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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.

2. FlowLogo architecture

FlowLogo is implemented in the NetLogo platform, an agent-based programming environment for simulating complex phenomena. NetLogo has become a popular research tool to explore the connections between micro-level behaviours of individuals and macro-level patterns that emerge from their interactions (Tisue and Wilensky, 2004). NetLogo is open-source and it is available for most operating systems. A models library and online repositories (e.g., https://modellingcommons.org, https://www.openabm.org) give users access to ABMs published in environmental and social science literature, many of which can be used as seed models for groundwater applications. NetLogo is bundled with a series of extension packages and toolkits relevant for GW-ABM workflows. Three were used in this study: matrix extension (to solve the groundwater flow equations), Matlab extension, (to generate geostatistical realisations of hydraulic parameters); and BehaviourSpace (to perform automated parameter sweeping in a parallelized way). Other packages not shown here but relevant for GW-ABM workflows allow working with GIS files, System Dynamics models (Ahmad and Simonovic, 2000; Zarghami and Akbariyeh, 2012), and the R statistical package to perform parameter estimation (Thiele and Grimm, 2010; Thiele et al., 2014).

At its core, FlowLogo is a 2D implementation of the groundwater flow equation in NetLogo, plus a set of GUI tools to simplify the creation and edition of the groundwater agents to uniquely include socio-economic dynamics and behavioural traits. It relies on some of the functionalities embedded in NetLogo, making the implementation and use of the code much simpler than with general-purpose programming languages. We could have implemented the same framework in C++ or Python, but this would have come at the price of steeper learning curve and limited supportive features for ABMs (Thiele et al., 2011). Optimising ABM code has taken several decades. Standard ABM libraries now exist (for reviews see Nikolai and Madey, 2009; Railsback et al., 2006) and among such libraries NetLogo is widely used.

2.1. The groundwater flow simulator

The first component of FlowLogo is the groundwater simulator (Fig. 1a). It solves the governing equations of groundwater flow using a 2D finite-difference solution scheme in transient, heterogeneous and anisotropic conditions, for confined or unconfined aquifers. To ensure the convergence of this solution scheme, we implemented a direct solution of the groundwater flow equations (matrix inversion) based on NetLogo's matrix extension package.

Hydraulic parameters can be set directly in FlowLogo, or by using external programs to simulate their spatial distribution, for instance, via geostatistical methods. The accompanying GW-ABM example in Section 3 demonstrates this process for sequential Gaussian simulations of hydraulic conductivity generated via Matlab scripts, deployed within FlowLogo using the Matlab extension package. The groundwater simulator provides predefined procedures that automatically assemble the system of linear equations representing boundary conditions and stresses, such as: wells, springs, drains, rivers (fixed stage, losing or gaining), fixed-head, fixed-flow, evapotranspiration (constant or head-dependent rate), lateral or areal recharge. These groundwater elements can be implemented directly in the program code, or interactively using the buttons and controls provided in the graphical interface. The groundwater simulator is customisable using NetLogo language. Details of the implementation and benchmarks against MODFLOW-2005 are provided in Sections 1 and 2 of the supplementary material of this article, respectively.

2.2. The social simulator

The second component of FlowLogo is the social simulator (Fig. 1b). It uses NetLogo language to define the behaviours and interactions of agents, including feedbacks between agents and the groundwater simulator (i.e., the thin vertical arrows in Fig. 1). Fig. 2 presents a conceptual framework to define the different scales of decision-making and interactions in the social simulator.

We see several advantages of using NetLogo code to deploy institutional and consumer agents. Because it can be quickly learnt and productively used by a novice with little programming background, it makes the development of customised agents straightforward. This avoids the need to include pre-programmed functionalities for designing groundwater agents, which would only limit the scope and applicability of the platform. We believe that it is more efficient to conceptualise and code agents case-by-case, giving users the option to represent the wide range of behavioural models and processes of varying complexity that are typical in groundwater management situations e.g., taxes, allocation quotas, trading rules, regulation, monitoring, etc. Offering a workflow to easily represent the diversity of such processes is a major aim of this work. To this end, the discussion and example code that follows is intended as an introductory guide to the design of groundwater agents. Also, the program file for model described in Section 3 contains ca. 2000 lines of code with generous comments that describe and demonstrate the implementation of the social component in an example GW-ABM.

Because NetLogo is popular and widely used, FlowLogo users also have the option of accessing model libraries and online repositories of published ABMs in economics, environmental and social science literature (e.g., www.modellingcommons.org, www.openabm.org). Existing NetLogo code can be freely downloaded from these repositories and used as seed models for groundwater agents. This allows for easily deploying a wide variety of agent types whose traits and behaviours are grounded on theory from various disciplines (An and Wilensky, 2009).

Individual agents are defined by combining descriptive characteristics: a set of behaviours (e.g., decision making model, actions/responses, goals, etc.), and a set of constraints and labels identifying types and roles (Rounsevell et al., 2011). For example, the code shown in Fig. 3a defines a farmer agent facing a cropping decision related to limited surface-water deliveries that can be compensated by increasing groundwater pumping.

Several theoretical models of decision-making can provide agents with cognitive abilities. For a detailed review of decision models used in agent-based simulations the reader can refer to (L. An, 2012). (Janssen and Ostrom, 2006; Poteete et al., 2010; Robinson et al., 2007; Smajgl and Barreteau, 2014; Smajgl et al., 2011; Windrum et al., 2007) report on grounding agent decision models to empirical data. Heuristic strategies, for example, offer a transparent view of the decision-making process and lends itself to empirical grounding with a range of qualitative or quantitative data (Rounsevell et al., 2011). They involve Boolean evaluations of social and/or groundwater state variables that return a true/false result and trigger a subsequent action. This approach is implemented in FlowLogo using simple 'if/then/else' rules. The following code in Fig. 3b shows how the farmer agent could make a cropping decision based on capital, soil pH, and groundwater levels.

Individual agents exert groundwater demands via pumping wells. Some might operate one or perhaps a few wells (e.g., farmers, domestic users) while other agents may operate a network of production wells (e.g., water utilities, mining companies). Agents can also perform activities that recharge water to the aquifer, such as a regulator commissioning managed aquifer recharge infrastructure. Agents may also impact groundwater availability

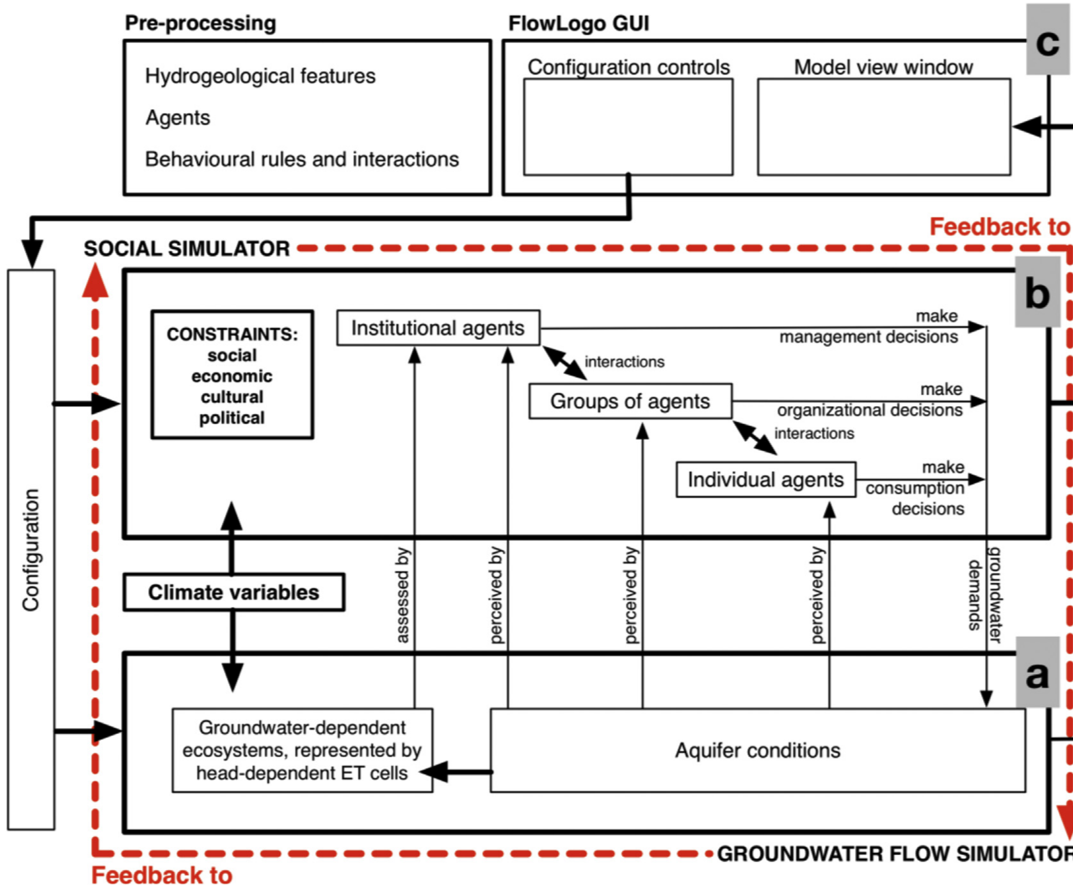

Fig. 1. FlowLogo architecture: (a) groundwater simulator, (b) social simulator, (c) GUI.

indirectly (via surface–groundwater interactions), such as an operator controlling dam releases (and changing the stage of river cells in the model). Individual agents typically have fixed locations in FlowLogo models, yet their groundwater demands can vary in space and time, as for instance when agents build new wells, trade water entitlements, operate multiple wells (e.g., drinking water company), or when groundwater is not their only source of water. Fig. 3c shows how two farmer agents might override their cropping decision when they opt to trade water entitlements (within the same sub-basin) based on their expected profits:

