Simulation modelling for water governance in basins

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Accelerating future water shortages require development of operational water governance models, as illustrated by three case studies: (1) upstream–downstream interactions in the Aral Sea basin, where science acts as problem recognizer, emphasizing scoping policies; (2) impact and adaptation of climate change on water and food supply in the Middle East and North Africa, where science acts as a mediator between perspectives, emphasizing scoping and a start of implementation policies; and (3) green water credits in Kenya, where science acts as advocate, emphasizing scoping and implementation policies in close interaction with stakeholders, including impulses from applied to basic research.

Keywords: water resources modelling; hydrology; food security; Kenya; Aral Sea; MENA; Caucasus

Introduction

Water governance aimed at increasing food production

Water-related problems are diverse and location-specific. The ideal condition of having the appropriate amount of good-quality water at the desired place and time is most often not satisfied. Because so many different problems may have to be solved, the broad concept of integrated water resources management (IWRM) was introduced and has been advocated over the last decade (e.g. Vannevel, 2011). In the early phases of IWRM the feeling prevailed that by integrating the more classical technical approaches with socio-economic aspects, overall water management could be improved. More recently, IWRM has been expanded by integrating all water resources, not only water in streams and reservoirs as was the original base for IWRM. This extended approach to IWRM is now being advocated and is often referred to as including ‘blue’ and ‘green’ water, making the distinction between free water in streams and reservoirs and water available in soils to be used by the vegetation or crop, respectively (Falkenmark & Rockström, 2010, p. 607). This expansion was necessary because many policy makers still limit water issues primarily to drinking, sanitation, industrial and irrigation use. Misconceptions that ‘irrigated agriculture is the major consumer of water’ are still frequently heard, ignoring the fact that the natural landscape and rainfed agriculture are evaporating (that is, consuming) a much higher volume of water (Molden, 2007).

More recently, terminology discussions have resulted in a new simple term, ‘water governance’, replacing both ‘sustainable water management’ and ‘integrated water resources management’ and indicating the increasing importance of water management in a broad societal context (Biswas & Tortajada, 2010). Water governance is defined as “the

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range of political, social, economic and administrative systems that are in place to develop and manage water resources, and delivery of water services, at different levels of society” (Rogers & Hall, 2003). The water governance concept acknowledges a major political challenge for the coming decades, which is the increasing international and intersectoral competition for scarce water, particularly considering the strongly growing demand for food, which is becoming ever more serious because of the expected population growth and the impact of climate change and variability.

A substantial number of studies have been undertaken during the last two decades related to water and food. In fact, the first global assessment of food supply and demand was published in 1798 by Thomas Robert Malthus, who famously predicted that short-term gains in living standards would inevitably be undermined as human population growth outstripped food production. However, more recent scenario studies at the global level indicate that agricultural production potential is sufficient to meet the estimated needed increase of 40% by 2050 (Molden, 2007). An optimistic scenario assumes significant progress in upgrading rainfed systems while relying on minimal increases in irrigated production, thus reaching 80% of the maximum obtainable yield. This could lead to an average yield increase from 2.7 metric tons per hectare in 2000 to 4.4 tons in 2050 (representing 1% annual growth). Without expansion of the current irrigated area, the total cropped area would have to increase by only 7% over the coming decades to keep pace with rising demand for agricultural commodities – a much lower rate than the 24% increase that occurred from 1961 to 2000. This 7% increase is feasible, as indicated by Rockström et al. (2009), who define nine planetary boundaries, among them the land use boundary. These planetary boundaries define the safe operating space for humanity with respect to the Earth system.

Other studies also provide a positive view and claim that sufficient food can be produced to feed current and future generations, but only when farmers and policy makers embrace suggestions made by the research community (e.g. Nelson et al., 2009; Rosegrant, 2003; Earthscan, 2009). To produce 40% more food by 2050, substantial amounts of water are required. Gleick (2000) showed that large differences can be found in terms of daily water requirements for food production between regions, ranging from 1760 litres per day per person for Sub-Saharan Africa (with low-calorie, low-meat diets) to 5020 litres for North America (with high-calorie, high-meat consumption). Obviously, if this food is produced in areas where water is not limiting, these numbers are less relevant, despite the overwhelming interest in ‘virtual water’ (representing the volume of water needed to produce 1 kg of agricultural produce; see Hoekstra & Mekonnen, 2012).

