases the productivity and income of the workers (consistent with Hutton et al. 2007). Fields that are connected to water storage systems are able to grow high-value crops, but also require more labor.

Migration impacts the village economy in several ways. The most direct impact is reducing the amount of labor available in the village. If there is insufficient labor to work in all the fields, migration will reduce the income generated by agricultural activities in the village. When the available labor is low, investing in water storage will have little impact on the income generated in the village. In the model, migration also has an impact on storage construction and maintenance costs through social capital. The effect of reducing social capital is modelled as increasing the cost of collective activities such as building and maintaining storage structures. When a migrant leaves, social capital is shocked downward. Lower social capital makes it more difficult to build storage, increases the probability that storage will fail, and reduces the amount households are able to save.

FIGURE 2. Elements of the village model. Households contain people who work in the fields or migrate to the city. Households own fields. Taps supply potable water to some households. Water storage systems supply water to some fields.



Note: HH = Household.

TABLE 2. Model entities, ownership, role and decisions taken.

Agent	Owner	Role	Decisions
Field	Household	Grow crop	
Tap	Village	Drinking water	
Person	Household	Labor/remittances	
Household	Village	Sustenance, storage maintenance	Migration, labor allocation, land trading
Village	N/A	Social capital	
Town/city	N/A	House migrants	
Storage	Village	Store water	

Note: N/A – Not applicable.

However, migrants also send remittances back to the household, offsetting some or all of the impact their absence has on household income earned from activities in the village.

Model Entities

Within the model, households are the decision-making entity, with the other six serving as placeholders and/or performing specific functions. Each entity is briefly described below, with a more detailed representation in the Appendix.

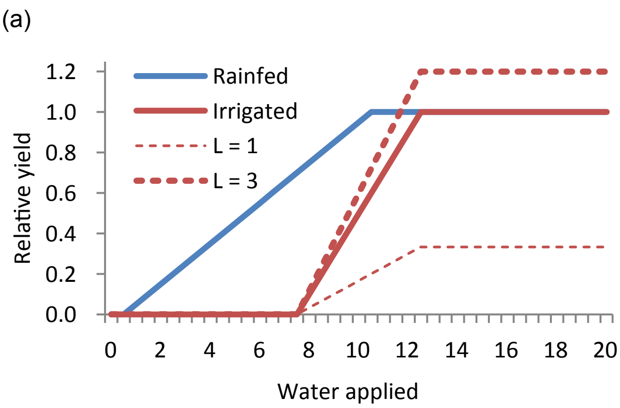
Fields. Crops are grown on fields, require labor and water to grow, and are chosen depending on whether or not the field is irrigated and also on the season. The amount of labor applied to a field is determined in the labor market, where households hire labor. Each worker has a unique productivity on a field, depending on whether the household that the worker is part of has a tap and the number of workers already being used on the field. If households need to borrow money to cover the basic living expenses, they will try to sell a field.

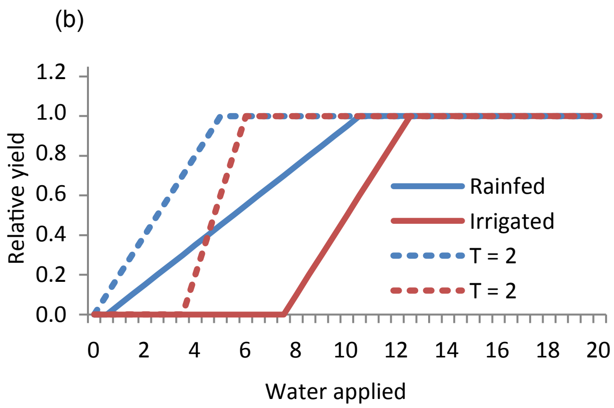
Figure 3 shows the crop-water relationship, and how that relationship is impacted by labor applied and the level of technology used in the field. Between the minimum amount of water required and the maximum amount of usable water available, yield increases linearly with the provision of additional water. Each crop has a specific labor requirement, with a reduction in yield in proportion to the shortage of labor relative to what is required. A worker who is allocated to a field works only on that field for the entire season (similar to Holtz and Pahl-Wostl 2012). Labor from households with clean drinking water is assumed to be more productive, which is reflected as the higher crop yield achieved from the same labor. Each field uses a level of technology, representing (with one number) the various ways that water can be used more or less efficiently to grow a unit of yield. Increasing technology reduces the water required per unit of yield. Each investment in technology halves the gap between the maximum and current productivity levels, with the maximum productivity doubling when the investment in technology is zero.

Taps. Taps deliver potable water to attached households, which are those nearest households for which the tap has enough capacity. Potable water reduces the incidence of waterborne diseases, increasing labor productivity and reducing subsistence costs. Taps are fed from a perennial water source unrelated to storage.

People. People provide labor when they are employed, contributing their earnings to household income. The model does not consider age or gender. If the household has a tap, members are more productive and earn more income when

FIGURE 3. Crop production as a function of water and labor. (a) L = 1 and L = 3 represent one and three units of labor applied to an irrigated field, and (b) T = 2 represents a technology level of two for an irrigated and a rainfed field.





employed. Migrants pay a remittance to their household of origin.

Households. Households contain people, own fields and have access to taps. They accumulate wealth and pay subsistence costs for members living in the village, and pay an irrigated area-based proportionate share of the maintenance cost of functioning water storage systems. Households supply labor for agricultural work in the village. Migration is a household decision, which is made by comparing the average household income per person against remittance income, adjusted to take into account migration costs. In the model, all migration is permanent. Households also buy or sell fields, attempting to sell when they must borrow money to cover household costs. The role that networks play in facilitating migration is not considered.

All workers offer themselves for hire in the labor market, and are hired by the household that pays the highest wage. For labor hired to work on fields the household owns, that labor contributes the total potential revenue to household income. If the worker is hired by a different owner, the contribution to household income is only the wage earned. Therefore, all else being equal, households retain workers for their own fields. However, a household without access to irrigation may choose to have its members work for another household that has irrigated fields, particularly in the dry season.

Villages. Villages contain a collection of households, taps and water storage systems, and the linkages between them. Households, themselves, contain a collection of people and fields. The level of social capital is a property of the village. Other village properties include migration costs, crop options and their growth parameters, crop prices and precipitation levels.

Social capital (referred to as 'cooperative spirit' in the tournament) 'lubricates' water storage construction and maintenance, expressed as an increasing cost with decreasing social capital. It is calibrated to lie between zero and one, and reflects the inequality of wealth distribution per person (a modified Gini coefficient [Gini 1912]), the inequality of access to potable drinking water and recent out-migration from the village.

Town/City. In the model, a town/city is a collection of people who have migrated, receive a wage and pay a share of that wage as a remittance to their household of origin.

Storage. Storage systems are filled with a fixed annual baseflow and an additional input that reflects precipitation. Water is delivered to fields to fill, if possible, the soil moisture deficit. The remaining water is carried forward to the next season. If storage is not maintained, it fails. A failed storage system is unable to deliver water to the attached fields. Further details about such systems are not incorporated into the model. The probability of failure decreases with increasing maintenance, up to a minimum unavoidable risk of failure. The cost of achieving the minimum risk of failure is a share of the construction cost and increases with declining social capital.

The conceptualization of the household and village model elements drew from the sustainable livelihoods framework. The five capital assets, natural, physical, social, human and financial are represented. Natural capital is the fields and the particular environmental conditions of the village. Physical capital includes the water storage infrastructure and the field technology. Each village has a level of social capital. Each household has financial capital, wealth in cash that increases (or decreases) by the residual of income after expenses. Human capital is reflected in the impact on productivity of providing clean drinking water. The model did not include education, typically a core component of human capital.

Time Sequence

There are two crop seasons, *Kharif* (rainy) and *Rabi* (dry), each year. Policy choices are implemented once a year after the dry season. The sequence of events for each crop season is crop choice, labor market activities, precipitation and irrigation, crop growth, migration decision and land market activities (Table 3).

TABLE 3. Sequence of events that occur during each cropping season.

Step	Description
Crop choice	The crop is chosen for each field. The crop choice is made assuming that there will be normal levels of precipitation and water, and sufficient labor.
Labor market	Labor is allocated. Each worker, in turn, offers to provide their services. The household that the worker comes from offers to pay the full revenue amount that is earned. Other households offer a one-third share of the revenue amount that is earned. The worker will provide their services to the household that is willing to pay the most. Either all the labor is allocated or the labor demand at the end of the market phase is zero.
Precipitation and irrigation	Precipitation falls. Water is collected in the storage systems after the precipitation is received for the season. This water is then made available to all the fields by following two steps. First, all storage systems, in turn, offer one half of the stored water to each field. Second, all storage systems, in turn, offer the remaining water. This ensures that all attached fields get some water.
Crop growth	Crops grow in response to the amount of water and labor applied, and the levels of technology used in the field. All the crops are sold and wages are paid. Revenue (wages earned by household members, and remittances, net subsistence and maintenance costs) is added to household wealth.
Migration decision	Households compare their average wage earnings per person (net subsistence costs) against remittances (net interest on loans taken to pay for migration costs). If migration provides a higher return, a member will take this option.
Land market	Households with negative wealth attempt to sell land. The profit history of the field is used to determine the asking price. This asking price is equal to the size of a loan that could be financed from these profits. If none of the households in the village can afford this asking price, the selling price will be the wealth of the wealthiest household. If none of the households have any wealth, the land will not sell.