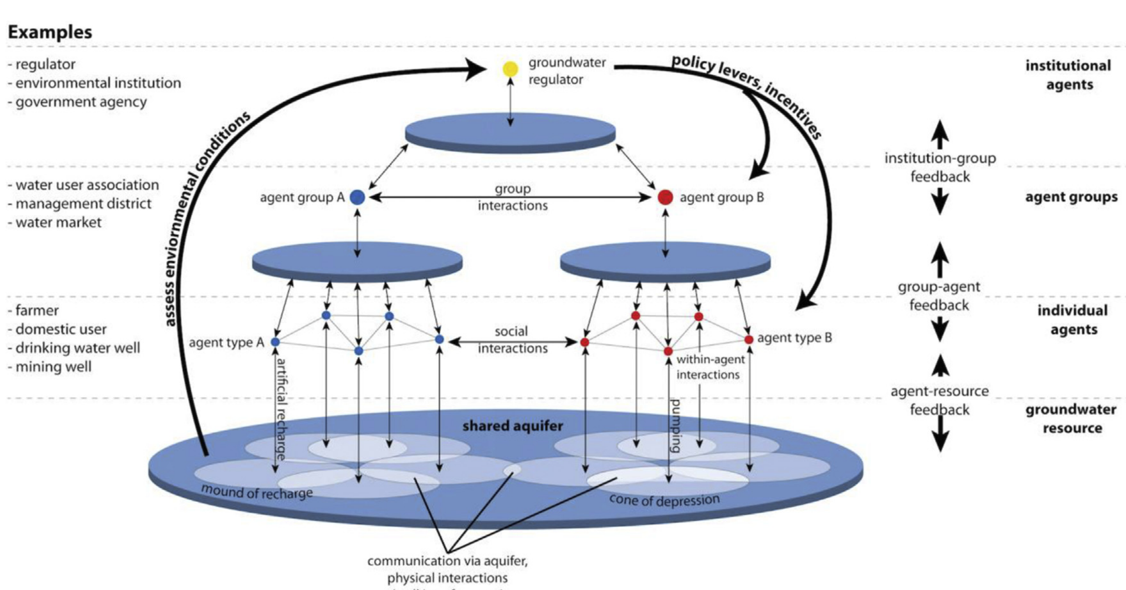

Fig. 2. Scales of decision-making and modes of interaction in the social simulator.

a

```
breed [farmers farmer]          ;;creates a breed of "farmer" agents

farmers-own                     ;;variables specific to these agents
[
  sub-basin                     ;;the sub-basin that the agent belongs to, e.g., "sub-basin 1"

  crop                          ;;a string, e.g., "cotton"
  land-area                     ;;irrigated area, [ha]
  pump-level                    ;;[m]

  portofolio                    ;;a list with the agent's portofolio e.g., ["fallow", "crop", "pasture"]
  cropping-decision             ;;the option from the portofolio that is chosen

  surface-water-delivery        ;;the delivery to the agent this year, [m3]
  unmet-demand                  ;;agent's total water demand - surface-water delivery [m3]

  groundwater-allocation        ;;the agent's groundwater entitlement, [m3]
  pump-on?                      ;;true if unmet-demand > 0, otherwise false
  pumping-rate                  ;;f(unmet-demand, agent's pumping schedule) [m3/d]
  current-head                  ;;the head at the agent's location, [m]
  soil-pH                       ;;the current pH of the soil at the agent's location

  capital                       ;;[$]
]
```

b

```
ask farmers
[
  set well-depth random-normal 50 10          ;;assume that farmers have well depths randomly distributed with mean=50m sd=10m
  set head-tolerance 5                        ;;assume pumps can only work with >5m of water above them
]

to crop-decision                              ;;define decision function
  ask farmers                                 ;;run this code for all farmer agents
    [
      ifelse soil-pH-here < 5.5               ;;if soil is acid
      [
        ifelse capital > capital-needed-for-pasture and current-head < pump-level + head-tolerance  ;;and capital and drawdowns allows it
        [
          set cropping-decision "pasture"     ;;plant pasture to increase pH
          update-pumping-rate                 ;;calculate the pumping-rate f(cropping-decision, unmet-demand)
          set pump-on? True                   ;;turn on the pump
        ]
        [
          set cropping-decision "fallow"      ;;otherwise
          set pump-on? False                  ;;and turn the pump off
        ]
      ]
      [                                       ;;if soil is not acid
        ifelse capital > capital-needed-for-crop and current-head < pump-level + head-tolerance  ;;and capital and drawdowns allows it
        [
          set cropping-decision "crop"        ;;plant crops
          update-pumping-rate                 ;;calculate the pumping-rate f(cropping-decision, unmet-demand)
          set pump-on? True                   ;;turn on the pump
        ]
        [
          set cropping-decision "fallow"      ;;otherwise fallow
          set pump-on? False                  ;;and turn the pump off
        ]
      ]
    ]
end
```

c

```
to trade-entitlements                                               ;;defines trading function
  ask farmers                                                       ;;run this code for all farmer agents
  [
    calculate-expected-profits                                      ;;a function that the agents use to estimate this season's profits
    set potential-buyers farmers with [sub-basin = [sub-basin] of myself]  ;;trading is limited to agents within the same sub-basin

    if expected-profit < water-price * groundwater-allocation       ;;if selling the water is more profitable than cropping
    [
      set allocation-tranfer groundwater-allocation                 ;;the agent's groundwater allocation is offered to others
      ask max-one-of potential-buyers [expected-profit]             ;;the water is bought by the agent having the highes expected profit
      [
        set groundwater-allocation allocation-tranfer               ;;the allocation is then tranfered to the buyer
      ]
      set capital (capital + water-price * groundwater-allocation)  ;;the seller's earnings are increased
      set cropping-decision "fallow"                                ;;their fields are fallowed
      set pump-on? False                                            ;;and the pump is turned off
    ]
  ]
end
```

d

```
...
set potential-buyers farmers                                                ;;trading across all sub-basins
set potential-buyers farmers with [sub-basin = [sub-basin] of myself]      ;;trading within the same sub-basin
set potential-buyers farmers with [sub-basin = "sub-basin 1" or sub-basin = "sub-basin 2"]  ;;trading within the specific sub-basins
set potential-buyers farmers with [sub-basin = "sub-basin 1" and current-head > threshold]  ;;trading conditioned by groundwater heads
...
```

e

```
...
if mean [head] of patches < threshold [set trading "off"]         ;;turn off trading if heads reach a critical threshold
...
set quota 0.6                                                     ;;sets an arbitrary restriction of groundwater allocations
if mean [head] of patches < threshold
[ask farmers [set groundwater-allocation groundwater-allocation * quota]]   ;;reduce the allocations of all agents equally
...
```

Fig. 3. a. Example definition of a farmer agent. b. Example of a heuristic decision rule. c. Example of a water trading rule. d. Example of group interactions. e. Example of policy levers.

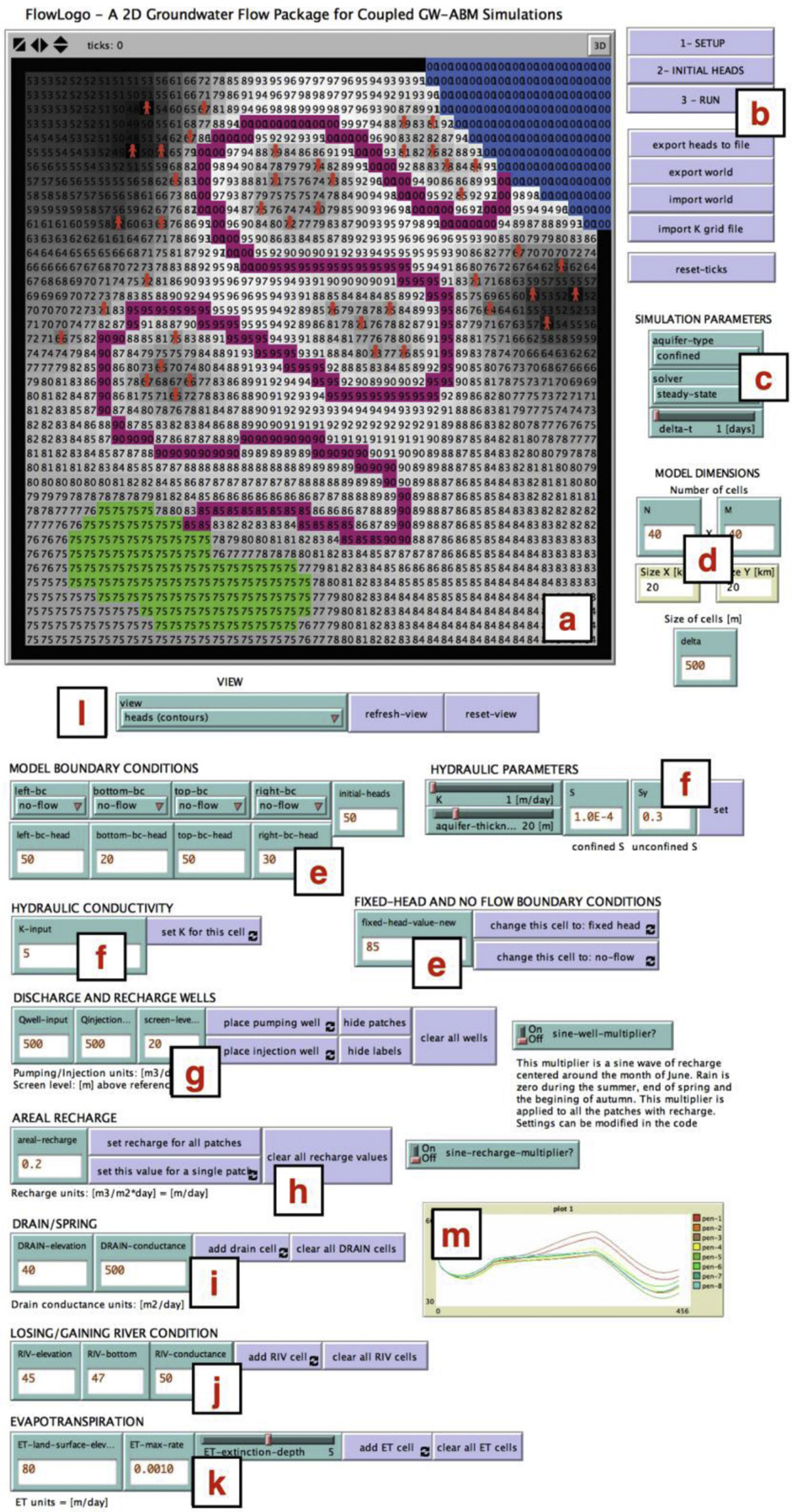

Fig. 4. Example of the FlowLogo GUI and groundwater model objects. (a) output window showing model domain with groundwater table heads (numbers), a lake (blue cells), a river (purple cells), and a wetland (green cells); (b) initialization, simulation, and import/export control buttons; (c) time step, confined/unconfined type and steady-state/transient

Individual agents engage in two kinds of interactions. The first kind are well interferences (Fig. 2), whereby agents perform activities (pumping) that leave a trace in the environment (cones of depression) affecting a subsequent action (the cost of pumping) by the same or a different agent. Such interactions thus act as a mechanism of indirect coordination between agents. This recursive relationship is modelled in FlowLogo by conditioning the behaviour of agents to the state variables in the groundwater simulator. The second kind of interaction is the direct communication between agents (Fig. 2). This is modelled in FlowLogo by providing the capacity for agents to share information or observe other agents within a spatial neighbourhood (e.g., farmers in the same sub-basin), within a social network (e.g., association of cotton farmers), or both. To represent variations in such interactions and information flows, NetLogo provides functions to create Moore and Von Neumann neighbourhoods from a distribution of possible sizes. To create socioeconomic ties between agents, one can use NetLogo 'link' objects (which create formal connections between two agents) and the capabilities of the network extension package to perform formal network analyses. Over time, the interactions of agents can be altered by adaptation rules (e.g., using threshold values in social or physical variables), or specific actions imposed by institutional agents or agent groups.