So far, many of the above studies have addressed the global scale from a strategic point of view, and this is certainly important to focus international policies. But global approaches ignore differences at smaller spatial scales, covering countries, regions and basins. Policy makers and practitioners face overwhelming operational problems at smaller scales trying to solve challenges associated with water availability. Major differences are found at smaller spatial scales, and a shift in attention to such scales therefore deserves priority when planning research (e.g. Tortajada, 2010a, 2010b). Considering the ‘think globally, act locally’ principle, when studying water governance, attention should therefore preferably be focused on the basin level, which represents a hydrological entity with its own internal dynamics governed by the hydrological cycle.

**The need for simulation modelling**

Relevant information, based on reliable data, is essential to assess not only the current condition of water resources in a given basin but also past trends and future possibilities.
To explore options for the future, tools are required that can explore the impact of future trends and possible ways of sustainable adaptation. Climate change implies that expert knowledge based on past conditions cannot adequately address such future trends. Simulation models that can explore future conditions are therefore appropriate and indispensable tools for such analyses. R.K. Linsley (1976) was a pioneer in the development of hydrological simulation models at Stanford University. He defined two main objectives of model applications: (1) to express hydrological processes and their interaction, by quantitative mathematical expressions, providing clarity and understanding; and (2) to use models for scenario analyses, exploring possible futures that obviously cannot be measured. The understanding of processes forms the basis for model development. Of course, any model is a gross simplification of a highly complex reality. The main challenge is therefore not to try to represent all known processes in a model, which is in fact impossible, but to simplify representations as much as possible and to concentrate on the most relevant processes of the model being constructed (Droogers & Bastiaanssen, 2002).

Exploring different future scenarios expressing, for example, possible effects of population growth and climate change, are the most important objectives when applying simulation models (Droogers & Aerts, 2005). These are often referred to as ‘projections’. Models are also applied at the operational level to develop ‘management scenarios’ or interventions to be used by water managers and policy makers. Examples are changes in reservoir operation rules, water allocation between sectors, investment in infrastructure such as water treatment or desalination plants, and agricultural and irrigation practices. In other words: models enable water resources managers to change focus from a reactive towards a proactive approach.

The information revolution of the last decade has had a major impact on the potential of using simulation modelling for water governance purposes. First, introduction of various remote-sensing techniques has allowed setting up and validation of models to an extent that was impossible before. Second, the rapid increase of computing capabilities has allowed interactive work with stakeholders and policy makers in terms of being able to quickly show the potential effects of suggested interventions. A completely new research paradigm is being established, as compared with traditional procedures where research was done, often with a strong research-oriented focus, followed by reporting after several months, when attention often had drifted away to other issues. The descriptions of case studies, later in this paper, will illustrate some of these changes.

Considering the outlook of accelerating future water shortages with adverse effects on food security, as discussed, there is an urgent need to develop operational water governance practices that can not only contribute towards improving existing practices but to also develop innovative new practices that can increase water productivity. So far, the main emphasis of hydrologists appears to be on developing models as an intellectual exercise, as an end in itself, and this needs to be expanded to make modelling a central and indispensable tool in decision-making processes by stakeholders and policy makers. In other words, too many hydrological journal articles end with a statement that “the model can mimic reality”, while articles in water management journals end with statements like “appropriate actions should be taken”. The gap between these two statements should be closed by developing state-of-the-art, operational simulation models that form the basis for successful planning and decision making in the real world.

This paper therefore has the following three objectives. First, it provides a review of the availability of simulation models and their features, with particular attention to the basin level. Second, it analyzes the selection process of models for a given application,
considering model availability and the associated costs, the type of problems to be studied, and data availability. Finally, the paper discusses the social and political context in which those models are to be applied, which is changing rapidly, following the information revolution all over the world, which implies a changing role of research versus its stakeholders, including the policy arena. In other words, how can models become an essential tool in decision making for water governance, rather than just an abstract study object for hydrologists?

Methodologies

Simulation models

The history of hydrological models is relatively short. One of the first was the Stanford Watershed Model (SWM) developed by Crawford and Linsley in 1966, but the main principles are still used in current catchment models, converting rainfall into runoff. The SWM did not have much physics; the catchment was just represented by a set of storage reservoirs linked to each other. The values of the parameters describing the interactions between these different reservoirs were obtained by trying to match the simulated and the observed streamflows. At the other end of the spectrum are field-scale models describing unsaturated flow processes in the soil and root water uptake. One of the first to be developed was the SWATR model by Feddes and Zaradny (1978), based on Richards’s equation. Since these models are based on points, using the concept that unsaturated flow is dominated by vertical transport of water only, much more physical theory could be built in from the beginning (Allen, Bastiaanssen, Droogers, D’Urso, & Steduto, 2004; Bastiaanssen, Allen, Droogers, D’Urso, & Steduto, 2007).