Policy Variables

Policy options in the tournament are implemented as shares of a budget assigned to one of seven different envelopes (Table 4). Money in each envelope accumulates from one period to another until there is enough to purchase at least one of the items attached to that envelope. The purchasing of items is prioritized according to what will generate the greatest benefit. Three budget categories involve expanding water infrastructure: building long-term (LT) storage, building short-term (ST) storage, and installing new drinking water taps. Repairing existing storage was another option related to infrastructure. Water-use efficiency options included enhancing the level of technology used in the field and improving social capital. The latter reduces the costs of constructing and maintaining storage systems. The final policy envelope was direct payment to households.

The effectiveness of the money assigned to each budget category depends on the structure of the village, and interactions between the budget categories. Investing in social capital reduces the cost of building and maintaining storage systems, thereby allowing more systems to be built from the same amount of funds allocated for this purpose. Investing in field efficiency increases the income generated from the water supplied by storage infrastructure. Similarly, providing drinking water increases the income generated per worker, which also increases the income per unit of water.

Migration reduces the amount of labor available in the village. Investments in water storage makes more water available for crop production, but if there is insufficient labor then the potential crop production will not be achieved. When a village has reached a low level of population, investing in water storage will generate little or no benefit. Providing an income subsidy, which is directed at the households that earn

TABLE 4. Policy options as a share of a budget assigned to seven different categories.

Budget category	Cost (NPR)	Impact	Priority
Long-term (LT) storage	Building - NPR 1,000,000 per system. Maintenance NPR 60,000 per season. Both scaled by social capital.	Connect to four fields. Stores up to 5,200 m^3. Unavoidable failure probability 0.05 per season.	Villages with largest moisture deficit.
Short-term (ST) storage	Building - NPR 300,000 per system. Maintenance - NPR 30,000 per season. Both scaled by social capital.	Connect to four fields. Stores up to 5,200 m^3. Unavoidable failure probability 0.3 per season.	Villages with largest moisture deficit.
Repair existing storage	Half of the construction cost, scaled by social capital.	Ensures that failed storage systems are functioning again.	Random selection of failed storage.
Install drinking water taps	NPR 40,000 per tap.	Connects up to three houses. With the tap, labor productivity increases 1.6 times. Sustenance cost decreases 0.8 times.	Households without a tap connection.
Field efficiency	NPR 20,000 per increment per field.	Moves efficiency from the current level to halfway of maximum efficiency.	Least efficient fields.
Social capital	NPR 30,000-45,000 per year per village.	Set social capital to one at the beginning of the year.	Villages with the lowest social capital.
Household subsidy	NPR 17,000 per person per season.	Add NPR 17,000 per person to the wealth of receiving households.	Households with the lowest wealth.

Note: In late 2013, USD 1 was trading for approximately NPR 100.

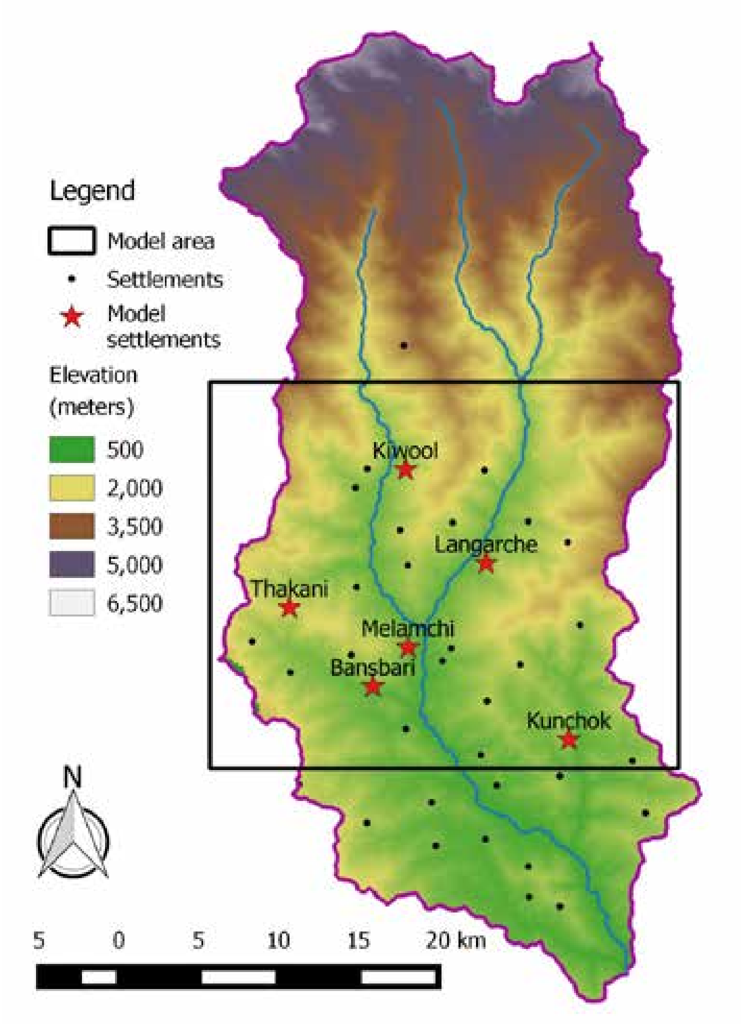
the lowest income, reduces out-migration and therefore helps sustain the village labor force. Being targeted at low-income households, the income subsidy also reduces inequity and thereby helps maintain social capital. Remittances can increase or decrease inequity, depending on how they compare to the income generated from agricultural activities and the households that receive them.

Calibration

The model was calibrated to roughly represent the conditions in six villages in the Indrawati Subbasin of the Koshi River Basin (see Figure 4). Values for the various prices, crop growth functions, yields, etc., were collected from various sources. Calibration details are available from the authors on request.

Each village had an average precipitation that was based on estimates from climate models which accounted for elevation and topography or, if available, historic averages. Climate scenarios were sequences of scaling factors, which were applied to the village averages to calculate a unique precipitation for each village. The same scaling factor was applied to all the villages, which means that precipitation changes were proportional – villages with higher average precipitation had a larger absolute reduction during the dry years. The climate scenario of the tournament had an overall average scaling factor of 0.88 for the ten-year policy period.

FIGURE 4. Map of the Indrawati Subbasin. Model area and settlements represented are indicated in the map.



The Tournament

Structure of the Tournament

The model was used in a tournament held at the Hotel Himalaya, Kathmandu, Nepal, on December 2, 2013. It took place in the afternoon, as the second part of a dissemination meeting organized for project partners and other interested parties. These other interested parties included representatives from other NGOs working in Nepal and at least one self-identified private consultant. Twenty-eight people participated in the tournament. It ran from 2:45 pm to 5:00 pm.

Unlike the IDT, participants were not known until the beginning of the tournament. In preparation for an IDT workshop, confirmed invitees were assigned to teams in order to maximize the diversity of the teams. This was not possible for the Kathmandu tournament. Instead, we relied on the fact that people tend to organize themselves into groups based on familiarity. The room had been set up with eight round tables, each with chairs for six people. The interactions around the tables suggested that those sitting together were generally well known to each other.

To create more diverse groups, we ‘counted off’ participants, assigning each person a number between one and five. Numbers were assigned table by table, with the first number assigned at a new table being the next one after the last assigned at the previous table. In this way, two people initially seated at the same table could only end up in the same group, if there were more than five people at that table. There was only one such table. All the people who had been given the same number became a team, and the participants re-arranged their seating so that each team was together at one table. This resulted in two teams of five and three teams of six.

Since participants were not known until the start of the tournament, workbooks could not be distributed in advance. They were, therefore, distributed after the team assignment. Distribution was followed by two short presentations. The first described the work carried out by AAFC in developing the IDT. The second provided an overview of key information in the workbook, relevant details about how the model worked, policy options available and an overview of how the tournament would proceed. Given the time available, this tournament was run with one session where the chosen budget allocation was implemented for a ten-year model simulation.

Teams were given about 30 minutes to discuss their budget allocation. Each team wrote their allocation on a worksheet that was provided and this was collected by the facilitators. For all cases, the model was run for 10 years without any policy expenditures. For each team in turn, their policy expenditure choices were entered into the model and it was run for a further 10 years. During the model run and subsequent processing of the output, each team had a chosen spokesperson present a justification for their policy choice.

Two short scripts, written in the Practical Extraction and Reporting Language (PERL), were used to process model outputs in a format that made it easy to use in Microsoft Excel™ and generate a series of charts. These charts plotted village-level indicators, such as average household income and village population, at the beginning and end of the ten-year policy period, for each model village (Figure 5 shows an example). All indicators calculated are described in the Appendix, Table A1. After the team had given its justification, these charts were shown to all those present. When all five groups had finished, two further charts were shown that plotted watershed aggregate indicators (see Figure 6). Following this presentation of results, the entire group voted to select the winning team. Participants were then asked to complete a short questionnaire, and were also given the opportunity to contribute their thoughts on the tournament experience and its usefulness. The ABM and workbook are available on request.

Post-hoc Analysis

The model enables the chosen budget allocations to be analyzed on a wide variety of measures. The limited time during the tournament precluded examining many of these measures, and therefore limited the amount of information that participants had to inform their vote. Two of the possible analyses undertaken are briefly described here and the results are given below.