Individual agents typically aggregate into groups (Fig. 2). Groups do not exert groundwater demands directly, but can influence (locally) the behaviour of individual agents through formal and informal agreements. Examples of agent groups are water user associations and water markets. Formal agreements can be pumping quotas, taxes, schedules, groundwater levels or water trading rules. Examples of informal agreements are social norms of compliance and mutual monitoring between farmers. Groups can be created in FlowLogo in two ways. The first is to give agents identification 'tags' that act as signals of specific attributes. These tags can relate agents with a group (e.g., a junior/senior water right holder), to classify agents according to certain criteria (e.g., crop type, management district), or to promote/inhibit interactions between agents sharing the same classification type (e.g., between farmers growing the same crop, between surface water and groundwater users). The second way to create groups is by representing them with actual agents. In this case, groups have the same abilities as individual agents (i.e., communicate, reason, interact, adapt, etc.). This approach allows modelling groups that interact within scales (e.g., between groundwater and surface water user associations) and across scales (e.g., basin and inter-basin water markets). The code in Fig. 3d shows that by changing a single line of the water trading rule presented in Fig. 3c, one can change farmer interactions.

At the highest level are institutional agents (Fig. 2). Their role is to provide feedbacks to agents below them, through a set of policy levers and incentives. Examples of institutional actions are farmer subsidies, issuing of well permits, altering of water trading rules, and establishing well protection areas. During FlowLogo runs, the institutional agent can activate or vary such levers within a numeric interval (e.g., increase a tax, reduce quotas on groundwater withdrawals) (Fig. 3e), or define their implementation in specific areas (e.g., restrict withdrawals in areas with large drawdowns).

To drive these decisions, institutional agents will typically 'observe' drawdowns and/or environmental flows simulated by the groundwater simulator. This information is observed at discrete locations, as with a network of monitoring wells. The agent then processes this information (e.g., using a decision tree or optimization algorithm) that subsequently triggers specific policy/incentive actions. Although the institutional agent does not have an explicit location in space, FlowLogo models may include 'police' agents moving across the landscape that monitor and enforce the activities of groundwater agents.

2.3. FlowLogo GUI

Fig. 4 shows a sample layout of a FlowLogo GUI. It displays a group of farmer agents (red icons) pumping groundwater from a hypothetical basin delimited by impermeable bedrock outcrops (black, no-flow boundaries), a lake (blue, fixed-head cells), a river (purple, head-dependent flux river cells), and a wetland (green, head-dependent evapotranspiration cells). Agents and groundwater variables are set using pull-down menus, sliders and buttons (Fig. 4b–k) and by placing components on the model window with point-and-click actions (Fig. 4a). The spatial distribution and temporal dynamics of GW-ABM parameters, time series and histograms of simulated data is presented visually while the model is running. The code of the social simulator is linked to the FlowLogo GUI using NetLogo 'interface' objects (sliders, buttons, switches, input windows, pull-down menus). This approach allows users to develop interactive modelling environments from where they can explore combinations of policy interventions and incentives for a given groundwater management problem.

3. GW-ABM implementation example

In this section we present a tutorial that illustrates the process of developing GW-ABMs in the FlowLogo modelling environment. It is based on a synthetic model of an expanding agricultural region that depends exclusively on groundwater for irrigation. The scenarios below are not presented to make specific management recommendations beyond our synthetic example, nor do they necessarily represent assumptions based on empirical data. They are given to illustrate how coupled social-groundwater dynamics can be simulated with the platform, to describe how those processes are conceptualised into a GW-ABM and to show how the workflow is enhanced by the NetLogo environment. We have intentionally used simple behavioural rules to facilitate the interpretation of the model, and to show that complex group behaviours can emerge from the interaction of individual agents operating on such simple rules (Arthur, 2014; Aulinas et al., 2009; Epstein, 2014; Epstein and Axtell, 1996; Miller and Page, 2009; Smaldino and Epstein, 2014).

The following section is organised as follows. Section 3.1 describes how to develop a conceptual model for a GW-ABM. Section 3.2 demonstrates how the groundwater component is laid out, and Section 3.3 illustrates how the social component is formalised. Section 3.4 shows how the model components are scheduled. Section 3.5 shows how to design scenarios, how the parameter space is explored with batch simulations, and how the results can be presented and analysed. Section 3.6 briefly demonstrates sensitivity analyses, uncertainty quantification and linkage with external packages.

The program files of FlowLogo and the example model can be accessed and downloaded from the following link: https://www.openabm.org/model/4338/version/1/view.

simulation switches; (d) grid definition; (e) model boundary conditions settings; (f) hydraulic parameters; (g) add recharge and discharge wells; (h) add areal recharge; (i) add drains and springs; (j) add river cells; (k) add evapotranspiration cells; (l) interface view settings; and (m) time series of groundwater heads at selected locations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.1. Conceptualising the GW-ABM

The model represents a hypothetical groundwater basin at an early stage of agricultural development and its transition into a period of rapid economic growth. It includes the temporal and spatial dynamics of water stress experienced by farmers, the operation of wells supplying drinking water for an urban centre, and the cumulative impacts on a river. The aim of the model is to test whether different policy levers and incentives lead to variations in farmer stress and sub-optimal groundwater usage.

Our assumptions draw on general issues that are common, for instance, in agricultural catchments in the coastal areas of northern Chile (e.g., Copiapó Basin), western United States (e.g., Central Valley), and the inland agricultural regions of Australia (e.g., Murray-Darling Basin). These are examples of growing agricultural economies with growing concerns on the availability of groundwater. In these areas, aquifers have been depleted to a point where higher energy costs, diminishing well yields, dry bores, water-stressed crops, and environmental degradation have impaired further growth of irrigated agriculture.

The result is typically a pattern of oscillations around the aquifer's carrying capacity, which for this case is expressed by the number of groundwater users that can pump from the aquifer in a profitable manner. As irrigation develops, groundwater abstraction overshoots the carrying capacity of the aquifer. Caps on groundwater withdrawals imposed by the regulator or farmers cutting back their water demands due to increased pumping costs may temporarily correct this overshoot. Then, a sequence of wet years and/or farmers slowly recovering from financial stress may bring the catchment back down below its carrying capacity (i.e. it undershoots). The pattern repeats with too many farmers turning on their pumps and the system overshooting again. Our aim is to develop a GW-ABM exhibiting this pattern of 'overshoot and oscillation', and then assess how a set of hypothetical mechanisms may 'dampen' these oscillations.

3.2. Groundwater component

The model represents a 15 × 30 km basin, discretised into 20×40 cells (Fig. 5a). Grid cells represent 750 × 750 m^2 farm plots. The basin is defined by no-flow boundary cells to the East, West and South (black cells, Fig. 4a); constant flux cells depict long term lateral recharge at a fixed rate of 925 L/s from the North (dark-blue cells, Fig. 5a), representing a distant recharge source (and average annual climatic conditions). Underlying this basin is a semi-confined sand aquifer of 20 [m] thickness, $K = 10^{-4}$ m/s and $S = 10^{-4}$. This aquifer is a high-quality groundwater source suitable for irrigation, and is hydraulically connected to a river. The river is simulated with stage-dependent flux cells (light-blue cells, Fig. 5a). Numbers on river cells represent the flow gained from the aquifer in L/s for each cell (light-blue colour coding, Fig. 5a) or flow seeping into the aquifer (red colour coding, in subsequent figures) at specific time steps. Brown cells in Fig. 5a represent the town's location. The stage and bottom of the river are set at 50 m and 47 m, respectively. The conductance of the riverbed is 50 m^2/day. The model is transient with a time step of one day and simulations extend for 50 years. We used a steady-state run with no pumping stresses as the initial condition for each simulation.

3.3. Agent component

The model has three kinds of agents: (1) farmers, (2) a town, and (3) a regulator. Farmer and town agents make land use decisions linked to the construction and operation of a well. The regulator agent constrains these decisions based on a set of policy levers. Table 1 summarises model parameters in the **BASE** scenario (i.e., baseline situation) and the different mechanisms considered for each agent. For brevity, in this example we only focus on adaptation strategies of farmers and policy levers of the regulator. Although we do not explore adaptation mechanisms for town agents, strategies such as drilling drinking water wells in areas of high transmissivity or establishing protection zones for these wells, could be easily included in the model.