A huge number of hydrological models exist, and applications are growing rapidly. The number of pages on the Internet including “hydrological model” is over 5.8 million, using Google in January 2014. Using the same search engine with “water resources model” returns 150 million pages. The number of existing hydrological simulation models is probably in the tens of thousands. Even if we exclude the one-off models developed for a specific study and count only the more generic models, it must exceed a thousand. Some existing model overviews cover numerous models. Amongst others (with the number of models mentioned) are: IRRISOFT (2014), 114; USGS (2014), 110; EPA (2014), 211; USACE (HEC, 2014), 18; and REM (2014), 681.

No standard model or models appear to be emerging for catchment modelling, which is in contrast to groundwater modelling, where ModFlow is the de facto standard. Two hypotheses for this lack of standard in catchment models can be given. First, model development is still in its initial phase, despite some 25 years of history, and therefore it is easy to start developing one’s own model that can compete with similar existing ones within a reasonable amount of time and effort. Indeed, a serious hydrologist is considered to have his/her own model or is supposed to have at least developed one during his or her PhD studies. Second, hydrological processes are so complex and diverse that each case requires its specific model or set of models.

It is therefore interesting to see how models can be classified and to see whether such a classification might be helpful in selecting the appropriate model when decisions related to water management and food production have to be made. Probably the most generally used parameters are the spatial scale the model deals with and the amount of physics included (Figure 1). These two characteristics determine other model characteristics, such as data needs, expected accuracy, required expertise, and user-friendliness.
Basin-scale models

Since the 1990s a growing consensus states that the river basin is the appropriate scale at which to make decisions related to water and food. The number of basin authorities is on the rise and there are nearly no basins that do not have any form of river-basin authority or a plan to develop them. Obviously, decision making at the river-basin scale requires the support of appropriate tools. The focus on better tools, often referred to as ‘water information systems’, is somewhat limited to collecting more data and storing those data in a better organized way (Parris, 2011). The repeatedly heard complaints that there are not enough data may be due to the fact that available data are not used and are therefore lost or improperly stored. This may be so because the interests of decision makers are focused on the impact of potential interventions, which requires a forward-looking approach, while data, by nature, only provide information on the past (Figure 2). As modelling approaches are more commonly used, the value of data will become evident, because they are indispensable for calibrating and validating these models; and then, as a consequence, more emphasis may be put on data collection and storage.

The changing societal setting in which models are applied

Traditionally, research was assigned from the top down and results were implemented without much consideration of stakeholders’ involvement; this has changed dramatically during the last decades. It is true all over the world, even though large differences can be observed among countries. Not only has people’s educational level improved significantly, but the information revolution has opened up a wide body of knowledge to all interested citizens, for whom ‘to google’ has become a new verb. Research can no longer thrive in splendid isolation, because society increasingly demands value for money, and ultimately this applies also to modelling basin hydrology. That is why the term ‘water governance’, as cited in the introduction, is quite appropriate.

In ‘t Veld (2010) has coined the term ‘knowledge democracy’, which is meant to enable a new focus on the relationships between knowledge production and dissemination,
the functioning of the media and our institutions. One of the underlying insights is that scientific knowledge by its very structure never directly relates to action, because it is fragmented and partial. This presents a huge challenge for policy makers, scientists and the media. Politics is not only confronted with the question of what knowledge to select for policy decisions but also, and almost more importantly, how the decision-making process should be arranged in order to adequately incorporate the different types of knowledge, with the ultimate objective to produce specific results applicable to the real world.

Issues of sustainable development are vital for any society, and they are associated with so-called ‘wicked’ problems that not only are difficult to define but don’t have simple, straightforward solutions either (Bouma, van Altvorst, Eweg, Smeets, & van Latesteijn, 2011). Realizing integrated water resource management and water governance of basins certainly qualify as wicked problems. There is no single, perfect procedure, nor can the problem be defined specifically. Many stakeholders are involved, with often quite contrasting opinions and interests, some of them commercial (Edelenbos, van Buuren, & van Schie, 2011). Different levels of government are often involved, and so are non-governmental organizations and action groups. Somehow, all or at least most of these stakeholders have to agree to some form of compromise in the end to produce concrete results.

Bouma et al. (2011) studied programmes in the Netherlands focusing on sustainable development of agricultural production systems. They conclude that successful systems were established only thanks to highly persistent entrepreneurs supported by ‘knowledge brokers’: scientists with a high social intelligence who provided the right kind of knowledge, at the right time and place, in the right way, to the right person! (See also Pielke, 2007.) Programmes often took more than 10 years to materialize. This context, which is associated with wicked problems, poses major operational problems to disciplinary scientists, like hydrologists, who are used to solving clear-cut problems that have single solutions. Wicked problems cannot be ‘solved’; research can at most offer a range of possible options, each with a different balance of social, economic and environmental considerations, the basic elements of sustainable development. Simulation modelling functions as an excellent and indispensable tool to derive such scenarios. Then, stakeholders and policy makers have to make a choice from the options being presented.