An alternative to voting would be to rank teams using a weighted sum of their relative performance on all or a subset of the calculated indicators. An alternative format would be to allow participants to choose these weights at the beginning of the tournament, as part of a discussion about what successful watershed management should achieve. While there are an infinity of possible weightings, discussions around development issues suggest that maximizing income and/or wealth can be at odds with sustaining the village economy and/or minimizing emigration. We constructed several alternative weightings consistent with differing policy objectives, and examined the resulting ranking of the budget allocations chosen by the teams.

Policy budget choices were also assessed for their resilience, which is measured by the average performance of indicator variables over a range of precipitation sequences. The model was run for a range of climate scenarios, with performance measures recorded for each scenario. Given the computational burden, it was not practical to report resilience results during the tournament.

A total of 1,024 precipitation scenarios were used. The scenarios included all possible combinations of the scaling factors [0.4, 0.8, 1.2 and 1.6] for years 13 to 17. The precipitation scenario used during the tournament had an average scaling factor of 0.8 over years 13 to 17. Results for sequences with the same total precipitation were grouped together and averaged (similar to Schlüter and Pahl-Wostl 2007).

Results

Results of the Tournament

The budget divisions chosen by the five teams are shown in Table 5. The first four budget items related to constructing or maintaining physical water infrastructure. Four of the teams invested in short-term storage, with two allocating 40% of their budget to building new short-term storage. One team opted for investing in long-term storage instead, devoting a third of their budget to this item. All teams devoted funds to repairing storage, ranging from 4 to 14%. Beyond storage, installing new drinking water taps was another important budget item. For teams 1 and 3, this item accounted for the largest share of the budget. Total budget expenditure on physical water infrastructure ranged from a low of 61.3% to a high of 86%.

The remaining three budget options are 'softer'. All the teams, except for team 5, chose to spend on improving the efficiency of crop water use at the field level. All the teams devoted some funds to building cooperative spirit (the term used for social capital in the workbook), and all chose to devote some funds to emergency relief. Teams 4 and 5 stood out, in that team 4 spent 2.76 as much on 'soft' budget items as team 5 did.

Figure 6 shows the radar plots used to summarize watershed-level averages for the indicators recorded. Along each dimension, values are relative to the maximum that any team realized. In Figure 6(a), clockwise from the top, the axes are total wealth ('Wealth'), total income from all sources ('Income'), net revenue from farming activities ('Profit'),

TABLE 5. Budget allocations. Share of total budget allocated to each category of expenditure.

Team	#1	#2	#3	#4	#5
Build new short-term storage	20.0	0.0	20.0	40.0	40.0
Build new long-term storage	0.0	33.3	0.0	0.0	0.0
Repair failed storage	4.0	4.0	10.0	8.0	14.0
Install new drinking water taps	50.0	29.3	43.6	13.3	32.0
Subtotal	**74.0**	**66.7**	**73.6**	**61.3**	**86.0**
Improve efficiency of crop water use	10.0	13.3	16.0	20.0	0.0
Build cooperative spirit (social capital)	14.0	12.0	6.0	12.0	12.0
Provide emergency relief to households	2.0	8.0	4.4	6.7	2.0
Total	**100**	**100**	**100**	**100**	**100**

income from wages received for farm labor ('Wages'), income from remittances ('Remit'), income from subsidy payments ('Subsidy'), cost of sustaining the household ('Sustain'), cost of supporting the migration of household members ('Migrate') and maintenance costs for water storage ('Maintain'). The line bounding the shaded area is the result when no policy is applied.

The radar plot clearly highlighted the differences between the teams, particularly between teams 4 and 5. The budget choices of team 4 generated the highest wealth, total income, share of income from agricultural profits

FIGURE 5. Reproduction of one of five charts used to show village-level details following justification by teams of their budget allocations.

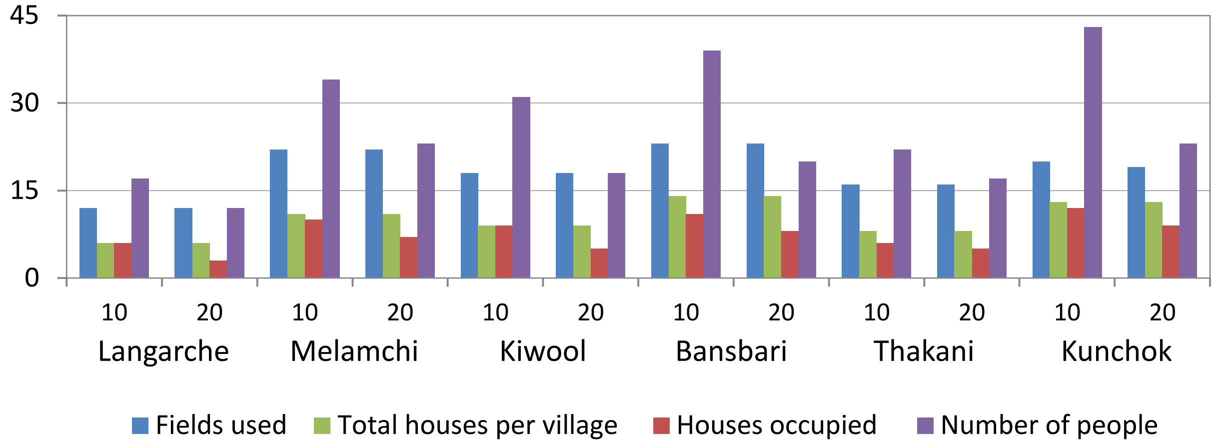
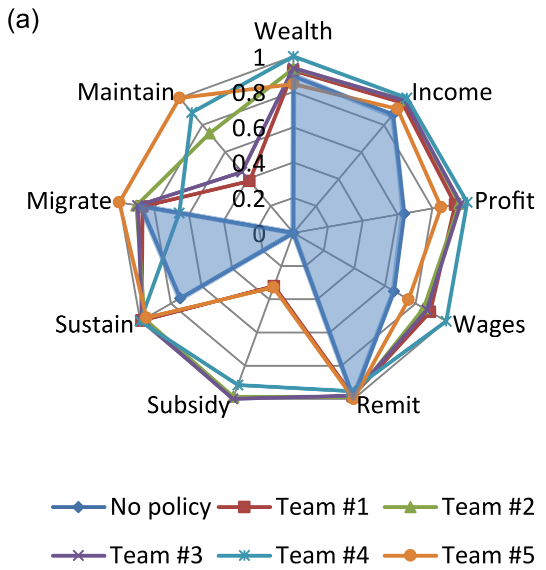
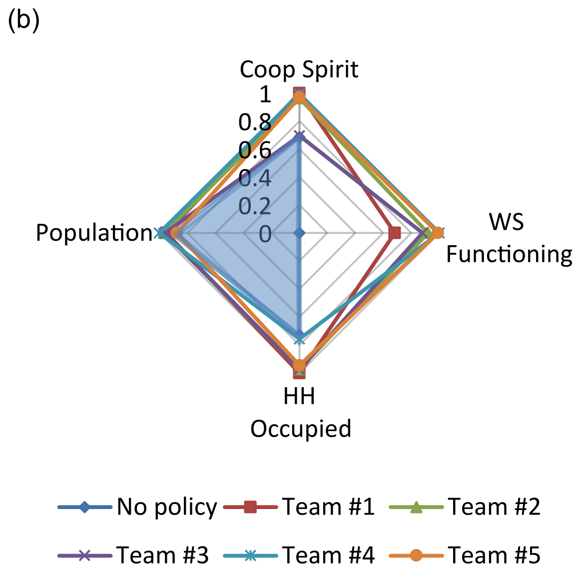


FIGURE 6. Radar plots used to compare watershed-level performance of teams in the tournament.





Notes: Income, Profit (net revenue) and Wages - activities in the village. Remit = remittance income for household. Sustain (sustenance), and Subsidy are emergency relief payments. Migrate and Maintain (maintenance) - household costs. Wealth is total household savings, accumulated over the course of the simulation as total income less total expenses. Coop Spirit = cooperative spirit. WS Functioning - number of functioning water storage (WS) systems. HH Occupied = number of households (HH) with at least one person living in the village. Population is the total number of people living in the watershed. All measures are relative to the highest level realized for that measure by any team.

and wages received for farm labor. It also had the lowest amount spent on migration costs and the smallest share of income from remittances. In contrast, team 5 had the lowest total wealth and income, as well as the lowest share of income from agricultural profits and wages received for farm labor. It had the highest income from remittances, highest amount spent on migration and the highest expenses for maintenance of water storage infrastructure. Households responded to the strategy of team 5 by having members migrate away.

Figure 6(b) shows four additional dimensions of the household responses. Team 4 sustained the highest population in the village and the highest number of functioning water systems, and was second to team 2 by 0.8% for cooperative spirit. However, the total number of households occupied (households with at least one member living in the village) was the lowest. The policy choices of team 4 led more households to completely migrate away, while allowing the remaining households to fully utilize their labor. The policies chosen by most of the other teams resulted in most households using migration as a livelihood strategy.

Voting to select a winner was almost unanimous, with team 4 receiving 15 votes, team 5 receiving 3 votes, and all the other teams received no votes. This suggests that, among the participants, there was relatively broad agreement about what is considered to be a success in watershed management.