3.3.1. Farmer agents

Farmer agents are characterised by: *spatial location*, *pumping rate*, *water stress* and *land use strategy*. Farmers have a fixed location in space. We assume identical irrigation schedules and groundwater withdrawals for all agents. In real situations, we would expect variability between farmers, crop rotations and the possibility of farmers switching to more water-efficient crops. For simplicity however, this model considers a monocrop catchment with an average water requirement of 5 ML/ha/year, corresponding to cotton in Australia (Australia, n.d.). The seasonality of pumping is approximated using a sinusoidal schedule peaking in the beginning of January (southern hemisphere summer). Assuming that 60% of the land is left for other uses (50% fallow, 10% infrastructure), the pumping schedule for farmer agents is approximated using the following equation:

$$Q = 1000*sin(2\pi/365*(t + 81.75)) \quad (1)$$

Where **Q** is in m3/day and t is in days (0 < t < 365). Negative values of **Q** are equated to zero (non-irrigation season).

Water stress is defined as the number of consecutive years that agents experience drawdowns greater than a maximum acceptable depth, set to $\mathbf{H_{threshold}}$ metres below pre-development conditions for the whole basin (here 30 m as used for the lower Murrumbidgee groundwater source in Australia; Kumar, 2013). This represents the technical and/or economic constraints of pumping from a deeper water table. Water stress for each agent is assessed at the time of peak irrigation (January). We assume that non-stress years offset stress years, allowing farmers to partially recover from previous financial stress (i.e., profits from non-stress years allow farmers to repay debts). After $\mathbf{S_{critical}}$ consecutive years of stress, however, agents reach a critical level of debt and pumping at the site is set to nil (and the agent is removed from the model). This represents farmers that decide not to pump and grow dryland crops (or no crops), farmers that sell their land and water entitlements, or farmers going bankrupt. These sites are returned to the pool of available locations for the following year. Fig. 5b shows a simulation with farmers undergoing different levels of water stress, assuming $\mathbf{S_{critical}}$ equal to 3 years.

When issued with new well permits, farmers rank the available land options (i.e., unoccupied land cells) according to their land use strategy. Initially, this strategy comprises sites that meet three criteria: (1) proximity to the river (better soils, amenity); (2) proximity to the urban area (easier access to services); and (3) minimum drawdown at peak irrigation season (i.e., 1st of January). In the baseline situation, a farmer's best estimate of drawdown at an undeveloped site is the drawdown of the nearest active well (i.e., nearest neighbour approximation). Cell rankings according to the three criteria are multiplied and combined into an overall ranking. The 'best' locations are those with the highest overall ranking. Therefore, the overall ranking of a cell (x,y) is calculated as follows:

$$R_{overall-farmer}(x,y) \;= R_{river}*R_{town}*R_{drawdown} \quad (2)$$

Where $\mathbf{R_{overall\text{-}farmer}}$ is the overall ranking of cell (x,y); $\mathbf{R_{river}}$ is the ranking of the cell according to its distance to the nearest river

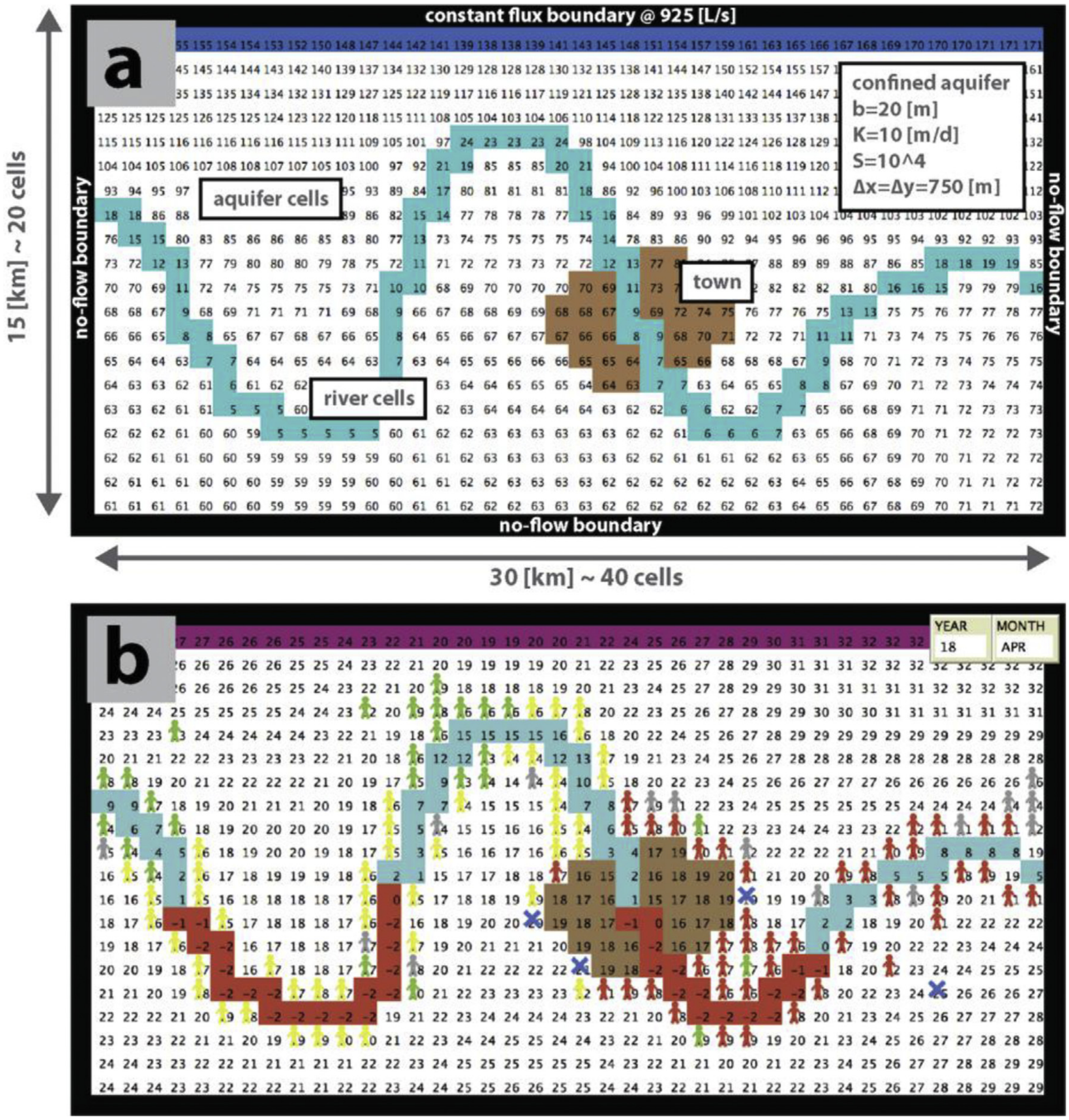

Fig. 5. Groundwater and agent components of the GW-ABM as implemented in FlowLogo. (a) Groundwater component: numbers in 'aquifer' cells represent steady-state groundwater heads in [m] for a no-pumping scenario used as the initial condition; values in 'river' cells represent fluxes in [L/s] for a particular time step. (b) Agent component: a sample simulation for the BASE scenario in April of year 18. Numbers show groundwater drawdowns in [m]. Assuming $S_{threshold} = 3$ years: 0–1 years of stress (green agents); 2 years of stress (yellow agents); and 3 years of stress (red agents). Grey agents are inactive farmers that have not commenced pumping. Blue crosses are town agents. Red cells show sections of the river under losing conditions, light blue cells are gaining sections (numbers in river cells are water fluxes in [L/s]). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cell; $\mathbf{R_{town}}$ is the ranking of the cell according to its distance to the nearest town cell; and $\mathbf{R_{drawdown}}$ is the ranking of the cell according to its drawdown in January 1st (using the information provided by the regulator agent). Ties between cells are broken down at random; thus representing a source of variability (randomness) in decision-making. Once identified, the 'best' sites are reserved (grey farmer agents are added to the model, Fig. 5b) and remain inactive until the following season, when incoming farmers become active and pumping begins (grey agents turn green, Fig. 5b). This delay avoids incoming farmers to begin pumping in the middle of irrigation season (unrealistic); and simulates a lag between a farmer's land purchase decision and commencement of pumping (e.g., the time needed to drill a new well, or to transfer water entitlements).

Two hypothetical adaptation mechanisms are considered for these agents:

1. **Strategic land use (SLU)**: we endow agents with a preference for sites away from active wells. This mechanism acts as a 'rule of thumb' that integrates the concept of well interference (i.e., superposing cones of depression) to the agents' strategic choices. We incorporate this trait by adding the term $\mathbf{R_{farmer}}$ to Eq. (2), which ranks a cell according to its distance to the nearest farmer (cells far from farmers are preferred). We assume that farmers do not know of physical constraints (i.e., high T-K, high S), as it occurs in many real-world situations (conversely, physical constraints could be known to some extent and production wells clustered in areas of good aquifer properties). The **SLU** mechanism explores the effects of farmers adapting their land use decisions to socioeconomic changes.
2. **Risk aversion (RAV):** we endow agents with a memory and the ability to calculate the risk of different land purchases, defined

Table 1
Agent types, baseline parameters and mechanisms for our example GW-ABM.

Agent	Parameter	Value	Mechanisms
Farmer	Crop water requirement	5.2 ML/ha/year	★ Strategic land use (SLU)
	$\mathbf{H_{threshold}}$: maximum acceptable drawdown	30 m	★ Risk aversion (RAV)
	$\mathbf{S_{critical}}$: critical water stress	3 years	
	h: sub-optimality factor	1.5	
	irrigated area (farm plot)	750×750 m^2	
Town	New drinking well required every population	5 years	
	serviced by each well per capita consumption drinking well yield	10,000	
		200 L/person/day	
		20 L/s	
Regulator	**NWP**: number of well permits per year	15	▲ Full monitoring scheme (FMS)
	$\mathbf{S_{subsidy}}$: subsidy period	2 years	▲ Well protection areas (WPA)
	well protection radius	750 m	▲ Subsidy scheme (SUB)

as the probability of unacceptable financial stress at each location:

$$risk = \frac{\#\, farmers\ reaching\ the\ stress\ threshold\ at\ this\ cell}{current\ year} \tag{3}$$

We include this mechanism by adding the term $\mathbf{R_{history}}$ to Eq. (2). $\mathbf{R_{history}}$ is a cell's rank according to the risk at the site (cells with low probabilities are preferred). $\mathbf{R_{history}}$ is only activated after the tenth year of simulation. We do this to allow some 'history' of risk accumulating prior to farmers using this information. Thus, as the basin develops, agents undergo an adaptation process where they learn to avoid risky sites.