As discussed, hydrologists have to learn to not see their models as an end in themselves. But next, they also have to be prepared to see whether or not their results are being used in the highly complex and confusing context of modern society. And if their work is ignored, they should be prepared to explore new, innovative ways to present their
information (Bouma et al., 2011; Edelenbos et al., 2011). Petersen (2011) discusses the use of simulation models for policy advice, distinguishing four types of policy problems based whether there is (1) agreement among stakeholders on relevant norms and values, and (2) consensus about relevant knowledge (Figure 3). Thus, distinctions are made between science as problem recognizer, advocate, mediator between perspectives, or problem solver. He also demonstrates various ways to deal with modelling uncertainties when dealing with policy problems. His scheme will be applied in discussing the case studies later in this paper.

A framework for science–policy–stakeholder interfaces

Pahl-Wostl, Lebel, Knieper, and Nikitina (2012) analyze key factors related to successful water governance based on 29 basin case studies and find that knowledge is an important factor. Edelenbos et al. (2011) present a framework on knowledge production in the Netherlands as derived from water management projects. They distinguish three main actors (stakeholders, civil servants and experts), and conclude that knowledge should be properly synchronized between those three. At a higher level, Petersen (2011) and Weiland, Weiss, and Turmpenny (2013) argue that fundamental scientific knowledge is needed to guide policies. However, direct impact of such knowledge on political decisions appears to occur only in a minority of cases, and research usually has a much more indirect impact on policy through longer-term learning. In addition, Pielke (2007) claims that input of knowledge for decision making has increased substantially during the last decades, and Pielke and Wilby (2012, p. 10) argue that “the scientific enterprise is diverse enough to offer information that can be used to support a diversity of perspectives on just about any subject”.

An essential aspect in discussing water governance is the distinction of two levels of policy making as well as in the associated science. One level focuses on policy planning (‘scoping’ in Figure 4) and the other on implementation. Scoping policies originate from high-level decision makers, focusing on broad, strategic decisions such as whether focus should be on food production, the environment, hydropower, etc. (arrow A in Figure 4). Implementation policies will be based on this type of strategic decision and on the local knowledge base, influencing the stakeholders living in that particular basin (B). Stakeholders’ knowledge can be mobilized and used by implementation policies (D) and

![Figure 3. Four types of policy problems, with associated roles for research. Reprinted from Petersen (2011).](image-url)
might, in turn, influence scoping policies (C). Obviously, the degree to which these processes operate varies substantially from country to country, as will be demonstrated in the three case studies.

The framework also includes the scientific actors, distinguishing basic science from applied science. In the context of this study, basic science usually focuses on hydrological processes by defining physical laws to be incorporated in simulation models. Interaction with stakeholders (F) is limited. Applied science uses these models for a particular basin. Currently, as stated above, many modelling studies are focused on writing a paper in an applied science journal, putting much emphasis on the basic science involved if only to satisfy reviewers’ demands (E). The possibility that basic science influences stakeholder thinking (F) on major environmental issues such as climate change, acid rain and food security cannot be excluded, but the process is rare. However, applied hydrological basin studies that go beyond basic aspects and aim for a realistic focus on scoping policies and stakeholder interests would be more likely to affect stakeholder and policy thinking. As it is, however, no arrows can as yet be shown between applied science on the one hand and implementation policies and stakeholders on the other.
Based on three case studies, this article will argue that three linkages should be added to the framework to achieve successful water governance (Figure 4, lower diagram). First of all, the scientific community should develop a form of applied science that is more in line with stakeholder and policy demand, which could result in more effective use by implementation agencies (G), while implementing agencies should make it very clear what they need from applied science (H). This in turn will trigger applied scientists to actively interact with their colleagues in basic science to better focus the basic research agenda (I).

Three illustrative case studies

Introduction

Use of simulation models to support and improve water governance practices will be illustrated for three different case studies in the context of the presented framework. All case studies have a focus on food issues and follow, when possible, a proactive approach in close interaction between local stakeholders and policy makers. The case studies differ significantly in terms of agreement on relevant norms and values as well as in consensus about relevant knowledge, as defined by Petersen (2012) and expressed in Figure 3. Also, relations between policy, science and stakeholders, as represented in Figure 4 and described by Edelenbos et al. (2011), are quite different, as will be analyzed to address the objectives of this study in terms of the selection of models and an evaluation of their potential in a given socio-economic context.

