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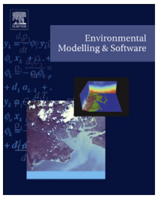

An agent-based platform for simulating complex human–aquifer interactions in managed groundwater systems

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ABSTRACT

This paper presents and illustrates FlowLogo, an interactive modelling environment for developing coupled agent-based groundwater models (GW-ABMs). It allows users to simulate complex socio-environmental couplings in groundwater systems, and to explore how desirable patterns of groundwater and social development can emerge from agent behaviours and interactions. GW-ABMs can be developed using a single piece of software, addressing common issues around data transfer and model analyses that arise when linking ABMs to existing groundwater codes. FlowLogo is based on a 2D finite-difference solution of the governing groundwater flow equations and a set of procedures to represent the most common types of stresses and boundary conditions of regional aquifer flow. The platform is illustrated using a synthetic example of an expanding agricultural region that depends on groundwater for irrigation. The implementation and analysis of scenarios from this example highlight the possibility to: (i) deploy agents at multiple scales of decision-making (farmers, waterworks, institutions), (ii) model feedbacks between agent behaviours and groundwater dynamics, and (iii) perform sensitivity and multi-realisation analyses on social and physical factors. The FlowLogo interface allows interactively changing parameters using 'tuneable' dials, which can adjust agent decisions and policy levers during simulations. This flexibility allows for live interaction with audiences (role-plays), in participatory workshops, public meetings, and as part of learning activities in classrooms. FlowLogo's interactive features and ease of use aim to facilitate the wider dissemination and independent validation of GW-ABMs.

Software availability

Name of software: FlowLogo 1.0—coupled groundwater and agent-based simulation
Developer: Juan Carlos Castilla-Rho
Contact details: Juan Carlos Castilla-Rho, UNSW School of Civil and Environmental Engineering, Kensington Campus, Sydney NSW 2052, Australia. M: +61 0478074291, E: j.castilla@unsw.edu.au
Availability: online for free download at the CoMSES Net Computational Model Library at: https://www.openabm.org/model/4338/version/1/view
Hardware required: 2.9GHz Dual-core processor, 8GB RAM (minimum)
Software required: NetLogo 5.2 or higher (Free) (Wilensky, 1999)
Programming language: NetLogo
Cost: Free

1. Introduction

There is an increasing recognition that groundwater resources generate complex socio-ecological issues (Zellner, 2008). Effective and fair solutions to groundwater management thus require a holistic approach based on the knowledge and expertise of many disciplines. This approach, however, is not always mirrored in

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classical groundwater modelling tools. What may be described as a complex problem is often compressed into a model that describes a well-defined problem with simple cause-effect relationships (Pahl-Wostl, 2007).

Agent-based models (ABMs) have come forth as a way to model, as opposed to simplify, the complexity of socio-ecological systems (Aulinas et al., 2009; Bousquet and Le Page, 2004; Kelly et al., 2013; Parker et al., 2003). ABMs use the concept of an 'agent' (a computational representation of real-world actor) to simulate behaviours and interactions of decision-making entities, including feedbacks between human and environmental processes, physical and institutional constraints, and the different spatiotemporal scales in which these dynamics unfold (Miller and Page, 2009). ABMs allow framing socio-ecological issues based on a set of agent behaviours, and from these simple rules complex system behaviour 'emerges' (Mitchell, 2009). In practice, this is the basis for efficient groundwater-resource management (Foster and Garduño, 2012; Foster and Perry, 2010).

In groundwater management, ABMs show significant potential to design policies and incentives that may help balancing the need to produce crops, to provide drinking water and to ensure the long-term sustainability of aquifers. ABMs can also help detect key human and institutional actions that may lead to the sustainable exploitation of aquifers in real-world scenarios. For example, (Blomquist and Ostrom, 1985; Ostrom, 1990) give empirical evidence of cases where self-monitoring has led to efficient management of shared groundwater resources over long periods of time, with little or no intervention of a regulator. Using ABM we can ask: what other mechanisms may have such positive impacts on groundwater use?