Eq. (4) shows how both mechanisms are incorporated to an agent's land use strategy. These mechanisms can be activated separately, or together.

$$R_{overall-farmer}(x,y) \ = R_{river} * R_{town} * R_{drawdown} * \left[R_{farmer}\right] * \left[R_{history}\right] \tag{4}$$

Finally, we introduce sub-optimality to the decision-making of farmer agents (i.e., farmers that do not conform or do not make rational decisions), by altering the way they act upon the ranking of cells within the modelled domain. A sub-optimality factor (h) is used to define a 'pool' with the h*NWP highest-ranked sites. Then, each year farmers choose at random NWP sites from this pool to place new wells. Defined in this manner, $h = 1$ represents *optimal* decision-making, while higher values depict increasing levels of *sub-optimality* in the decision-making. In Section 3.6, we use this parameter to test robustness of adaptation and/or policy mechanisms against different levels of uncertainty in agent behaviours.

3.3.2. Town well agents

Town agents are shown as blue crosses in Fig. 5b. They are characterised by *spatial location* and *pumping rate*. Unlike farmers, town wells pump throughout the year. In this model each town well supplies drinking water for 10,000 people at a rate of 200 L/person/day. Every five years a drinking water well is added to the model, reflecting an increase in the town's population. The town selects well sites using a simple strategy that comprises two criteria: (1) proximity to town (reduces distribution costs); and (2) minimum drawdown during peak irrigation season (reduces pumping costs and increases water security):

$$R_{overall-town}(x,y) \ = R_{town} * R_{drawdown} \tag{5}$$

Where $\mathbf{R_{overall\text{-}town}}$ is the overall ranking of cell (x,y) assigned by town well agents; $\mathbf{R_{town}}$ is the rank of the cell according to its distance to the nearest town cell; and $\mathbf{R_{drawdown}}$ is the rank of the cell according to its drawdown in January 1st.

3.3.3. Regulator agent

This agent constrains the behaviour of farmers and provides information on the spatial distribution of drawdowns. It has no explicit location in space. In the **BASE** scenario, the regulator issues a maximum number of well permits per year (**NWP**), and establishes a simple monitoring program based on drawdown data from active well sites. We investigate the effects of three policy levers:

1. **Full monitoring scheme (FMS):** The regulator performs intensive monitoring of the basin, and detailed potentiometric maps are generated yearly. Farmer agents have a better picture of drawdowns across the basin, and $\mathbf{R_{drawdown}}$ is no longer inferred from other wells. When **FMS** is active, farmer agents have an accurate estimate of the drawdown at every cell of the modelled domain.
2. **Well protection areas (WPA):** No new wells can be constructed closer than WP_{radius} [m] from an active well. Here we consider $WP_{radius} = 750$ [m], meaning that there is a prohibition to pump in a property contiguous to a property with an existing well. WPA's of different sizes can be explored using the *FlowLogo* interface. We assume that the location of town wells is not constrained by existing WPAs (for water security).
3. **Subsidy scheme (SUB)**: Loans and economic support extend the maximum period agents can endure with water stress. When active, **SUB** increases a farmer's stress threshold $\mathbf{S_{critical}}$ by an additional period of $\mathbf{S_{subsidy}}$ years. We assume that subsidies provide two additional years of financial support to farmers experiencing water stress; thus increasing the maximum period of stress from three to five years (i.e., $\mathbf{S_{critical}} = 3$ years and $\mathbf{S_{subsidy}} = 2$ years).

The small set of hypothetical operating and policy mechanisms described above illustrate some of the questions that can be explored using FlowLogo models. Besides these man-made regulation/constraints, we could also consider constraints imposed by the natural environment, such as farmers selectively drilling new wells with a knowledge of the hydrogeology and seeking to drill in areas of high T and S, or regulator agents imposing environmental requirements, such as minimum environmental river flows.

3.4. Running the model using FlowLogo

The model is run according to Fig. 6, which shows a flowchart with the coupling and scheduling of social and groundwater processes, and the stage at which each leverage mechanism

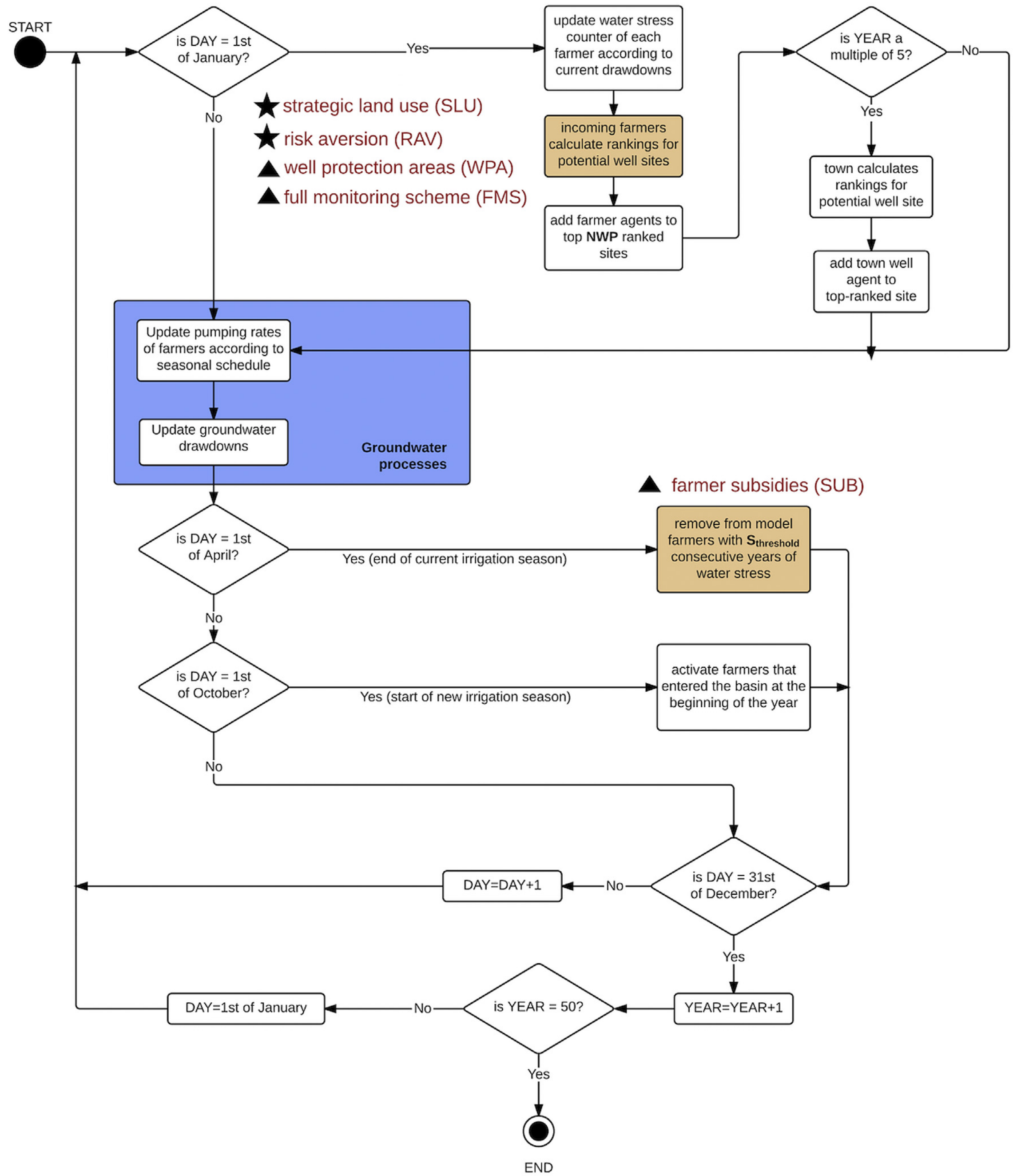

Fig. 6. Scheduling of major groundwater and agent processes, showing implementation points (orange boxes) for farmer adaptation (stars) and policy levers (triangles) mechanisms. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

intervenes. Fig. 7 shows a screenshot of the resulting interface for this specific example.

Table 2 describes a representative set of six scenarios (from the 32 possible combinations) of agent adaptation and policy levers developed using the modelling environment shown in Fig. 7. For instance, in the **BASE** scenario agents can install wells in areas experiencing water stress. There is no adaptation and information is limited, since the regulator only disseminates drawdown data collected at locations with operative wells. Other scenarios add more complex mechanisms on top of **BASE**, such as **BASE** + **SLU** + **FMS,** which represents agents making strategic decisions. Here, the **SLU** trait prompts farmers to drill new wells as far as possible from other farmers (with the aim of minimising well interferences); and the **FMS** policy of the regulator gives agents a full picture of water table depths.

3.5. Exploring GW-ABM scenarios

Fig. 8 presents probability density functions (pdfs), for two hypothetical groundwater management objectives, based on the outputs of 20 realisations for each scenario described in Table 2. The shape of each pdf describes the relative likelihood that the two objectives take on a given value. The two management objectives represent different interests: the regulator is interested in minimising peak average drawdowns (environmental objective), farmers want to avoid water stress (social objective). A burn-in