These three case studies are:

- Upstream–downstream interactions in the Aral Sea basin
- Water and food in arid regions: role of climate change
- Green water credits in Kenya

These simulation models could only be applied by using existing data sources. The most important ones include soil maps, climate data, land-cover information, digital elevation models (DEMs) and socio-economic data. Details of those data sources can be found in the references included in the description of each case study.

Upstream–downstream interactions in Aral Sea basin

Introduction

Water governance in the Central Asian region faces big challenges. The hydrological regimes of the two major rivers in the region, the Syr Darya and the Amu Darya, are complex and vulnerable to climate change (Immerzeel, Van Beek, & Bierkens, 2010). Water diversions to agricultural, industrial and domestic users have reduced flows in downstream regions, resulting in severe ecological damage. The administrative-institutional system is fragmented, with six countries sharing control, often with conflicting objectives.

In the Central Asian region, these water-related issues have been prominent since the break-up of the USSR, with conflicting interests between the upstream countries (Kyrgyzstan, Tajikistan and Afghanistan) and the downstream countries (Uzbekistan, Turkmenistan and Kazakhstan). Afghanistan and Turkmenistan were not actively involved in this study because Afghanistan has only a small area in the Amu Darya and Turkmenistan has political constraints. In short, the upstream–downstream conflict consists of opposed demand patterns for energy and water resources in space and time.
Kyrgyzstan and Tajikistan need to release water from a number of large reservoirs during the cold months to generate hydropower for heating, but the winter releases frequently cause flooding in downstream areas. To have enough hydropower generating capacity during those cold months, these upstream states collect water in their reservoirs during the warmer summer months – just when the downstream countries have pressing needs for irrigation water. Cotton is an important cash crop, and wheat is considered essential to meet national food security goals (Stucki, Wegerich, Rahaman, & Varis, 2012). Aside from lack of irrigation water, soil and ecosystem degradation are major concerns as well. Future climate change poses additional challenges. The discharge in the Syr Darya and especially the Amu Darya rivers is driven mainly by snow and glacial melt (Lutz, Droogers, & Immerzeel, 2012). The impact of a warming climate on these key hydrological processes is not sufficiently understood, and therefore the badly needed adaptation strategies cannot be developed. While future changes in precipitation levels are hard to predict, there is a solid consensus that average global temperatures are rising. As a result, more precipitation is likely to have the form of rain in the upstream areas, and the ice volume in the Tien Shan and Pamir mountain ranges is likely to shrink. The former will impact the seasonality of the runoff, and the latter will at least temporarily increase average annual flows.

The ongoing construction of new dams in Kyrgyzstan and Tajikistan is adding tension to the existing situation (Rahaman, 2012). The Soviet-era hydropower projects Kambarata I and II in Kyrgyzstan and the Rogun Dam in Tajikistan are being considered again as a result of increased access to international donor money by Russia and China. For the downstream countries, these developments have raised major concerns because it could imply that the upstream states will not need energy deliveries in the winter from Kazakhstan, Uzbekistan and Turkmenistan. The upstream countries could therefore relax their operations in summer, with severe potential impacts to irrigated agriculture and the overall economy. From this perspective, it is not surprising that tensions are increasing between the countries involved. Although the new infrastructure can be effective in regulating river flow and in adding management options that are direly needed, measures need to be taken to avoid serious flow impediments that will strongly affect the region (Rahaman, 2012).

Approach

The unfavourable developments in this geopolitically important and fragile region call for urgent attention from the international community. The Asian Development Bank has therefore taken the initiative to fund an exploratory study to better characterize existing and future hydrological conditions in the region. Considering the conflicting demands, there is no agreement yet on relevant norms and values, and lack of data implies that there can as yet be no consensus about relevant data. The modelling exercise relates therefore to an unstructured problem, where science will have to act as a problem recognizer (Figure 3). In the analytical framework of Edelenbos et al. (2011), expert knowledge is transferred to bureaucratic knowledge on a relatively high level. Implementation of policies, let alone stakeholder involvement, has not yet materialized.

An explorative modelling study was undertaken in close collaboration with four of the six countries (Kyrgyzstan, Tajikistan, Uzbekistan, and Kazakhstan) to explore to what extent climate change is affecting potential interventions. Given the limited data availability, especially from the mountainous upstream part of the two basins, extensive use of remotely sensed data was included in the modelling efforts. A two-tier model approach was required (Lutz et al., 2012): the SPHY (Spatial Processes in HYdrology) model was set...
up, given its strong mountain hydrology components. SPHY was developed using the best components of existing and well-tested simulation models (see the Appendix in the online supplemental files at http://dx.doi.org/10.1080/07900627.2014.903771). SPHY is fully distributed and implemented on a regular grid. SPHY runs on a daily basis on a 6 arc-minute grid (∼10 × 10 km) and was set up for the period 2000–2050. The WEAP (Water Evaluation And Planning) model (Yates, Sieber, Purkey, & Huber-Lee, 2005) was applied to link upstream and downstream processes and to express effects of human interventions.