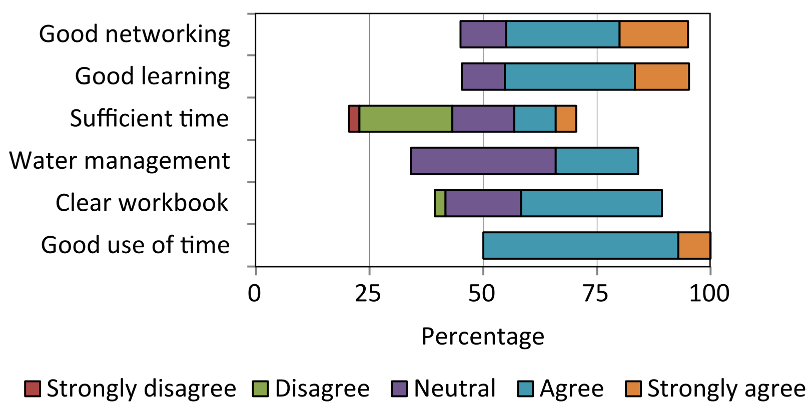
Feedback from the Tournament

After the winning team was chosen, an open discussion was held with the participants. Overall, the feedback was positive, with participants seeing potential in further development of this approach. Participants largely agreed that it was a challenging and enjoyable exercise that gave them the opportunity to work with people they would not usually interact with, and also think about dimensions of water resources management that they usually don't consider. There was some concern that the model was unrealistically simple. Suggested improvements included more realistic natural resource processes, non-linearities in the various relationships, and an inclusion of markets, particularly agricultural markets.

The post-tournament questionnaire included six Likert scale questions. These were answered by between 20 and 22 respondents. Figure 7 shows a divergence plot for the responses received. They are generally positive in relation to the value of the tournament for networking and general learning, and as a good use of time. When it came to learning about water management, the majority gave a neutral response. Given that most of the participants were, to an extent, water management professionals, this isn't surprising.

There was disagreement in relation to the workbook and the amount of time available for the exercise. Participants found some parts of the workbook confusing. Questions that came

FIGURE 7. Divergence plot for responses received to the post-tournament questionnaire, which included six Likert scale questions. Responses range from 'strongly agree' to 'strongly disagree'.



up were clarified by the facilitators during the exercise. However, these responses suggest that the workbook can be improved. Dissatisfaction with the limited time to conduct the exercise is also not surprising. Previous tournaments have lasted a day, with the workbook being provided to participants several days in advance. This was not possible in the current situation.

The open-ended feedback questions reinforced the results of the other feedback received. Participants were again very positive about how the tournament challenged them to think outside their normal areas, and to work with people who they would not usually interact with. There was some dissatisfaction expressed about the time allocated for the exercise, and about the aspects that were missing from the model, such as agricultural markets. Some participants also felt that the village-level details were not clearly presented. A few participants also stated that they would have preferred a secret ballot rather than a show of hands.

The question "Do you see this type of tournament being useful in water management planning?" received the most responses. In general, all the responses to this question indicated that the tournament had value, particularly the way that the model integrated a number of features in the village economy. Concerns about the simplicity of the model were expressed once again. In the Nepali context, it was suggested that the tournament be undertaken at the district level, where budget decisions similar to those made in the tournament actually take place.

Results of the Post-hoc Analysis

Table 6 provides the scores for the indicators given in Figure 6. The three different weighting schemes (A, B and C) for aggregating the scores are shown in the last three columns of the table. The first weighting scheme 'A' puts all the weight on the final wealth and average income. Weighting scheme 'B' is biased towards sustaining rural villages. Positive weight is placed on locally generated income and on measures consistent with sustaining the village population, and a negative weight on migration effects. With negative weights, the score for a team decreases, if these measures increase. Weighting scheme 'C' is similar to 'B', without the negative weights.

Table 7 shows the rankings of the five teams for each of the three weightings put forward in Table 6. Applying weightings A

TABLE 6. Relative indicator scores. Maximum values (=100) in each row are highlighted in bold. Minimum values in each row are highlighted in bold and italics.

	Team						Weights		
	None	#1	#2	#3	#4	#5	A	B	C
Final Wealth	***88.8***	92.1	93.2	93.4	**100.0**	84.3	1		
Average Income	***87.9***	96.2	98.3	98.0	**100.0**	91.7	1		
Average Profit	***63.9***	93.0	95.5	96.3	**100.0**	84.9		1	1
Average Wages	***65.8***	89.5	85.2	87.3	**100.0**	75.4		1	1
Average Remittances	99.3	98.2	98.9	98.1	***95.4***	**100.0**		-1	
Average Subsidy	***0.0***	32.0	98.8	**100.0**	91.6	32.8			
Average Sustenance Costs	***73.9***	99.2	97.4	98.8	**100.0**	95.9			
Average Migration Costs	87.5	86.7	90.2	89.4	***65.5***	**100.0**		-1	
Average Maintenance Costs	***0.0***	38.5	73.8	45.2	89.3	**100.0**		-1	
Cooperative Spirit	***68.5***	**100.0**	96.3	69.6	99.2	97.1		1	1
Water Systems Functioning	***0.0***	68.2	91.9	88.2	**100.0**	99.1		1	1
Households Occupied	***73.0***	**100.0**	97.3	97.3	75.7	94.6		1	1
Population	91.6	95.0	96.6	95.8	**100.0**	**87.4**		1	1
Taps per household	***33.3***	**100.0**	**100.0**	**100.0**	83.3	**100.0**		1	1
Total water systems	***15.3***	57.6	84.7	57.6	**100.0**	**100.0**			1

TABLE 7. Team rankings for each of the three weighting schemes included in Table 6. The 'No policy' column contains the results when the simulation is run for 20 years without any expenditure being made towards policy budget envelopes.

Weighting scheme	No policy	Team #1	Team #2	Team #3	Team #4	Team #5
A	5	4	2	3	1	6
B	6	1	4	3	2	5
C	6	5	2	4	1	3

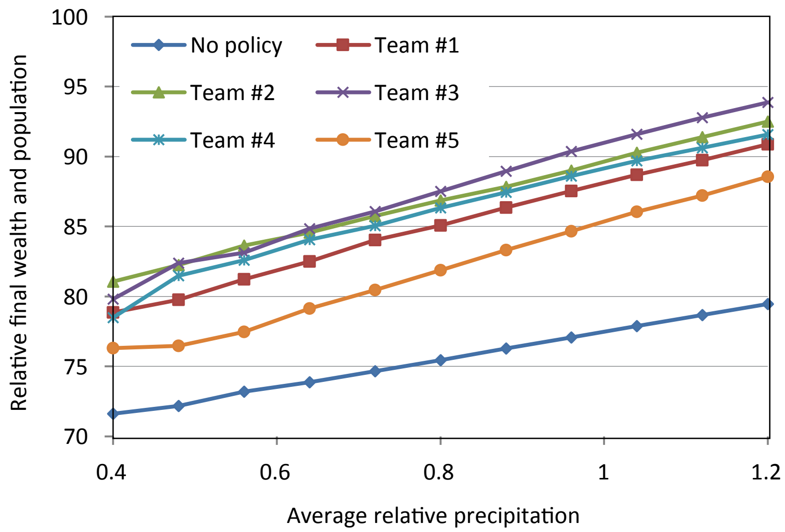
and C gives team 4 the highest rank. Either of these rankings is consistent with how the majority voted. Weighting scheme C gives team 5 a third place ranking. To be consistent with those people who voted for team 5, a weighting scheme that gives team 5 a first place ranking is needed. The three weighting schemes provided do not do this. Such a weighting scheme would emphasize drinking water access, total amount of functioning water storage, remittance income and little else. A scheme such as this is difficult to relate to objectives commonly considered.

If the vote count can be interpreted as ranking the teams, a corresponding weighting scheme would need to give team 5 a second place ranking. Of the three weighting schemes described, scheme C is the closest to achieving this. Interpreting the vote this way, the teams as a whole placed a strong emphasis on sustaining the rural villages.

Figure 8 plots one possible representation of the resilience results. In this plot, equal weight is given to final wealth and village population. Each point represents the average of all the sequences for which the mean precipitation over the variation interval was the same. The points with average relative precipitation of 0.4 have only one observation, while the remainder of those shown have more than one observation. Variation in performance that follows from differences in patterns that have the same total precipitation were not considered.

For the population and wealth balance reported in the figure, team 2 has the best performance when precipitation is at the lowest. As precipitation increases, team 2 eventually moves to second place, behind team 3. Team 4,

FIGURE 8. Rural population and final wealth by precipitation levels. Final wealth and population are relative to the highest realized in any simulation run. Relative precipitation is in relation to the normal climate.



the vote winner, is never the best. Their results are, therefore, driven by the particular precipitation sequence used in the tournament. Their results are sufficiently different for other sequences that, on average, scores slightly lower than teams 2 and 3. Had these results been available during the tournament, a different voting outcome may have prevailed.

