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Assessment and Management of Water Resources in Developing, Semi-arid and Arid Regions

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Assessing and managing water resources in developing and dryland regions is still fraught with difficulties. The typical tool chain of water resources management starts with the collection of data, subsequently processes and analyses the collected information within the natural and socio-economic setting, and finally generates end products that inform decision-making. However, several of these steps often turn out to be problematic when faced with development issues and severe strains on water resources.

Many of these regions are characterised by very complex hydrological systems that often exhibit extreme behaviour, such as strong monsoon seasons or extended drought. Commonly used models and analysis techniques may not represent these processes, or at best they are seldom tested for adequacy and robustness. The complexity of the water cycle contrasts strongly with the poor data availability, which limits the number of analysis techniques and methods available to researchers. Finally, technical solutions should take into account the socio-economic setting in which they will be embedded, and address the need for capacity development to ensure that newly introduced technologies and solutions improve the regional skills in water resources management.

This special issue aims to highlight the diversity and complexity of the issues faced in a context of development and resources scarcity. It brings together a collection of papers that

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deal with various aspects of the tool chain of water management, ranging from novel data collection methods that may alleviate data scarcity and improve knowledge about the system (Forsythe et al. 2012; Rodrigues et al. 2012), to participatory identification of pathways for sustainable development (Tiwari and Joshi 2012).

Indeed, data scarcity is still a major bottleneck for improving water resources management. Worldwide, river flow monitoring networks are in decline (Hannah et al. 2011) and other hydrometeorological measurements tend to follow the same fate. On the other hand, advances in remote sensing and numerous recent satellite missions have generated a wealth of potentially relevant data that may lead to improved water resources management. Especially for monitoring processes such as precipitation, soil moisture change, vegetation growth and surface water storage, the high temporal frequency and good spatial coverage of satellite images may prove invaluable. However, scientists are only slowly coming to grips with the weaknesses of the data. Especially in regions of high spatial and temporal variability such as tropical and subtropical mountain ranges, satellites may not pick up the strong gradients that are of relevance for localised water resources management. For example, in this issue, Forsythe et al. (2012) analyse pathways to extract meaningful quantitative information from the MODIS and TRMM satellites at the village scale in the upper Indus basin. In a very different application, Rodrigues et al. (2012) show the usefulness of LANDSAT images to identify the presence and estimate the volume of small reservoirs in the Brazilian savannah. They complement their data with local questionnaires and interviews. Drawing upon so-called local expert knowledge is indeed another useful approach to deal with scarcity of *hard*, i.e., traditionally monitored data. Indigenous communities and local resources managers often have a profound knowledge of local natural systems. This information tends to be under-utilised, especially in top-down approaches where external actors impose guidelines and practices that may not respond to local needs. Avoiding this pitfall is the concern of Tiwari and Joshi (2012) who work in the Indian Himalaya. They explore the use of a community-oriented framework to identify the resource utilisation patterns of local communities and their linkages with externalities such as highland-lowland interactions.

A next step in the tool chain is the transformation of raw data into useful information for decision-making. Decision makers are often concerned with quantifying the characteristics of the current system (e.g., mean states, frequency of extremes) as well as the potential impacts of management scenarios on those characteristics. For both applications, computer models are useful tools. They can be used to assimilate available data to estimate variables that have not been measured directly (e.g., streamflow measurements in an ungauged catchment) or to simulate the impacts of potential management scenarios, which can then be evaluated before a decision is taken. It comes as no surprise then, that several papers in this issue evaluate the use of models and suggest improvements. However, classical models developed in a scientific context or for applications in data-rich, temperate areas may not be suitable for their application in data scarce regions. Pande et al. (2012) tackle the issue of available data and constraints using mathematical programming, which allows flexible calibration and simulation with parsimonious models. Moharram et al. (2012) take a similar approach, in which they are applying a simple genetic algorithm for the optimisation of groundwater extraction in the Western desert of Egypt using limited data.

Examples of the use of models to integrate data and resolve complex, unmonitored fluxes are given by Törnqvist and Jarsjö (2012) and Gunkel and Lange (2012). Törnqvist and Jarsjö (2012) use a distributed hydrological model of the Aral Sea drainage basin to quantify irrigation efficiencies at the farm and the basin scale. The latter allows taking into account tail flows and groundwater recharge. Even though the farmer may consider these fluxes a loss, they may contribute to river flows and alleviate water shortages downstream. As such,

it is an example of accounting for externalities (from the farmers' viewpoint) of localised decision-making. In a similar approach, Gunkel and Lange (2012) integrate distributed rainfall radar data with vegetation and soil data into the distributed hydrological model TRAIN-ZIN to resolve the water balance of the Lower Jordan basin.

One common denominator in modelling and interpreting modelling results is the due attention that has to be paid to uncertainties and modelling errors. Deterministic modelling results tend to be of limited use in decision-making. Models are simplifications of reality and therefore, by definition, wrong. Single model outputs may only be indicative of a trend. Rather, it tends to be much more useful to present model results in terms of probabilities and risks, which can be interpreted in a specific management context. Rossi et al. (2012) and Kloss et al. (2012) take this approach by applying Monte-Carlo simulations to modelling crop water requirements and reservoir management, respectively. This allows them to generate stochastic functions of crop water production and the risk of failure of a water distribution system. Although many issues still have to be solved with regard to a proper quantification of uncertainties of model predictions (see e.g., Beven et al. 2011; Buytaert et al. 2012), such approaches have proven to be extremely useful in developing management practices and operation rules for risk management.

Lastly, scientists should always explore novel approaches to alleviate water scarcity. The paper of Bakken et al. (2012) is an example of a novel and undoubtedly controversial approach to water resources. The mining of sub-marine groundwater is obviously unsustainable in the long term, but it may alleviate water shortages in regions where other sources of water are scarce or not (yet) available. This merits at least an exploration of its practical use, hydrogeologic potential and economic and environmental consequences.

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