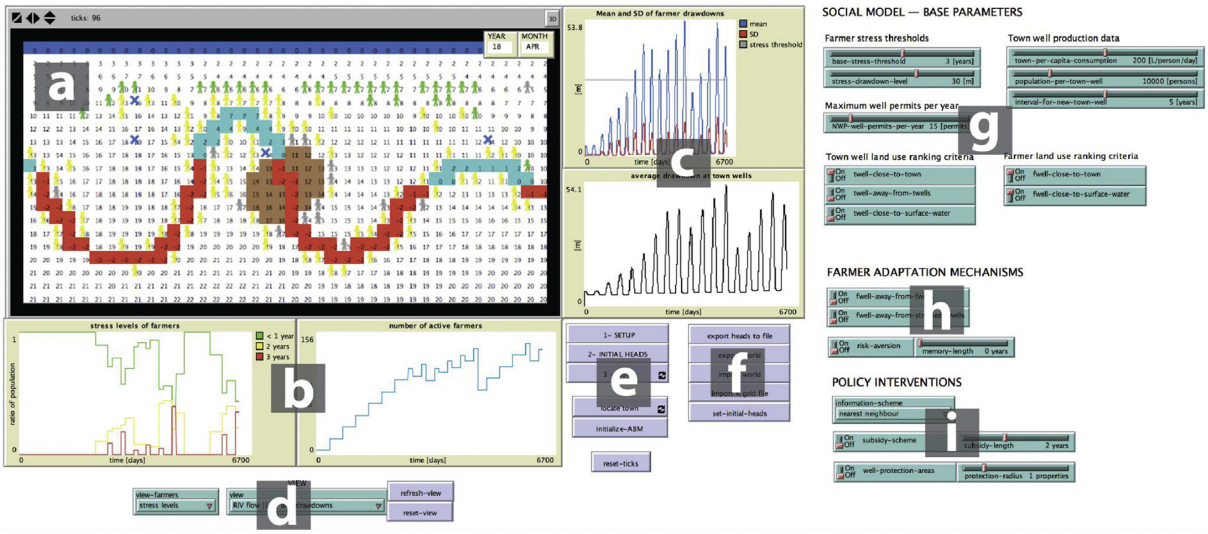

Fig. 7. Interactive GW-ABM design environment for our example: (a) model window showing coupled social-groundwater outputs; (b) social output plots, histogram of water stress (left) and time series for number of active farmers (right); (c) groundwater output plots, time series for average and standard deviation of drawdowns at farmer (top) and town wells (bottom); (d) pull-down menus with model output display options; (e) simulation control buttons; (f) data export/import options; (g) sliders and switches to set base parameters for agents; (h) controls for farmer adaptation and learning mechanisms; (i) controls for policy intervention mechanisms.

period of 10 years was used, thus the analysis only considers the outputs between years 10 and 50. The narrower pdfs of **BASE** + **SLU** and **BASE** + **SLU** + **FMS** indicate that the **SLU** and **FMS** mechanisms allow agents to self-organise in space and time in such a way that, on average, water stress fluctuates in a narrower range of values (Fig. 8a). One could argue that in these two scenarios the capacity of the aquifer is being used more efficiently. This however imposes a higher environmental burden on the aquifer, i.e. a larger overall drawdown (Fig. 8b). The wider pdfs of the remaining scenarios suggest relatively more unstable conditions and a system oscillating across a wider range of values. These oscillations trigger intermittent bursts of high farmer stress. In the subsequent period the capacity of the aquifer is underutilised due to a drop in number of active farmers. As a consequence, the average drawdowns are below the levels observed in the more ‘stable’ scenarios.

We use the concept of Pareto front to investigate further investigate the trade-off between both management objectives. The Pareto front describes how improving one particular criterion results in worsening the performance of another other criterion. Fig. 9 shows the Pareto analysis illustrating the trade-off between two management objectives, for all possible combinations of agent strategies (32 scenarios × 20 realisations per scenario). Strategies along the Pareto front (solid line in Fig. 9) are considered optimal. All points along the Pareto front are equally optimal, and it is the decision-maker's role to choose among them. All the points not on the Pareto front are suboptimal models that can be discarded.

The Pareto approach facilitates defining management goals, but it does not show how long the system will take to attain those goals nor the uncertainty in model predictions. This information can be obtained from time series statistics. Fig. 10 presents time series of 5-year rolling statistics (centred window) including means, standard deviations, and 95% confidence bounds, for four representative scenarios. We selected 5-year windows to filter out the seasonal effects of pumping. Rolling means (Fig. 10a–b–e–f) show that **BASE** + **FMS, BASE** + **WPA** present no significant differences compared to the baseline. **BASE** + **SLU** and **BASE** + **FMS** + **SLU** however, show decreases in farmer stress and increases in average drawdowns, compared to **BASE** (Fig. 10c–d–g–h). Also, Fig. 10c–d reveal potential synergistic effects when the **FMS** and **SLU** mechanisms are used conjunctively (farmer stress is slightly lower in this case). Rolling standard deviations (Fig. 10i–p) indicate the magnitude of oscillations under each scenario. Consider, for example, the case where a primary management goal is the social stability of the system, and the policy-maker sets a target represented by a

Table 2
A subset of six scenarios for our example GW-ABM.

Scenario	Mechanism type	Comments/Parameters
BASE		Agents prefer sites close to the town (proximity to services), close to the river (amenity, better soils), and having lesser drawdowns during peak irrigation season. Drawdowns are only known at existing well sites.
BASE + **SLU** **(strategic land use)**	★ farmer adaptation	Agents prefer sites as far as possible from active wells and from farmers experiencing water stress.
BASE + **RAV** **(risk aversion)**	★ farmer adaptation	Agents calculate risk at each site based on historical information. Sites with lower risk are preferred.
BASE + **FMS** **(full monitoring scheme)**	▲ dissemination of information	The regulator collects and disseminates detailed potentiometric maps. An accurate estimation of drawdown exists a every site.
BASE + **WPA** **(well protection areas)**	▲ policy intervention	The regulator sets restriction areas around existing license holders. Here, we assume WPAs with a distance of 750 [m], so each neighbouring cell in this case.
BASE + **SUB** **(subsidy scheme)**	▲ policy intervention	The regulator subsidise farmers ($\mathbf{S_{subsidy}}$) for period of 2 years i.e., allowing farmers to withstand water stress for 5 years. After this period, they stop pumping.
BASE + **SLU** + **FMS**	★▲ combined	The SLU and FMS mechanisms are activated together.

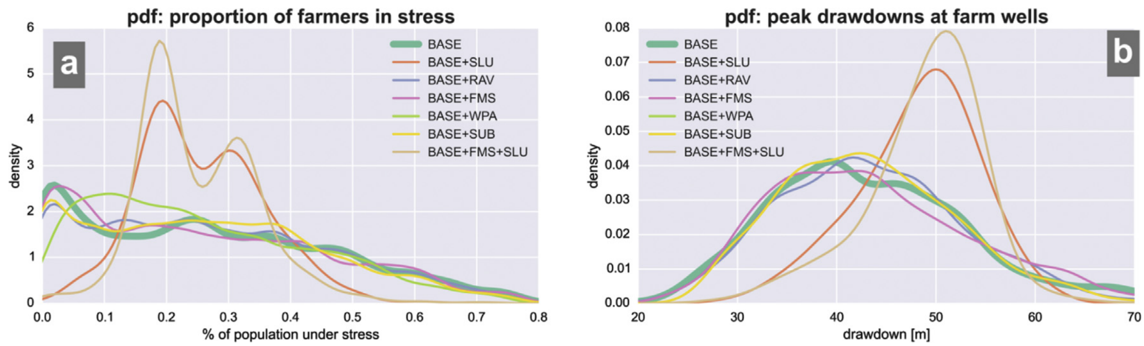

Fig. 8. Probability density functions for social and groundwater outcomes, under six representative scenarios and a sub-optimality factor of h = 1.5. (a) Proportion of farmers in stress; (b) average drawdown at farm wells in peak irrigation season (1st January).

standard deviation of 10% farmers in stress (i.e., the allowed magnitude of the oscillations). Fig. 10i–j shows that this goal is not met in **BASE** + **FMS** or **BASE** + **WPA** within the period of analysis. On the other hand, **BASE** + **SLU** (Fig. 10k) and **BASE** + **FMS** + **SLU** (Fig. 10l) exhibit a twofold increase in stability (i.e., a reduction in the standard deviations) compared to **BASE** throughout most of the simulation period. This analysis suggests that **BASE** + **FMS** + **SLU** appears to be the better choice as the target of a standard deviation of 10% is met in year 18 whereas in **BASE** + **SLU** this target is reached in year 25.

The information provided by time series can be analysed spatially using the FlowLogo model view. Fig. 11 shows the detailed evolution of the system within one year (t = 18) for the **BASE** and **BASE** + **FMS** + **SLU** scenarios. For **BASE**, in January (Fig. 11a) we see a situation of overshoot and large drawdowns: pumping is clustered next to the river and town, and the majority of farmers is under stress (red and yellow agents). Farmers are also pumping near town wells and incoming farmers (grey) are pumping next to stressed farmers. As we progress into autumn and winter (Fig. 11e), the situation is reversed: most farmers reach their stress threshold and stop pumping. The system will then undershoot in the following year, and the capacity of the aquifer is underutilised. This situation results in large oscillations throughout the period of analysis. **BASE** + **FMS** + **SLU**, on the other hand, shows a situation of stable development: in January (Fig. 11b) farmers are strategically located across the whole basin in a way that minimizes well interferences. For April, (Fig. 11d) drawdowns are approximately half the magnitude of **BASE** at the same time of year, and the river is not losing water to the aquifer. In June, we only see residual drawdowns in the northeast part of the basin (Fig. 11f), whereas in **BASE** residual drawdowns are dispersed (Fig. 11e). Also, in **BASE** + **FMS** + **SLU** the town locates its wells close to the urban area and next to the river; potentially leading to long-term savings in terms of extraction and distribution of pumped water. The situation depicted for **BASE** + **FMS** + **SLU** is a stable long-term condition, since few farmers ever reach their maximum stress levels. This analysis reveals an important trade-off between a stable system with higher drawdowns and an oscillating system with lower drawdowns.