Discussion

Our objective was to develop a model integrating a few of the main observations from several field studies in the Koshi River Basin, and to use that model to engage individuals from our partner organizations with the complexity of those interactions. Broadly speaking, the objective was met. Participants were clearly engaged with the tournament, and thereby engaged conceptually with the interactions between the results they had been told about earlier in the day. Our results demonstrate that an ABM can be built fairly quickly to capture some important high level interactions observed as part of a multi-disciplinary project. This ABM can then be used as an educational tool with those interested in developing a better understanding of the problem under study. Unlike companion modelling, where the subjects of the model are also those who will make use of it, our tournament participants are in a position to influence decisions that impact on people in the model.

A number of lessons follow from this exercise. Several are relevant for further development of the model and tournament. Some lessons can also be drawn out for investments in water storage in rural villages.

Role-playing games can be an effective way to engage experts with system complexity. The use of educational gaming has been growing, and some argue that the complexity of watershed management makes it an ideal tool for engaging experts with that complexity. In developing countries, the use of computer technology and complex models can be challenging outside of major centers. One solution is to develop the main lessons into a game that does not require electronics or computer technology. McCartney et al. (2007) report a game that uses marbles and a tabletop board with blocks that represent connections in a watershed. This type of game can be very valuable for demonstrating interconnections between communities in a watershed. However, it will be challenging to deal with the multiple interacting components that make up a complex system.

The decisions available to participating experts should match the policy options being played. The policy tools used in this game were budget envelopes directed towards water storage and related activities. However, many of those participating in the tournament were technical experts who do not have the authority to make budget decisions or choose where to spend budgets that were decided elsewhere. The value for these participants came, in part, from an exposure to the budget allocation challenges faced elsewhere in the government.

It was suggested that the tournament may be more effective with district-level staff in Nepal, who have budget envelopes somewhat similar to those used in the tournament. These administrators are also more closely connected to the results of these expenditure decisions. District offices are also likely to have reliable electrical power and relatively easy transportation access, which are important for both preparation and execution of a tournament.

The 'right' level of detail is needed to make the model results credible. The experts brought in to participate in the tournament naturally compare the structure of, and outcomes from, the model against their own knowledge. If there are large inconsistencies between simulation results and what experts know, the credibility of the model will be lost. Model results also need to be expressed in a way that establishes the credibility of the model and is easy to understand.

For this tournament, village-level details were not presented effectively. The bar graphs were difficult to interpret and compare across the teams (for example, see Figure 5). Some participants were also unconvinced by the way that social capital – cooperative spirit – was included in the model. However, participants did not challenge the need to consider social capital, suggesting that this aspect of the tournament was effective.

Building the model as a participatory exercise, involving both those represented in the model and those who may use it, would increase the ownership and value of the model. Both levels are important. Including only those represented in the model has elsewhere led to models that policymakers do not find useful. Including only policymakers may generate models that stray away from important ways that stakeholders respond to policy.

The value of investments in water storage is attenuated by migration. Initial discussions early on in the project tended to view migration as revealing failure of development policies, and water storage as a means to strengthen rural economies and reduce migration. As the research proceeded, it became even clearer that migration is an important livelihood strategy. Throughout history, people have migrated in response to pressures and opportunities. Rural development policy should, therefore, aim to ensure a smooth transition for individuals and households that do migrate, while strengthening the situation of those who stay.

The field research highlighted the existence of an interaction between migration, cooperative spirit and the ability of communities to make full use of water storage infrastructure. Within the model, migration was an economic decision, where households compared the contribution of a potential migrant to household income if they stayed behind without migrating and the cost of migration. The field research found that the economic need and/or opportunity were important drivers of migration, but not the exclusive drivers. The model did not include additional drivers such as the role of networks and marketable skills. Also, the model did not consider seasonal migration. Further enhancements to the model will include such features.

Social capital – cooperative spirit – was a critical ingredient in making the construction and operation of water storage systems successful. Within the model, reduced social capital increased the cost of building and maintaining water storage systems. This meant that less storage would be built, and existing storage is more likely to fail, when social capital is low. Ongoing migration, growing inequalities in wealth and access to water all reduce social capital. The evolution of social capital is far more complex. However, communities with less cooperative spirit had trouble keeping water storage functioning, and households with remittance income tended to be less involved in the community. Migration also reduces the amount of labor available in the village, thereby reducing the value generated by investments in water storage. While the model did not consider the quality of labor, this too is affected when migration draws away the most productive segment of the population.

Policy can affect how migration and water storage interact. Team 4, the winning team, spent the most on 'softer' policies. Their choices resulted in the highest village population, but the lowest number of households occupied. Team 4 spent relatively less on repairing storage, yet in the end tied with team 5 for the number of water systems, and was slightly better at keeping them functioning. The policy choices of team 4 also resulted in more households migrating as a whole than for the other chosen policies, while households that remained were almost complete.

In the model, having a smaller number of intact households and a stable population is better for social capital than having a large number of households that have some dependence on remittance income. The economy of the model village was restructuring toward a smaller number of farmers who each own more land

and cultivate that land effectively. This is the same transition that is being observed around the world. The model was not built to generate this result. However, the fact that this result occurred, and that it also generated the highest village-level income from agriculture and the highest overall growth in wealth, suggests that the model effectively captured some of the important interconnections between migration and rural agrarian economics. This result also emphasizes the emerging contemporary perspective that rural livelihoods may be best supported by working with migration, such that some households are able to easily move while those who stay can make the most of their situation (see, for example, World Bank 2011).

The 'best' policy enhances the joint contribution of water and labor. Water and labor are both scarce resources in rural villages. This is a relatively new phenomenon, which is driven by recent rapid emigration. When rural populations were stable and growing, enhancing water supplies enables greater use of available local labor. However, when rural populations are declining, enhancing water supplies may have little benefit without also enabling the remaining labor to make better use of these water supplies. Thus, the most effective use of the limited resources available to support rural economies should be directed at activities that enhance water supplies in ways that those people most likely to remain in the village can make the best use of.

Conclusion

Watersheds are complex social-ecological systems. While management of these systems is difficult, policy choices do matter. However, policy impacts occur through a complex web of interactions that are often not appreciated, if they are understood. Decision makers need to be aware of the potential for unanticipated impacts, able to change their choices to account for these impacts, and willing to use these results to develop a better understanding about how the complex system works.

We developed an ABM that integrates several dimensions of the interaction between water storage, social capital and migration. This model was used in a role-playing tournament, which allowed water management experts to engage in the complexity of watershed management. The tournament was well received. Participants had the opportunity to interact with people that they seldom do around water management challenges. They also engaged with the complexity of watershed management. The building and execution of the model itself demonstrated that several important interactions can be effectively built into a model, and the complex interactions between the model entities can highlight effects that were not designed *ex-ante* into the model.

We conclude with two broad results. First, role-playing tournaments can be an effective way to engage technical and policy experts with the complex interactions between the social and physical dimensions present in watershed management. Second, migration and the economic changes which drive these interactions are forces that need to be accepted, and investments in water storage need to be selected depending on how they fit into these trends. Our model, and the fieldwork that supported its development, emphasize this second result. Our first result points at a tool that can broaden the view of decision makers and thereby lead to improved management decisions.

References

Adhikari, K.P.; Goldey, P. 2010. Social capital and its “downside”: The impact on sustainability of induced community-based organizations in Nepal. *World Development* 38(2): 184-194.

AMEC Environment and Infrastructure. 2012. *Summary report: Colorado drought tournament, September 18, 2012*. Available at http://vintage.joss.ucar.edu/events/2012/drought_forum/2012DroughtTournament.pdf (accessed on April 20, 2015).

Axtell, R.L.; Epstein, J.M.; Dean, J.S.; Gumerman, G.J.; Swedlund, A.C.; Harburger, J.; Chakravarty, S.; Hammond, R.; Parker, J.; Parker, M. 2002. Population growth and collapse in a multiagent model of the Kayenta Anasazi in Long House Valley. *Proceedings of the National Academy of Sciences of the United States of America* 99(suppl 3): 7275-7279.

Barnaud, C.; Promburom, P.; Trébuil, G.; Bousquet, F. 2006. Companion modelling to support collective land management in the highlands of northern Thailand. In: *Proceedings of the International Conference on Natural Resources Related Conflict Management in Southeast Asia, September 6-8, 2005*, eds., Laohasiriwong, S.; Ang, M. Khon Kaen, Thailand: Institute of Dispute Resolution, Khon Kaen University. Pp. 90-112. Available at https://cgspace.cgiar.org/handle/10568/17366 (accessed on April 20, 2015).

Barnaud, C.; Promburom, T.; Trébuil, G.; Bousquet, F. 2007. An evolving simulation/gaming process to facilitate adaptive watershed management in northern mountainous Thailand. *Simulation & Gaming* 38(3): 398-420.

Barreteau, O.; Bousquet, F.; Millier, C.; Weber, J. 2004. Suitability of multi-agent simulations to study irrigated system viability: Application to case studies in the Senegal River Valley. *Agricultural Systems* 80(3): 255-275.

Becu, N.; Perez, P.; Walker, A.; Barreteau, O.; Le Page, C. 2003. Agent based simulation of a small catchment water management in northern Thailand: Description of the CATCHSCAPE model. *Ecological Modelling* 170(2-3): 319-331.

Berkes, F.; Colding, J.; Folke, C. 2003. *Navigating social-ecological systems: Building resilience for complexity and change*. Cambridge, UK: Cambridge University Press.

