Environmental Modelling & Software 46 (2013) 90–103

Contents lists available at SciVerse ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

An integrated modelling tool to evaluate the acceptability of irrigation constraint measures for groundwater protection

Ivan Portoghese [a,*], Daniela D'Agostino [b], Raffaele Giordano [a], Alessandra Scardigno [b], Ciro Apollonio [c], Michele Vurro [a]

[a] Istituto di Ricerca sulle Acque del C.N.R. (IRSA-CNR), Via De Blasio 5, 70132 Bari, Italy
[b] Mediterranean Agronomic Institutes of Bari (MAIB-CIHEAM), Via Ceglie 9, 70010 Valenzano, Bari, Italy
[c] Politecnico di Bari, DICATECh, Via E. Orabona 4, 70125 Bari, Italy

ARTICLE INFO

Article history:
Received 4 May 2012
Received in revised form
19 February 2013
Accepted 1 March 2013
Available online 30 March 2013

Keywords:
Bayesian Belief Networks
Groundwater protection policy
Stakeholder involvement
Conflict mitigation

ABSTRACT

In many arid and semi-arid regions agriculture is the main user of GW, causing problems with the quantity and quality of water, but there are few institutional policies and regulations governing sustainable GW exploitation. The authors suggest an integrated methodology for enabling local GW management, capable of combining the need for GW protection with socio-economic and behavioural determinants of GW use. In the proposed tool, integration is reinforced by the inclusion of multiple stakeholders, and the use of Bayesian Belief Networks (BBN) to simulate and explore these stakeholders' attitude to GW exploitation and their responses to the introduction of new protection policies. BBNs and hydrological system properties are integrated in a GIS-based decision support system – GeSAP – which can elaborate and analyse scenarios concerning the pressure on GW due to exploitation for irrigation, and the effectiveness of protection policies, taking into account the level of consensus. In addition, the GIS interface makes it possible to spatialize the information and to investigate model results.

The paper presents the results of an experimental application of the GeSAP tool to support GW planning and management in the Apulia Region (Southern Italy). To evaluate the actual usability of the GeSAP tool, case study applications were performed involving the main experts in GW protection and the regional decision-makers. Results showed that GeSAP can simulate farmers' behaviour concerning the selection of water sources for irrigation, allowing evaluation of the effectiveness of a wide range of strategies which impact water demand and consumption.

1. Introduction

In many arid and semi-arid regions, the overexploitation of groundwater (GW) impoverishes water quantity and quality, requiring more stringent regulations of GW use. Irrigated agriculture produces almost half of the world required food and fibres (United Nations, 2003), and is the main user of GW in many parts of the world, especially in arid and semi-arid regions, where it accounts for up to over 80% of GW use (Llamas and Martínez-Santos, 2005). The key water management challenge in these areas is to develop strategies aiming at finding a compromise between water resource sustainability and agricultural income (Molina et al., 2010).

Achieving sustainable use of GW will require changes that go beyond improving efficiency of water use, and implies a radical change in water policy and the implementation of innovative governance (Holtz and Pahl-Wostl, 2011). A key challenge for achieving GW sustainability is to frame the hydrological implications of various alternative management strategies in such a way that they can be evaluated properly and then effectively enforced. Assessment of the ability of GW to support water use is a fundamental issue and appropriate resource management must definitely assume GW as a common resource (Llamas and Martínez-Santos, 2005).

On the other hand, it is clear that any improvement in the efficiency/sustainability of GW use, given the continuing global trend towards GW exploitation, will have implications on water demand management, and also on the generally accepted world view of agriculture (Gleeson et al., 2010).

* Corresponding author. Tel.: +39 0805820540; fax: +39 0805313365.
E-mail addresses: ivan.portoghese@cnr.it, ivan.portoghese@gmail.com (I. Portoghese), dagostino@iamb.it (D. D'Agostino), raffaele.giordano@cnr.it (R. Giordano), scardigno@iamb.it (A. Scardigno), ciro.apollonio@libero.it (C. Apollonio), michele.vurro@cnr.it (M. Vurro).

1364-8152/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.envsoft.2013.03.001

Many times, the best attempts to solve GW management problems actually worsen the situation, because the policies selected create unexpected side effects. These unexpected dynamics often create resistance to policies, with the tendency for an intervention to be delayed, diluted, or defeated by the system's response to the intervention itself (Sterman, 2000). The increasing awareness of the uncertainty and complexity of water resources management is challenging the traditional management regimes based on a top–down approach and is decreasing the trust of decision-makers regarding the usefulness of simulation models to support decision-making (Knűppe and Pahl-Wostl, 2011; Borowski and Hare, 2007).

Avoidance of policy resistance requires expansion of the boundaries of the model used as the basis for decisions, so that decision-makers become aware of and understand the implications of the feedbacks created by their decisions (Sterman, 2000). Therefore, integrated models are required to take the complexity of the world into account as a response to the challenges of integration in water management itself (Borowski and Hare, 2007; Sterman, 2000).

Integration takes place broadly across sectors, and is basically a process of knowledge integration and integration across scales. This integration is reinforced by the inclusion of a divergent group of stakeholders as part of the modelling process. Modelling becomes a process of co-production of knowledge, based on the awareness that there may simultaneously be many different and equally valid ways of understanding a problem and finding solutions (Brugnach and Ingram, 2012). In scientific literature, these approaches are named participatory modelling.