The outcome of the study indicated that overall water shortages would increase from about 10% currently to 35% in 2050 for the Syr Darya Basin. Figures for the Amu Dayra Basin are 25% and 50% respectively, indicating higher vulnerability. Details of the models themselves (SPHY and WEAP) are provided in the Appendix; detailed methodology and output can be found in Lutz et al. (2012). The difference between the hydrological flow regimes of the two basins has been quantified using the model output. A typical example is shown in Figure 5, where the impact of the retreat of glaciers is clearly noticeable for the runoff of the Amu Dayra Basin. The results indicate not only that annual flows will be reduced but also a large seasonal shift, where more flows will occur early in the year, at the cost of lower flows during summer, when water is mostly needed.

Efforts by international donors are in progress to ensure that countries will collaborate on these issues. Technical staff from ministries of the countries involved are now starting collaborative research based on the data generated by the modelling approaches as presented above. Following this, the international donor community hopes that eventually political negotiations and treaties will emerge from these initiatives, to be based on continued research in future, also exploring future management scenarios (World Bank, 2009). The modelling arrangement, as used in this study, is directly applicable to this future work.

Figure 5. Flow composition for two contrasting reservoirs in the Aral Sea basin.
Evaluation

This case study in Central Asia’s main river basin has first focused on scoping policies by using modelling techniques in the context of problem recognition, realizing that there is as yet no agreement on relevant norms, values or knowledge. Acknowledging the independence of the five countries was very important in this early phase of the work. Use of remote-sensing data was crucial in filling data gaps. The innovative approach in his study has provided a direct and unusual link between applied science and scoping policies, which is unusual and is not pictured in the analytical framework as presented in Figure 4. The results of this study have already somewhat influenced possible implementing policies (A in Figure 4). Given the uncertainty as to what to do and how to act, technical staff engaged with implementing policies asked applied science for advice (H), which was provided (G). This represents only an initial phase of activities at this time, where interaction of research with experts and bureaucrats was most important and where stakeholders were not yet directly involved (Edelenbos et al., 2011).

Water and food in arid regions

Introduction

Availability of water and food in the Middle East and North Africa (MENA) region, as defined by the World Bank, is falling as a result of changes in climate, population, economic development and irrigation demands (Khaled & Abdel, 2006). Political pressure is high to address these problems because they are bound to lead to national and regional instability, as is being demonstrated by the dramatic changes in the region that were initiated by high food prices, which were due to low yields, which in turn were primarily caused by water shortages (The Economist, 2012; Werrell & Femia, 2013). As different countries are involved, agreements on future policies on water and food are very difficult to realize. Still, there is agreement that, in principle, availability of quantitative data for the entire region will be a necessary starting-point to arrive at programmes that a wide range of participants can support. Even though substantial amounts of data are available at the local or regional level, their diversity and incompleteness seriously hamper the necessary area-wide approach.

Approach

The World Bank, among others, has been active in trying to establish strategic plans to face the problems mentioned above, and this resulted in funding of a MENA programme exploring the future potential for water and food supply in the region (World Bank, 2012). Because of the wide variety of countries involved, with their different political systems and interests, there appears to be no agreement yet on relevant norms and values. Still, there is a certain consensus about relevant knowledge, particularly because water and food science is rather well developed in several of the countries involved. The problem can therefore be classified as moderately structured, where science can play a role as mediator between perspectives (Figure 3). The study used two simulation models and a combination of local and global data-sets. Current and future water resources were assessed using the SPHY model as described above for the period 2000–2050. In addition, a water allocation model to link water supply and water demand and to explore adaptation strategies was used. This model, MENA-WOF (MENA Water Outlook Framework), was developed using the WEAP package (Yates et al., 2005) and considers, within each country, streams, reservoirs, groundwater, irrigation demands, domestic demands and industrial demands.
MENA-WOF was run on a monthly base for the period 2000–2050 as well. The two models were interlinked and set up for the entire MENA region. Since some of the countries receive water from upstream countries as well, the SPHY model was extended to capture these upstream regions. To obtain results relevant for decision makers, model results were aggregated and presented at the country level. Moreover, results were converted to reader-friendly graphs and figures, rather than being science-oriented. An example is shown in Figure 6, where current and estimated future water demand, supply and shortages for the period 2000–2050 are presented in a comprehensive way which is quite effective when interacting with stakeholders and policy makers.