Berman, M.; Nicolson, C.; Kofinas, G.; Tetlichi, J.; Martin, S. 2004. Adaptation and sustainability in a small arctic community: Results of an agent-based simulation model. *Arctic* 57(4): 401-414.

Bharati, L.; Gurung, P.; Jayakody, P. 2012. Hydrologic characterization of the Koshi Basin and the impact of climate change. *Hydro Nepal: Journal of Water, Energy and Environment* 11(1): 18-22.

Bouma, J.; Bulte, E.; van Soest, D. 2008. Trust and cooperation: Social capital and community resource management. *Journal of Environmental Economics and Management* 56(2): 155-166.

Brislawn, J.; Black, C. 2012. *Design and findings of the drought tournament gaming activity.* Presentation made at the CWCB Drought Conference, September 19, 2012. http://cwcbweblink.state.co.us/WebLink/0/doc/168090/Electronic.aspx?searchid=69b64a0e-0aff-4909-9511-949b1dc79b29 (accessed on April 21, 2015).

Byerlee, D. 1974. Rural-urban migration in Africa: Theory, policy and research implications. *International Migration Review* 8(4): 543-566.

Castella, J-C.; Kam, S.P.; Quang, D.D.; Verburg, P.H.; Hoanh, C.T. 2007. Combining top-down and bottom-up modelling approaches of land use/cover change to support public policies: Application to sustainable management of natural resources in northern Vietnam. *Land Use Policy* 24(3): 531-545.

Castella, J-C.; Trung, T.N.; Boissau, S. 2005. Participatory simulation of land-use changes in the northern mountains of Vietnam: The combined use of an agent-based model, a role-playing game, and a geographic information system. *Ecology and Society* 10(1): 27.

Chambers, R.; Conway, G. 1992. *Sustainable rural livelihoods: Practical concepts for the 21st century*. IDS Discussion Paper 296. Brighton, UK: Institute of Development Studies. Available at http://opendocs.ids.ac.uk/opendocs/handle/123456789/775 (accessed on April 20, 2015).

de Sherbinin, A.; VanWey, L.K.; McSweeney, K.; Aggarwal, R.; Barbieri, A.; Henry, S.; Hunter, L.M.; Twine, W.; Walker, R. 2008. Rural household demographics, livelihoods and the environment. *Global Environmental Change* 18(1): 38-53.

Ghimire, Y.N.; Shivakoti, G.P.; Perret, S.R. 2010. Household-level vulnerability to drought in hill agriculture of Nepal: Implications for adaptation planning. *International Journal of Sustainable Development & World Ecology* 17(3): 225-230.

Gini, C.W. 1912. Variability and mutability, contribution to the study of statistical distribution and relaitons. *Studi Economico-Giuricici Della R. Universita de Cagliari*.

Glaser, M.; Krause, G.; Ratter, B.M.W.; Welp, M. 2008. Human/nature interaction in the anthropocene: Potential of social-ecological systems analysis. *Gaia-Ecological Perspectives for Science and Society* 17(1): 77-80.

Gurung, T.R.; Bousquet, F.; Trébuil, G. 2006. Companion modeling, conflict resolution, and institution building: Sharing irrigation water in the Lingmuteychu Watershed, Bhutan. *Ecology and Society* 11(2): 36.

Harris, J.R.; Todaro, M.P. 1970. Migration, unemployment and development: A two-sector analysis. *The American Economic Review* 60(1): 126-142.

Hatley, D.C. 2013. *Gamification in environmental education*. MSc Thesis. College of Forestry and Conservation, University of Montana. Available at http://etd.lib.umt.edu/theses/available/etd-06272013-143834/ (accessed on April 22, 2015).

Hayami, Y. 2009. Social capital, human capital and the community mechanism: Toward a conceptual framework for economists. *Journal of Development Studies* 45(1): 96-123.

Henry, S.; Schoumaker, B.; Beauchemin, C. 2004. The impact of rainfall on the first out-migration: A multi-level event-history analysis in Burkina Faso. *Population and Environment* 25(5): 423-460.

Hill, H.; Hadarits, M.; Rieger, R.; Strickert, G.; Davies, E.G.R.; Strobbe, K.M. 2014. The invitational drought tournament: What is it and why is it a useful tool for drought preparedness and adaptation? *Weather and Climate Extremes* 3: 107-116.

Hoanh, C.T.; le Page, C.; Barreteau, O.; Trébuil, G.; Bousquet, F.; Cernesson, F.; Barnaud, C.; 2008. Agent-based modeling to facilitate resilient water management in Southeast and South Asia. In: *Fighting poverty through sustainable water use: Proceedings of the CGIAR Challenge Program on Water and Food (CPWF), 2nd International Forum on Water and Food, Addis Ababa, Ethiopia, November 10-14, 2008. Vol. 2. Increasing rainwater productivity; Multi-purpose water systems*, eds., Humphreys, E.; Bayot, R.S.; van Brakel, M.; Gichuki, F.; Svendsen, M.; Wester, P.; Huber-Lee, A.; Cook, S.; Douthwaite, B.; Hoanh, C.T.; Johnson, N.; Nguyen-Khoa, S.; Vidal, A.; MacIntyre, I.; MacIntyre, R. Colombo, Sri Lanka: CGIAR Challenge Program on Water and Food (CPWF). Pp. 271-274. Available at http://www.researchgate.net/profile/Bas_Bouman/publication/225160182_Optimizing_yield_water_requirements_and_water_productivity_of_aerobic_rice_for_the_North_China_Plain/links/548937f80cf2ef344790acd7.pdf#page=279 (accessed on April 22, 2015).

Hoekstra, A.Y. 2012. Computer-supported games and role plays in teaching water management. *Hydrology and Earth System Sciences* 16(8): 2985-2994.

Hoermann, B.; Kollmair, M. 2009. *Labour migration and remittances in the Hindu Kush-Himalayan region*. ICIMOD Working Paper. Kathmandu, Nepal: International Centre for Integrated Mountain Development (ICIMOD). Available at http://lib.icimod.org/record/26394/files/attachment_543.pdf (accessed on April 22, 2015).

Holtz, G.; Pahl-Wostl, C. 2012. An agent-based model of groundwater over-exploitation in the Upper Guadiana, Spain. *Regional Environmental Change* 12(1): 95-121.

Hutton, G.; Haller, L.; Bartram, J. 2007. Global cost-benefit analysis of water supply and sanitation interventions. *Journal of Water and Health* 5(4): 481-502.

Kapp, K.M. 2012. *The gamification of learning and instruction: Game-based methods and strategies for training and education*. John Wiley & Sons.

Kniveton, D.; Smith, C.; Wood, S. 2011. Agent-based model simulations of future changes in migration flows for Burkina Faso. *Global Environmental Change* 21(Supplement 1): S34-S40.

Lam, W.F. 1996. Improving the performance of small-scale irrigation systems: The effects of technological investments and governance structure on irrigation performance in Nepal. *World Development* 24(8): 1301-1315.

Lam, W.F. 1999. *Governing irrigation systems in Nepal: Institutions, infrastructure, and collective action*. California, USA: ICS Press, Institute for Contemporary Studies (ICS). Available at http://www.cabdirect.org/abstracts/20001804739.html (accessed on April 22, 2015).

Lam, W.F.; Ostrom, E. 2010. Analyzing the dynamic complexity of development interventions: Lessons from an irrigation experiment in Nepal. *Policy Sciences* 43(1): 1-25.

Lansing, J.S. 2009. *Priests and programmers: Technologies of power in the engineered landscape of Bali*. New Jersey, USA: Princeton University Press.

Lansing, J.S.; Kremer, J.N. 1993. Emergent properties of Balinese water temple networks: Coadaptation on a rugged fitness landscape. *American Anthropologist* 95(1): 97-114.

Lempert, R. 2002. Agent-based modeling as organizational and public policy simulators. *Proceedings of the National Academy of Sciences of the United States of America* 99(Supplement 3): 7195-7196.

Massey, D.S.; Axinn, W.G.; Ghimire, D.J. 2010. Environmental change and out-migration: Evidence from Nepal. *Population and Environment* 32(2-3): 109-136.

McCartney, M.; Lankford, B.; Mahoo, H.F. 2007. *Agricultural water management in a water stressed catchment: Lessons from the RIPARWIN project*. Colombo, Sri Lanka: International Water Management Institute (IWMI). 52p. (IWMI Research Report 116).

McCartney, M.; Smakhtin, V. 2010. *Water storage in an era of climate change: Addressing the challenge of increasing rainfall variability. Blue paper*. Colombo, Sri Lanka: International Water Management Institute (IWMI). 14p.

Michelini, J.J. 2013. Small farmers and social capital in development projects: Lessons from failures in Argentina's rural periphery. *Journal of Rural Studies* 30: 99-109.

Moench, M.; Dixit, A. 2004. *Adaptive capacity and livelihood resilience: Adaptive strategies for responding to floods and droughts in South Asia*. Nepal: Institute for Social and Environmental Transition.

Naivinit, W.; Le Page, C.; Trébuil, G.; Gajaseni, N. 2010. Participatory agent-based modeling and simulation of rice production and labor migrations in northeast Thailand. *Environmental Modelling & Software* 25(11): 1345-1358.