Finally, Fig. 12 shows water budget statistics computed over all

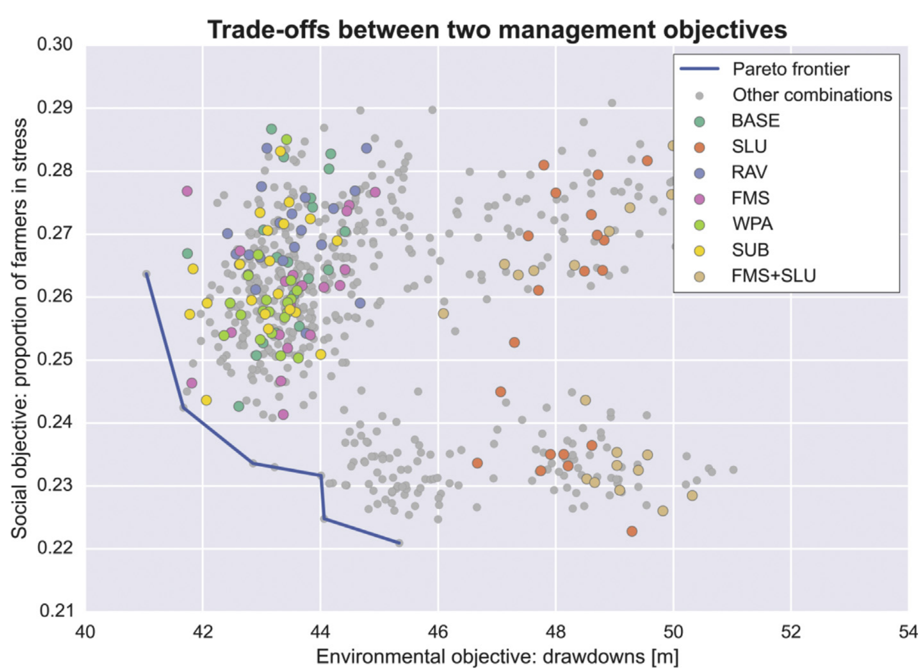

Fig. 9. Trade-offs and Pareto front for two hypothetical management objectives. The figure is based on 20 realizations per scenario, for all 32 possible mechanism combinations (20×32 = 640 simulations). Values correspond to time series means for each objective. Colours are the subset of representative scenarios chosen for this analysis; the remaining combinations of mechanisms are shown in grey. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

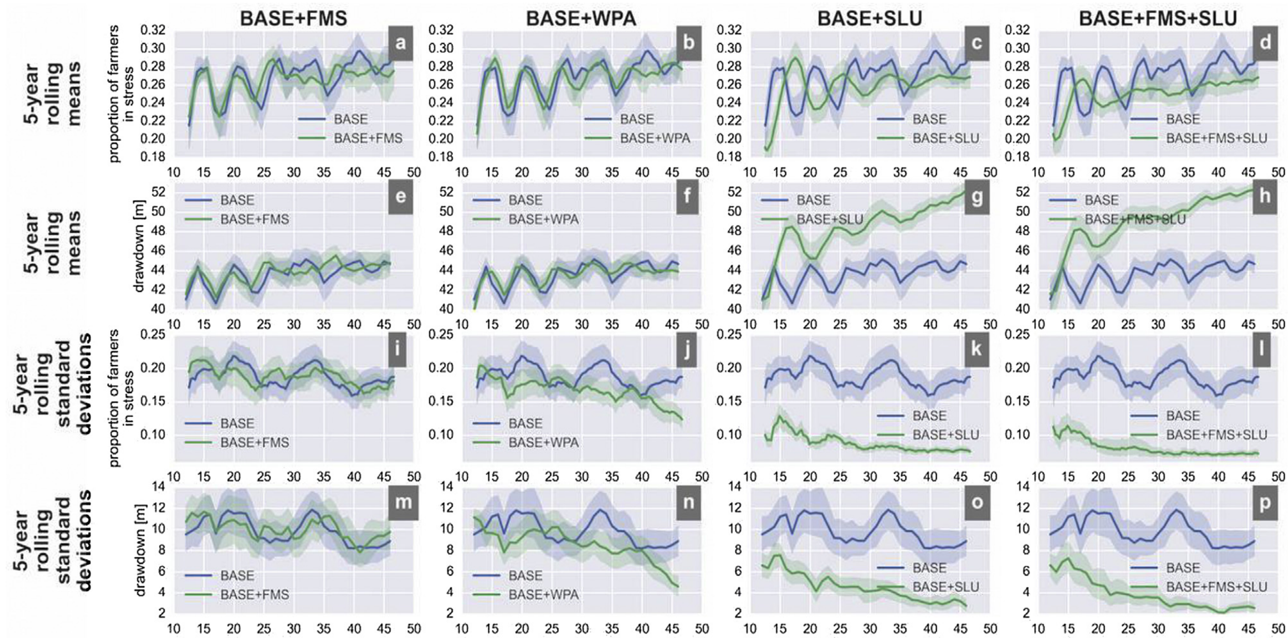

Fig. 10. Time series of four representative scenarios vs. BASE, showing different emergent patterns of environmental and social development. Shaded bands depict 95% confidence intervals.

realizations for a 40-year period. Not surprisingly, the larger drawdowns in **BASE** + **FMS** + **SLU** (see Fig. 10h) lead to higher river seepage than in the **BASE** case (Fig. 12a); however, in **BASE** + **FMS** + **SLU** the pumped volume is less (Fig. 12b). This counterintuitive effect is due to a more stable and controlled development of farmer populations in the **BASE** + **FMS** + **SLU** scenario (Fig. 12c).

3.6. Exploring coupled social–physical process uncertainty

To be effective, groundwater management strategies should deal with uncertainty. Therefore, a key task is to assess their performance over a range of social and hydrogeological conditions. Using FlowLogo, we demonstrate sensitivity analysis of GW-ABM scenarios subject to social and physical sources of uncertainty. The **BASE** + **FMS** + **SLU** scenario is used here.

Using NetLogo's parameter sensitivity functionalities (i.e., the “BehaviorSpace” tool), we first study the impact of increasing social diversity by extending the h parameter to $h = 5$ and $h = 10$. This results in higher levels of sub-optimality in the agents' decisions. Fig. 13a–d illustrate the impact of increased social diversity on the system (20 realisations for each case). Higher levels of sub-optimality have a negative impact on social stability: at $h = 5$ the system exhibits strong fluctuations in water stress (Fig. 13a), and by $h = 10$ farmer hardship increases dramatically (Fig. 13c). Higher social costs and instability lead to the aquifer's capacity being underutilised and a reduction in environmental impacts (Fig. 13b–d). Diversity, thus, emphasises the trade-off between our two hypothetical management objectives.

We then explore the effects of local scale geological heterogeneity using stochastic Gaussian simulation (SGS). SGS allows generating multiple equiprobable realisations of hydraulic conductivity, giving a realistic representation of its natural variability in space. We generated these realisations using NetLogo's Matlab extension and ran 20 simulations of the GW-ABM using different hydraulic conductivity realisations. The variogram used for SGS has a Gaussian covariance with a range of 10 cells, and a mean logK of 1 and standard deviation of 0.3. These parameters produce log-normally distributed conductivity fields having the same mean (10^{-4} m/s) as the simulations presented in Section 3.5. To isolate the effects of geological heterogeneity from the stochasticity of agent decision-making, we used a fixed random seed for all ABM runs. When we introduce geological heterogeneity in the model, the trade-off between both management objectives is reversed: social costs *and* peak average drawdowns increase together (see Fig. 13e–f). Also, the oscillations of the system increase. With this specific example we point out that ignoring geological heterogeneity results in predictions that are over-optimistic (i.e., under-estimating farmer stress). This emphasizes how important it is to integrate the entire modelling approach in a single platform where sensitivity analysis and uncertainty quantification can be carried out.

4. Discussion and conclusions

This paper describes FlowLogo, a coupled agent-based and a groundwater simulator offering a new environment for modelling complex human–aquifer interactions. We demonstrate its functionalities by implementing a hypothetical aquifer system, a set of agents representing groundwater users and their interactions. To the best of our knowledge, FlowLogo is the first integrated software offering a straightforward way to represent agent behaviours that evolve with groundwater conditions. It allows performing sensitivity and multi-realisation analyses on groundwater scenarios with complex socio-environmental couplings, allowing the exploration of agent and policy assumptions through a GUI.

The analyses of scenarios presented here illustrate the platform's potential as a decision-support tool, giving users the opportunity to perform management experiments on an ‘artificial society’ of adaptive agents that would otherwise be impossible or costly in real-world situations. The fact that behaviours and interactions of agents are fully programmable allows for a more flexible analysis of coupled social–environmental processes than previously possible with decision-making packages commonly used with groundwater codes (Ahlfeld et al., 2011; Schmid et al., 2006), where the human component is hard-wired to the