Based on these results, a stakeholder-driven process started. Decision makers from ministries of the 21 countries were confronted with the projections of water demand and supply over the coming 50 years. Based on this, they defined a number of potential adaptation strategies (interventions), which were explored using the modelling framework. These were: (A) improved agricultural practices (including crop varieties); (B) increased reuse of domestic and industrial water supply; (C) increased reuse of irrigation water; (D) expanding reservoir capacity (small scale); (E) expanding reservoir capacity (large scale); (F) desalination using solar energy; (G) desalination using fossil fuels; (H) reducing irrigated areas; and (I) reducing domestic and industrial water demand. Subsequently, national workshops were organized in about half of the countries, where participants were exposed to the threats but also to potential solutions, to create awareness. The estimated impact of these potential interventions is shown in Table 1, indicating that the projected water shortage is mainly due to socio-economic developments and that estimated climate change only contributes 18%. Costs of adaptation to water shortages by various measures as illustrated in Table 1 will be an estimated USD 147 billion annually by 2050 (Droogers et al., 2012).

Evaluation

Basin-scale models, as applied in this study, can be used in an exploratory manner to support decision makers by providing insight into future water issues and allowing estimates of the impacts as well as the costs of proposed interventions. Science functioned

Figure 6. Water demand and supply for the MENA region based on the average climate scenario.
here successfully as a mediator between perspectives (Petersen, 2011), combining a
scoping approach with an estimate of effects of a series of possible implementation
measures (arrow A in Figure 4), which was based on intensive and successful contacts with
researchers (G and H). Thus, expert and bureaucratic knowledge were well connected
(Edelenbos et al., 2011). Even though workshops in some countries established contact
with stakeholders (B and D), this was not common yet. Input by stakeholders later in the
process is likely to improve the quality of the selection of measures being proposed
(Edelenbos et al., 2011). Also, the applied science work triggered basic science (I) to focus
not on better representation of hydraulic processes but on improved understanding of costs
associated with the proposed adaptation options.

**Green water credits in Kenya**

**Introduction**

Soil and water conservation practices have been promoted for a long time (Liniger &
Critchley, 2007) with a focus on achieving local impacts rather than on upstream–
downstream interactions. Also, despite the availability of detailed data on suitable soil
conservation measures for different agro-ecological conditions, implementation in practice has been relatively low. Additional financial incentives for farmers may therefore be needed to achieve implementation, and this was framed here in the concept of ‘green water credits’ (Kauffman et al., 2014). Effective soil conservation measures will result in more upslope infiltration of water and soil conservation, enhancing plant growth and feeding aquifers. Less erosion also results in less damage downstream and reduced siltation of downstream reservoirs used for electricity generation and water supply.

**Approach**

Acknowledging the erosion problem in Kenya, and realizing that just producing more
traditional erosion studies would not lead to implementation of conservation measures,
scientists from various countries initiated the Green Water Project, funded by IFAD.
Here, norms and values were rather clear, as the negative effects of erosion for agriculture but also for water and electric supply are widely acknowledged. There is however no agreement on relevant knowledge, because the various stakeholders have different perspectives on the problem. So science is used here as an advocate (Petersen, 2011; Figure 3).

For a case study on the Upper Tana River in Kenya, a modelling framework was set up to evaluate potential benefits for upstream and downstream water users in case green water credits were implemented (Hunink, Droogers, Kauffman, Mwaniki, & Bouma, 2012). The SWAT (Soil and Water Assessment Tool), in combination with the WEAP, were applied to evaluate a total of 11 potential interventions (Hunink et al., 2012). SWAT is a distributed hydrological model providing spatial coverage of the entire hydrological cycle including atmosphere, plants, unsaturated zone, groundwater and surface water (Neitsch, Arnold, Kiniry, & Williams, 2009). WEAP allows linking upstream to downstream allocations in terms of water, sediments and financial terms. SWAT has a relatively high degree of physical detail; WEAP, a low degree (as illustrated in Figure 1). SWAT was selected for its strength in evaluating the biophysical impact of soil and water management measures. WEAP’s strengths are in evaluating upstream–downstream interactions, both in water allocation and in monetary valuation of water.