Naivinit, W.; Trébuil, G.; Thongnoi, M.; Le Page, C. 2008. Collaborative multi-agent modelling to improve farmers' adaptive capacity to manage water and migrations dynamics in northeast Thailand. In: *Proceedings of the 13th IWRA World Water Congress 2008*. Available at http://www.iwra.org/congress/2008/resource/authors/abs400_article.pdf (accessed on April 22, 2015).

Ostrom, E. 2001. Social capital: A fad or a fundamental concept? In: *Social capital: A multifaceted perspective*, eds., Serageldin, I.; Dasupta, P. World Bank Publications. Available at http://elibrary.worldbank.org/doi/book/10.1596/0-8213-4562-1 (accessed on June 3, 2015).

Pretty, J. 2003. Social capital and the collective management of resources. *Science* 302(5652): 1912-1914.

Price, J.; Janmaat, J.; Sugden, F.; Bharati, L. 2014. Valuing water storage systems in water scarce environments: A choice experiment in Nepal's Koshi River Basin. *Proceedings of the 11th Annual Meeting of the International Water Resource Economics Consortium (IWREC), Washington, DC, September 7-9, 2014*. Washington, DC, USA: World Bank.

Railsback, S.F.; Grimm, V. 2011. *Agent-based and individual-based modeling: A practical introduction*. New Jersey, USA: Princeton University Press.

Rusca, M.; Heun, J.; Schwartz, K. 2012. Water management simulation games and the construction of knowledge. *Hydrology and Earth System Sciences* 16(8): 2749-2757.

Sapkota, C. 2013. Remittances in Nepal: Boon or bane? *Journal of Development Studies* 49(10): 1316-1331.

Schlueter, M.; McAllister, R.R.J.; Arlinghaus, R.; Bunnefeld, N.; Eisenack, K.; Hoelker, F.; Milner-Gulland, E.J.; Müller, B.; Nicholson, E.; Quaas, M. 2012. New horizons for managing the environment: A review of coupled social-ecological systems modeling. *Natural Resource Modeling* 25(1): 219-272.

Schlüter, M.; Pahl-Wostl, C. 2007. Mechanisms of resilience in common-pool resource management systems: An agent-based model of water use in a river basin. *Ecology & Society* 12(2): 4.

Scoones, I. 1998. *Sustainable rural livelihoods: A framework for analysis*. IDS Working Paper 72. Brighton, UK: Institute of Development Studies (IDS). Available at http://opendocs.ids.ac.uk/opendocs/handle/123456789/3390 (accessed on April 22, 2015).

Shively, G.; Gars, J.; Sununtnasuk, C. 2011. *A review of food security and human nutrition issues in Nepal*. Staff Paper 11-05. West Lafayette, Indiana: Department of Agricultural Economics, Purdue University. Available at http://www.agecon.purdue.edu/staff/shively/Nepal_review.pdf (accessed on April 22, 2015).

Sugden, F.; Shrestha, L.; Bharati, L.; Gurung, P.; Maharjan, L.; Janmaat, J.; Price, J.I.; Sherpa, T.Y.C.; Bhattarai, U.; Koirala, S.; Timilsina, B. 2014. *Climate change, out-migration and agrarian stress: The potential for upscaling small-scale water storage in Nepal*. Colombo, Sri Lanka: International Water Management Institute (IWMI). 38p. (IWMI Research Report 159).

Tesfatsion, L. 2002. Agent-based computational economics: Growing economies from the bottom up. *Artificial Life* 8(1): 55-82.

Todaro, M.P. 1969. A model of labor migration and urban unemployment in less developed countries. *American Economic Review* 59(1): 138-148.

UN RCHCO (United Nations Resident and Humanitarian Coordinator's Office). 2013. *Why do people migrate? An overview of labour migration issues in Achham and Bajura*. Field Bulletin Issue 56. Kathmandu, Nepal: United Nations Resident and Humanitarian Coordinator's Office (UN RCHCO). Available at http://www.un.org.np/headlines/field-bulletin-56 (accessed on April 22, 2015).

World Bank. 2011. *Large-scale migration and remittance in Nepal: Issues, challenges, and opportunities*. Report no. 55390-NP. Washington, DC: World Bank Group.

Appendix. Model details.

Entities

The appendix provides mathematical expressions that are used to manage the variables for the different agents. Agents are grouped into sets: fields $i \in \mathcal{F}_{k,t}$, labor $j \in \mathcal{L}_{k,t}^{L} \cup \mathcal{L}_{k,t}^{F}$ (***L***ocal and ***F***ar), households $k \in \mathcal{H}_l$, villages $l \in \mathcal{V}$, storage $m \in \mathcal{S}_{l,t}$ and taps $\mathcal{T}_{l,t}$. A time subscript indicates that the set changes over time. Index subscripts indicate the set to which the agent (field, household, etc.) is attached.

People. Person i's productivity is $\alpha_i = 1 + \alpha I(\#\mathcal{T}_k > 0)$, where $I(\#\mathcal{T}_k > 0)$ is an indicator that is equal to one (1) when the count of taps serving the household k, $\#\mathcal{T}_k$, is greater than zero.

Field. The crop harvest from field i in the period t, $H_{i,t}$, is given by

$$H_{i,t} = \begin{cases} \overline{H}_i(l_{i,t}/\bar{l}_i) & \tau_{i,t}w_{i,t} \geq \overline{w}_i \\ \overline{H}_i(l_{i,t}/\bar{l}_i)(\tau w_{i,t} - \underline{w_i})/(\overline{w}_i - \underline{w_i}) & \underline{w_i} \leq \tau_{i,t}w_{i,t} < \overline{w}_i \\ 0 & \tau_{i,t}w_{i,t} < \underline{w_i} \end{cases} \quad (1)$$

Yield increases linearly from zero to $\overline{H}_i(l_{i,t}/\bar{l}_i)$ for technology-augmented water $\tau_{i,t}w_{i,t}$ provided to the crop in the interval $\underline{w_i} \leq \tau_{i,t}w_{i,t} < \overline{w}_i$. Technology is represented by $\tau_{i,t}$, a term which increases from one to reflect technology that enables a crop to grow with less water. Effective labor, $l_{i,t}$, divided by the labor needed, $\bar{l}_i$, scales crop yield. Labor that is more productive can boost crop yield.

$$MVP_l(j) = \begin{cases} p_t\overline{H}_i f_i(j)/\,\bar{l}_i & l_{i,t} < \bar{l}_i \\ 0 & l_{i,t} \geq \bar{l}_i \end{cases} \quad (2)$$

The marginal value product of labor for worker j on the field i is the crop price for the crop being grown on this field, p_t, multiplied by the marginal product of worker j. Given the linear nature of the production function – and assuming that the owner expects to get sufficient water to achieve maximum yield – the marginal product of labor is worker j's individual productivity $f_i(j)$ multiplied by the average product of labor that is unit productive. If the total effective labor, $l_{i,t}$, exceeds the labor needed, the marginal value product is zero.

$$d_{i,t} = \begin{cases} a_i(\overline{w}_i/\tau_{i,t} - w_{i,t}) & \tau_{i,t}w_{i,t} \leq \overline{w}_i \\ 0 & \tau_{i,t}w_{i,t} > \overline{w}_i \text{ or } l_{i,t} = 0 \end{cases} \quad (3)$$

Water demand by this field is equal to the difference between the water currently available on the field, $w_{i,t}$, and the amount needed to achieve maximum yield, $\overline{w}_i/\tau_{i,t}$, multiplied by the area of the field, a_i. If no labor is applied to this field, water demand is zero.

$$\pi_{i,t} = (1-\phi)p_t H_{i,t} \quad (4)$$

The period profit, $\pi_{i,t}$, for this field is the residual of the revenue after labor is paid. Labor is paid a share ϕ of the crop revenue.

Households. Household income is

$$Y_{k,t} = \sum_{i \in \mathcal{F}_{k,t}} \pi_{i,t} + \sum_{j \in \mathcal{L}_{k,t}^{L}} q_{j,t} + (\#\mathcal{L}_{k,t}^{F})r + s_{k,t} \quad (5)$$

where: $\mathcal{F}_{k,t}$, $\mathcal{L}^{L}_{k,t}$ and $\mathcal{L}^{\mathcal{F}}_{k,t}$ are the set of fields owned by household k, the set of household members who reside in the village and the set of household members who have migrated away, respectively. Profit from field i is $\pi_{i,t}$, the wage paid to worker j is $q_{j,t}$, the remittance paid by each household member who has migrated away is r and the subsidy received by the household is $s_{k,t}$.

Household costs include the sustenance cost for each member living in the village, $\gamma[1+\beta I(\#\mathcal{T}_{k,t}=0)]$, where γ is the basic maintenance cost (similar to Schlüter and Pahl-Wostl 2007), and β is a scaling factor that measures an increase in sustenance cost when the household does not have access to potable drinking water.

The household will have a member migrate away, if $(\sum_{t\in T} Y_{k,t}/T)/(\#\mathcal{L}^{L}_{k,t}) - \rho c_m < r$, where ρ is the discount rate, c_m is the cost of migrating and $(\sum_{t\in T} Y_{k,t}/T)/(\#\mathcal{L}^{L}_{k,t})$ is the average per person income of the household. Migration costs are paid out of the cash holdings of the household.