Answering this question can be challenging using conventional modelling tools. Tools such as simulation-optimisation (Barlow et al., 2003; Bredehoeft and Young, 1983, 1970; Morel Seytoux, 1975; Raul and Panda, 2013; Sedki and Ouazar, 2011; Young and Bredehoeft, 1972), evolutionary algorithms (Babbar-Sebens and Minsker, 2010, 2012; McKinney and Lin, 1994; Mirghani et al., 2009), econometric models (Brozovic et al., 2010; Katic and Grafton, 2012; Wan et al., 2012), game theory (Negri, 1989; Raquel et al., 2007; Saak and Peterson, 2007), and Bayesian networks (Henriksen and Barlebo, 2008; Henriksen et al., 2007; Portoghese et al., 2013) focus on equilibrium states (e.g., a global optimum, a Nash equilibrium), and describe social processes in an aggregate manner (e.g., using an optimisation function, a differential equation, a payoff matrix, etc.) based on the concept of a 'typical' agent assumed to be on average rational i.e. making optimal and fully informed decisions. This is unlikely to represent individual variations (heterogeneity) and random influences (stochasticity) in human decisions and interactions (Bonabeau, 2002; Rounsevell et al., 2011). These assumptions undermine the representation of complexity, which is critical for understanding the dynamics of coupled human-groundwater systems (Zellner, 2008). In contrast, ABMs can simulate large cohorts of independent, heterogeneous agents with clearly defined rules in systems that evolve (Miller and Page, 2009). ABMs thus can model groundwater systems affected by human activities, as these activities adapt to changes in socioeconomic and environmental factors.

The difficultly of coupling social-economic ABM models to existing groundwater flow modelling environments (e.g., MODFLOW) is reflected in the few publications where this has been achieved (Barthel et al., 2008; Mulligan et al., 2014; Reeves and Zellner, 2010). This contrasts with the large number of publications coupling ABMs with other biophysical models (An, 2012; Aulinas et al., 2009; Balbi and Giupponi, 2009; Bousquet and Le Page, 2004; Gunkel, 2005; Heath et al., 2009; Kelly et al., 2013). Early work on GW-ABMs reports lumped aquifer models implemented on an ABM grid (Carlin et al., 2007; Dray et al., 2006; Feuillette et al., 2003; Guilfoos et al., 2013; Heckbert et al., 2006; Moglia et al., 2010; Perez et al., 2003; Smajgl et al., 2009). Recent work is based on linked GW-ABMs (Barthel et al., 2005; Miro, 2012; Mulligan et al., 2014; Reeves and Zellner, 2010), where an ABM generates groundwater stresses (i.e. pumping rates) that are exported to a groundwater code e.g., MODFLOW (Harbaugh et al., 2000). The groundwater code then updates the physical state variables of the model and the new conditions inform or change the behaviour of agents in the following iteration.

We identify four main limitations in previous attempts to couple agent-based and groundwater flow models. First, when lumped models have been used, assumptions of homogeneous geology and infinite transmissivity constrain the analysis to steady-state conditions, and underestimate pumping costs and damages to linked ecosystems (Brozovic et al., 2010; Esteban and Albiac, 2011; Katic and Grafton, 2012; Koundouri, 2004). Second, linked GW-ABMs can be computationally expensive (Matthews et al., 2005) as they require communication via data files and libraries to synchronize both codes. Their implementation requires expertise in multiple programming languages and demands maintenance, given that ABM and groundwater software is under continuous development. This provides little insight on the actual development process of a GW-ABM and the independent replication its results. Third, linked GW-ABMs offer less flexibility for developing and adapting scenarios. For example, consider a model designed with agents responding to groundwater heads. If one wanted to explore scenarios where agents react to other variables (e.g., the stage of a river or the flow in a spring) one would not only need to modify the ABM, but also the data exchange library. Fourth, sensitivity analyses on a linked GW-ABM can be impractical in real-world management situations. For instance, if one wanted to explore the impacts of geological heterogeneity (i.e., the spatial distribution of hydraulic parameters and their uncertainty) on model output, it would be helpful to generate multiple alternative geological models, run batch simulations, visualise and analyse the output within a single software, without the detour via input/output files and revisions to both codes. The above issues suggest that an integrated simulation environment would facilitate the development and subsequent analysis of GW-ABMs. We propose FlowLogo as a first step towards a common language and standard procedures or templates to build GW-ABMs.

The aim of this work is to present FlowLogo, a new GW-ABM environment based on a finite-difference approximation to the governing equation of groundwater flow and is written in NetLogo, a widely-used and open open-source ABM environment (Heath et al., 2009; Railsback et al., 2006; Wilensky, 1999). FlowLogo is a research tool aimed at interdisciplinary groundwater studies and policy making at the basin scale, targeting researchers from a wide range of fields such as economics, social science, law, and hydrology. We show the application of FlowLogo's main features using a hypothetical example based on simple agent rules that yet lead to complex collective behaviours. Rather than a case study making specific policy recommendations, this example is intended as a guided tutorial for the typical stages of developing an agent-based groundwater model. Similarly, we analyse scenarios representing different combinations of policy levers and agent learning mechanisms to illustrate the platform's potential as a decision-support tool. We discuss the advantages of FlowLogo with respect to general-purpose programming languages, as well as prospective contributions of the platform for decision-support in a selection of groundwater depletion hotspots around the world.