The model results quantify the effects of reducing erosion on agricultural fields in terms of reducing inflow of sediments in reservoirs, positively affecting reservoir storage capacities and thereby the volume of water to be allocated for hydropower and irrigation. Figure 7 shows the average changes to three key indicators for 3 of the 11 measures studied (permanent vegetative contour strips, mulching, and tied soil ridges), based on the annual means of the 10-year simulation period. Reductions in reservoir sediment inflow are all comparable (around −10%), while basin-scale reductions of soil loss are much more divergent among the three scenarios (between −7% and −29%). The SWAT tool can also be used to assess the impacts, flows and water allocations spatially, to determine the preferred Green Water Credits (GWC) measure at each site. Figure 8 shows an example of a comparison of the effectiveness of different measures in the area. In this case, for some regions contour strips are more effective in reducing soil erosion while for other locations tied ridges work better. Such data are very important for the interaction with local land users.

Finally, the WEAP tool was used to quantify financial benefits of GWC measures where upstream (higher crop yields) and downstream (less sedimentation and more regulated flows) impacts are assessed. Potential economic benefits for each of 11 GWC...
measures were estimated by WEAP, and these numbers were crucial in discussions among stakeholders and policy makers (Figure 9).

During this study, three interactive workshops were organized with farmers’ organizations, representatives of water and electricity companies (KenGen and Nairobi Water Supply), and representatives from the Ministries of Water and of Agriculture, who were interested in soil conservation because it would extend the operating time of their water reservoirs. Representatives of commercial banks also took part in the discussions. This may result in payments to farmers for their soil conservation, considered as an “ecosystem service” (e.g. Kauffman et al., 2014). The role of models was very prominent during these workshops to express the advantages of soil conservation and the interactions between upstream and downstream water users in quantitative terms.

Evaluation
Application of the SWAT and WEAP simulation models produced a large body of relevant knowledge to demonstrate the positive effects of soil conservation for all stakeholders involved. This way, science played a successful role as an advocate (Figure 3). Close interaction through a series of workshops established effective contacts between the
scientific and implementation arenas (arrows G and H in Figure 4), with clear input by stakeholders (B and D). Edelenbos et al. (2011) correctly emphasize the importance of interaction between experts, bureaucrats and stakeholders that did occur in this study. This interaction was, however, complex and is bound to be different for different case studies because players and their interests will always be different (Kauffman et al., 2014).

Conclusions

Modern water governance is needed to ensure more productive use of water to support food production and simultaneously maintain a healthy and sustainable environment. Appropriate modelling tools are indispensable to support decision making by better understanding current and future water and food trends and by exploring the effectiveness of interventions. Application at the basin level is seen to be most effective for policy objectives. A review of available simulation models, differentiated by physical detail and required spatial scale, resulted in the selection of the SPHY, SWAT and WEAP models for the three selected case studies, and the choice process applies to comparable basins elsewhere.

The way in which models are to be applied in a given socio-economic context can be defined in terms of two criteria – agreement on relevant norms and values, and consensus about relevant knowledge – resulting in four types of model applications, as problem recognizer, mediator between perspectives, advocate, or problem solver. These distinctions reflect the diversity of socio-economic and political conditions encountered when formulating water governance practices in different countries.

A newly developed analytical framework for water governance at the basin level distinguishes and connects scoping and implementing policies on the one hand and basic and applied science on the other, including interaction with stakeholders. Hydrological
studies currently tend to focus too much on theoretical aspects, which do not answer the questions of stakeholders and policy makers. Application in the societal and political arena requires efforts to establish agreement on relevant norms and values, and consensus on relevant knowledge. Once these are established, science – represented here by hydrologic modelling – can contribute by recognizing and clarifying existing problems, acting as mediator between conflicting perspectives or, in a more advanced stage, as advocate of a certain approach. Only when there is complete agreement can modelling contribute directly to problem solving. Rather than present only theoretical considerations, practical case studies, as presented in this study, are needed to develop real-world operational approaches.

The framework was successfully tested and proved relevant in three case studies in basins. The upstream–downstream study in Central Asia connected applied science to scoping policies, modelling allowing problem recognition. The MENA study on water and food in arid regions connected applied science to scoping and implementing policies, modelling allowing mediation between perspectives. The green water credits study connected applied science to implementing policies in close interaction with stakeholders, providing impulses for basic science. Modelling allowed advocacy, representing optimal conditions for linking science, policies and stakeholders to achieve operational water governance, and can be seen as a guide for future developments linking science with policy.

Further work along these lines should develop into two directions. First of all, there is a need to refine and test the analytical framework presented here. The three studies described took place in developing countries and relatively new states, where stable and strong policies are developing. Testing the framework in basins with stable and established policy and science infrastructure would reveal other interactions. Second, the analytical framework can be used to undertake concrete actions leading to effective water governance. Only such real-world examples of science successfully interacting with society will be convincing in the end.

Supplemental data
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References