If cash holdings are negative, the household tries to sell a parcel of land. The household chooses the parcel with the lowest average profit as the one to try and sell. The asking price is $(\sum_T \pi_{i,t}/T)/\rho$, the present value of an infinite sequence of payments equal to $\sum_{t\in T}\pi_{i,t}/T$. The actual selling price is the minimum of this asking price and $\max_{k\in\mathcal{H}_l} W_k$, where $\mathcal{H}_l$ is the set of households in village l and W_k is the wealth of household k, if this maximum is greater than zero.

Storage. The amount of water stored in the water storage system m evolves as

$$S_{m,t+1} = \begin{cases} \min\{\overline{S}_m, [S_{m,t} + B_{m.t} + \psi_m P_{m,t} - D_{m,t}]\} & G_{m,t} = 1 \\ 0 & G_{m,t} = 0 \end{cases} \quad (6)$$

Where: $\mathcal{S}_{m,t}$ is the contribution to water in the current season that is carried over from the last season, $\mathcal{B}_{m,t}$ is the base yield that this storage is able to provide to the attached fields (independent of the amount of precipitation this season), $\psi_m P_{m,t}$ is the total contribution to yield in the current season from precipitation $P_{m,t}$ this season, $D_{m,t}$ is the water delivered to attached fields, and $G_{m,t}$ is an indicator that equals one (1) if the storage is working and zero (0) if it is not. The term ψ_m converts a precipitation depth into a total volume. It would incorporate the influence of the area that water is collected from, the efficiency with which it is captured, etc. The total amount of water carried over to the start of the next season, $S_{m,t+1}$, cannot exceed the maximum yield of this storage structure, $\overline{S}_m$.

$$G_{m,t+1} = \begin{cases} 1 & G_{m,t} = 1, \varepsilon_{m,t} > \theta_m + (1-\theta_m)(1 - m_{m,t}/C_{m,t}) \\ 0 & \text{otherwise} \end{cases} \quad (7)$$

If a storage structure is functional this period, it will continue to function in the next period if the realization of the random variable $\varepsilon_{m,t} \backsim u[0,1]$ is large enough. It must be greater than the sum of the exogenous probability that the storage will fail, θ_m, and the product $(1-\theta_m)(1-m_{m,t}/C_{m,t})$. In this product, $m_{m,t}$ is the unpaid maintenance cost for water storage system m this year, and $C_{m,t}$ is the total maintenance cost that must be paid in period t if the probability of failure isn't going to increase. If the maintenance cost is fully paid, such that $m_{m,t}$ is zero, then the probability of failure is simply θ_m.

The unpaid maintenance cost is calculated through an iterative algorithm. The steps are:

1. Calculate the basic maintenance cost $C_{m,t} = \underline{C}_m/k_{l,t}$ as the default cost divided by the social capital level $k_{l,t}$ in village l, and set $m_{m,t} = C_{m,t}$.
2. Iterate over all the attached fields, asking the field owners to pay a proportionate share of the maintenance cost, reducing $m_{m,t}$ by the payment made by each household.
3. If $m_{m,t} > 0$, multiply $m_{m,t}$ by 1.25, increase $C_{m,t}$ by $0.25 m_{m,t}$ and return to step (2).
4. Exit, if $\sum_{k\in\mathcal{H}_l} W_{k,t} = 0$ or $m_{m,t} = 0$.

Villages. Village social capital is based on the Gini coefficient. For this simulation, the Gini coefficient of cash holdings was calculated as

$$G_{l,t} = \frac{2\sum_{\mathcal{H}_{l,t}}\sum_{\mathcal{L}^L_{k,t}} k(W_k - \underline{W_l})}{n_{l,t}\sum_{\mathcal{H}_{l,t}}\sum_{\mathcal{L}^L_{k,t}}(W_k - \underline{W_l})} - \frac{n_{l,t}+1}{n_{l,t}} \quad (8)$$

where: W_k are ordered from low to high, the multiplying term $k \in [1, \ldots, n_{l,t}]$ is a counter, $\underline{W_l} = \min_{\mathcal{H}_l}\min_{\mathcal{L}^L_{k,t}} W_i$ and $n_{l,t} = \sum_{\mathcal{H}_{l,t}}(\#\,\mathcal{L}^L_{k,t})$. Subtracting $\underline{W_l}$ ensures that $0 \le G_{l,t} \le 1$.

The target social capital level $s^*_{l,t} = (1 - G_{l,t})(1 - v_{l,t})v_{l,t}$, with $v_{l,t} = \left[\sum_{\mathcal{H}_{l,t}} I(\#\mathcal{T}_{k,t} > 0)\right]/(\#\mathcal{H}_{l,t})$ The new level of social capital is $s_{l,t+1} = \mu(s^*_{l,t} - s_{l,t}) + s_{l,t}(n_{l,t-1}/n_{l,t})$. Social capital moves towards $s^*_{l,t}$ at a rate determined by μ, hit by negative shocks whenever somebody migrates away from the village. The size of this migration effect shock increases the smaller the village population.

Indicators

Table A1. Definitions of indicators reported in Table 6, and displayed in radar plots.

Indicator	Description
Final Wealth	Total wealth of all households in the watershed divided by the number of households, at the end of the twenty-year simulation run.
Average Income	Total income generated by all households over the second decade of the simulation run, divided by the number of households and the number of years.
Average Profit	As for *Average Income*, but for total net revenue gained from crop production (revenue less labor payment).
Average Wages	As for *Average Income*, but for labor income.
Average Remittances	As for *Average Income*, but for remittance income.
Average Subsidy	As for *Average Income*, but for subsidy income received.
Average Sustenance Cost	Total paid by all households for subsistence over the second decade of the simulation run, divided by the number of households and the number of years.
Average Migration Costs	As for *Average Subsistence Cost*, but for migration costs paid.
Average Maintenance Costs	As for *Average Subsistence Cost,* but for amounts paid to maintain water storage systems.
Cooperative Spirit	Average level of cooperative spirit across the model villages at the end of the twenty-year simulation run.
Water Systems Functioning	Average number of functioning water systems across the model villages at the end of the twenty-year simulation run.
Households Occupied	The number of households with at least one member residing in the village at the end of the twenty-year simulation run.
Population	The number of people residing in the village at the end of the twenty-year simulation run.
Taps per Household	Average number of households with access to a tap at the end of the twenty-year simulation run.
Total Water Systems	Average number of water systems per village, functioning or otherwise, at the end of the twenty-year simulation run.

IWMI Research Reports

163 *Demonstrating Complexity with a Role-playing Simulation: Investing in Water in the Indrawati Subbasin, Nepal.* John Janmaat, Suzan Lapp, Ted Wannop, Luna Bharati and Fraser Sugden. 2015.

162 *Landlordism, Tenants and the Groundwater Sector: Lessons from Tarai-Madhesh, Nepal*. Fraser Sugden. 2014.

161 *Is 'Social Cooperation' for Traditional Irrigation, while 'Technology' is for Motor Pump Irrigation?* Mengistu Dessalegn and Douglas J. Merrey. 2014.

160 *Understanding Farmers' Adaptation to Water Scarcity: A Case Study from the Western Nile Delta, Egypt.* Wafa Ghazouani, François Molle, Atef Swelam, Edwin Rap and Ahmad Abdo. 2014.

159 *Climate Change, Out-migration and Agrarian Stress: The Potential for Upscaling Small-scale Water Storage in Nepal.* Fraser Sugden, Lata Shrestha, Luna Bharati, Pabitra Gurung, Laxmi Maharjan, John Janmaat, James I. Price, Tashi Yang Chung Sherpa, Utsav Bhattarai, Shishir Koirala and Basu Timilsina. 2014.

158 *Water for Food in Bangladesh: Outlook to 2030.* Upali A. Amarasinghe, Bharat R. Sharma, Lal Muthuwatta and Zahirul Haque Khan. 2014.

157 *Land Reforms and Feminization of Agricultural Labor in Sughd Province, Tajikistan.* Nozilakhon Mukhamedova and Kai Wegerich. 2014.

156 *Global Water Demand Projections: Past, Present and Future.* Upali A. Amarasinghe and Vladimir Smakhtin. 2014.

155 *A Participatory Approach for Hydrometeorological Monitoring in the Blue Nile River Basin of Ethiopia.* Birhanu Zemadim, Matthew McCartney, Simon Langan and Bharat Sharma. 2013.

154 *Determinants of Adoption of Rainwater Management Technologies among Farm Households in the Nile River Basin*. Gebrehaweria Gebregziabher, Lisa-Maria Rebelo, An Notenbaert, Kebebe Ergano and Yenenesh Abebe. 2013.

153 *Facilitating Outcomes: Multi-stakeholder Processes for Influencing Policy Change on Urban Agriculture in Selected West African and South Asian Cities.* Priyanie Amerasinghe, Olufunke O. Cofie, Theophilus O. Larbi and Pay Drechsel. 2013.

Electronic copies of IWMI's publications are available for free.

Visit

www.iwmi.org/publications/index.aspx

Postal Address
P O Box 2075
Colombo
Sri Lanka

Location
127 Sunil Mawatha
Pelawatta
Battaramulla
Sri Lanka

Telephone
+94-11-2880000

Fax
+94-11-2786854

E-mail
iwmi@cgiar.org

Website
www.iwmi.org

IWMI is a member of the CGIAR Consortium and leads the:

RESEARCH PROGRAM ON
Water, Land and Ecosystems

ISSN: 1026-0862
ISBN: 978-92-9090-819-7