According to Voinov and Bousquet (2010), two main objectives may be achieved through the integration of stakeholders in the modelling process: i.e. development of a shared understanding of a system and its dynamics, and support for identification of the most suitable course of action, thus reducing the level of conflict among the different stakeholders (Gaddis et al., 2010). In several cases, the collective learning process aimed at achieving shared understanding also leads to a better decision-making process (e.g. Metcalf et al., 2010; Lynam et al., 2010). During these processes, stakeholders and scientists are involved in a debate in which assumptions are teased out, challenged, tested and discussed (Checkland, 2001). Participants become aware of each other's perspectives and key interests (Henriksen et al., 2007), and are required to negotiate a credible and legitimate knowledge base to inform and support the decision-making process (Vogel et al., 2007). Independently of the approach adopted, participatory modelling aims to explore options and enrich the debate (Sandker et al., 2010). It can help participants to confront the real drivers of changes and to recognize non-linearities (Garcia-Barrios et al., 2008).

As a consequence, the role of decision supports tools in the context of environmental decision-making processes is changing, and these can play a twofold role. On the one hand, decision support tools should support the elicitation of preferences, values and knowledge held by the different actors, and make knowledge accessible to inform the debate. On the other hand, models are also a shared platform through which this debate is organized and structured, and through which different sources of knowledge are integrated, including what emerges throughout the process (Guimãres Pereira et al., 2005).

Several models exist which are based on the integration between scientific and stakeholder knowledge, and a wide range of modelling methodologies have been used, including the Bayesian Belief Networks, agent-based modelling and system dynamic modelling (Stave, 2002).

The Bayesian Belief Network is largely considered a modelling tool suitable for eliciting and communicating the differences in understanding problems and for supporting the social learning process. According to the most recent findings, the construction of the network of nodes (i.e. variables), links between nodes, and the definition of the conditional probability of their occurrence, allowed participants to become aware of the interests and concerns of others (Henriksen et al., 2007; Molina et al., 2010; Castelletti and Soncini-Sessa, 2007).

Several examples of BBN implementation for GW management can be found in the scientific literature (e.g. Farmani et al., 2009). Most of them are based on stakeholders involvement (Martin de Santa Olalla et al., 2005; Henriksen and Barlebo, 2008; Henriksen et al., 2007; Molina et al., 2010). Among them, Martinez-Santos et al. (2010) proposed a BBN-based approach to support stakeholders involvement in conflicting water management situations. Their approach is based on the assumption that a conflict between different parties may simply reflect different knowledge frames, interests, and beliefs among the participants, that is, it could be based on ambiguity (Brugnach and Ingram, 2012). Thus, BBNs were used in their work to structure these different knowledge frames.

In line with the most recent researches, our work incorporates stakeholders and behavioural models of actors as a way of capturing the necessary socio-psychological elements which must be considered when testing policy options (Borowski and Hare, 2007; Hare and Deadman, 2004; Bousquet and Le Page, 2004; Giordano et al., 2007; Moss et al., 2001; Becu et al., 2003; Barreteau et al., 2003). BBNs have been innovatively used in this work to investigate differences in stakeholders' understanding of a problem, and to analyse and measure emerging conflicts due to the implementation of GW protection policies. We mainly refer to Object-oriented Bayesian Belief Network (OOBBN), which are defined in scientific literature as a special family of Bayesian Belief Networks which allow a structuring of the model domain into sub-domains, and with linkages from variables in one sub-domain to other sub-domains (Molina et al., 2010). Hereby, OOBBNs were developed in this work to provide a description of real-world GW management domain, characterized by different decision agents, each with her/his own decision model. The links between the sub-domains represent the impact of an action on others' decision model.

BBNs and hydrological system features were integrated in a GIS-based decision support system – GeSAP – able to elaborate and analyze scenarios concerning the pressure on GW due to exploitation for irrigation purposes and the effectiveness of protection policies, taking into account the level of consensus.

The GeSAP system was applied experimentally to support GW planning and management in the Apulia Region (Southern Italy).

The paper is organized as follows: Section 2 provides the description of the methodologies adopted to assess the pressures on GW and to evaluate the effectiveness of GW protection policies; Section 3 is dedicated to the description of the results obtained in the study area and to the discussion of the feedbacks collected with local decision makers concerning the application of the GeSAP GIS-based Decision Support System to the Apulia region; Section 4 presents summarizing and concluding remarks.

2. Materials and methods

In the absence of detailed hydrological and hydro-geological studies aimed at determining the amounts of percolation on local and regional scales, a simple but effective approach to investigate the sustainability of GW resources has to consider at least the first order controls of aquifer exploitation. These are: i) the average percolation amount, R, corresponding to the natural GW recharge per year; and ii) the volume of GW pumped per year, P, where the difference between R and P is assumed as a sustainability index for GW use. To be sustainable, GW use should ensure that a certain percentage of R is left for the remaining GW services such as feeding the baseflow of streams, preventing seawater intrusion, conserving wetlands, and so on. Defining GW sustainability strategies is an urgent need in many