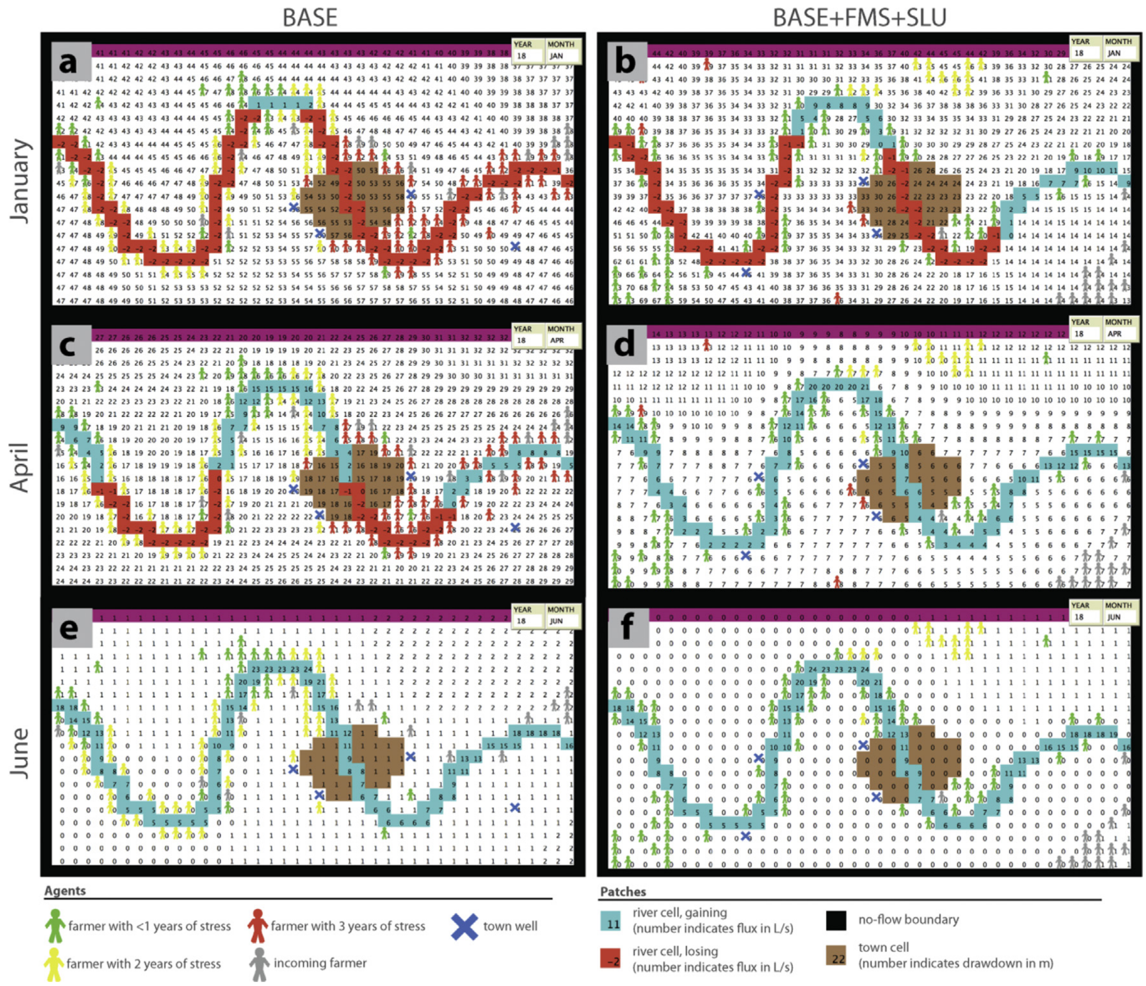

Fig. 11. Snapshots of different seasons in year 18 under the BASE and BASE + FMS + SLU; numbers show drawdown in [m], except in river cells where they represent flux in [L/s] blue river cells are gaining and red cells are losing). (a–b) Summer situation; (c–d) autumn situation; and (e–f) winter situation (southern hemisphere seasons). Note the differences in clustering around the town and river; the strategic location of incoming farmers (grey agents), and exploitation in wider areas of the basin under BASE + FMS + SLU.

software and limited to a fixed set of rules and interactions. In cases where agent characteristics are designed in close resemblance to their real-world counterparts, outputs from the GW-ABM could be translated into policy recommendations. The examples given in this paper as well as the codes on the repository are sufficient to be used as a base to design a new GW-ABM, even for users that do not have extensive programming experience.

FlowLogo is a research tool aimed at interdisciplinary groundwater research, targeting users from a wide range of fields such as economics, social science, law, and hydrology. In this context, FlowLogo helps overcome the technical difficulties presented in the opening of this article relating to the coupling of agent-based and groundwater models. The tutorial presented in Section 3 highlights the simplicity of developing a GW-ABM when the groundwater modelling code is embedded in NetLogo. As noted earlier, using a general-purpose language that interfaces with a groundwater code would come at the cost of limited supportive features for ABMs (Matthews et al., 2005; Thiele et al., 2011). To decrease

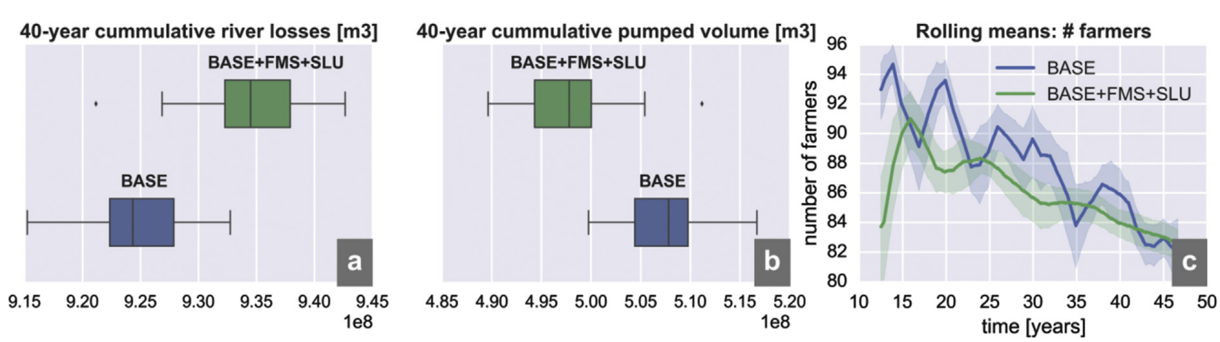

Fig. 12. Water budgets can estimate long-term trade-offs between surface- and groundwater flows.

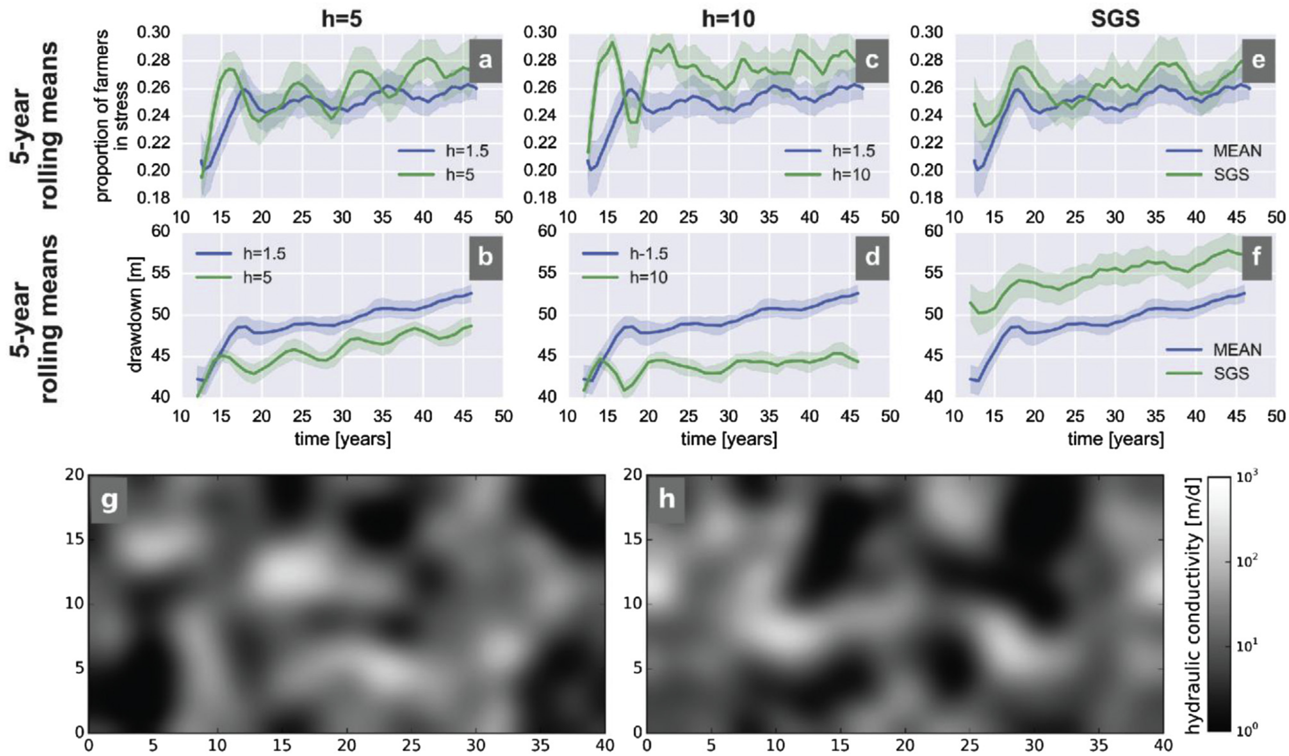

Fig. 13. Sensitivity analysis of agent rationality (a–d), and uncertainty in hydraulic parameters (e–f). Hydraulic conductivity realizations are shown in (g–h).

implementation time and the risk of making errors and to increase re-usability, traceability and communicability, it is helpful to use established software libraries or languages that were especially designed for implementing ABMs. As such, FlowLogo helps reduce the risk of programming bugs, it increases the readability of the source code, and it makes the overall implementation process much easier. In the future, our aim is to create a repository of FlowLogo case studies from which new users can borrow previously coded agents.

We acknowledge that groundwater codes like MODFLOW offer advantages over FlowLogo in terms of groundwater development. However, we believe that such functionalities are not necessarily needed in FlowLogo which targets models of management and policy in regional aquifers. For these kinds of problems, advanced groundwater code functionalities are not typically needed, and simpler, parsimonious models are often recommended (Doherty and Simmons, 2013; Hill, 2006; Voss, 2011a, 2011b). To this end, FlowLogo includes a toolkit with groundwater objects and boundary conditions that allow the user to represent the main features of regional groundwater flow. These features have been successfully benchmarked against MODFLOW (see Section 2 of Supplementary material).

Practical applications of FlowLogo should typically proceed in two stages (Poteete et al., 2010; Thiele et al., 2014). Our example illustrates the first stage: model evaluations are qualitative, suggesting general mechanisms or providing generic insights on emergent processes. For instance, we showed that stability (an emergent pattern) *might* emerge because of farmers engaging in strategic land use decisions (**SLU** mechanism). The second stage would be to parameterise the GW-ABM using social surveys to map interactions and actor characteristics to their agent counterparts, and subsequently validating the model against observations. The technical details of empirically grounding a GW-ABM and the data that is required for this task is reported in (Robinson et al., 2007; Rounsevell et al., 2011; Smajgl et al., 2011; Smajgl and Barreteau, 2014).

Many of the well-known hot spots of groundwater depletion are cases where management has not been able to balance the concerns and needs of all stakeholders. In these cases, FlowLogo would support the mapping of key stakeholder behaviours and interactions into agents, thus improving the representation of social–environmental dynamics within groundwater management models. Examples of possible applications are:

- Optimising irrigation in California's Central Valley (US). The platform could be used to explore the potential impacts of policy levers such as establishing a trading market of groundwater entitlements, the progressive banning of crops with high water demands (e.g., Almonds) or prioritising the efficient allocation of water over the seniority of water right holders (Culp et al., 2014).
- Improving water transactions in the Copiapó Basin (Chile). Agents can be used to explicitly model incentives targeting the transfer of entitlements between surface and groundwater users, or potential interventions to the currently unregulated water market (McFarlane and Norgate, 2012).
- Optimising the placement of groundwater recharge barriers in northern India (Bhattacharya, 2010). Here, FlowLogo could be used to broaden the scope of artificial recharge management models, by simulating legal/institutional constraints and the social/cultural acceptability of such schemes.
- Forecasting the lifespan of groundwater use in North-eastern China, using agents to represent the feedbacks between economic development and groundwater withdrawals for domestic, industrial, agricultural and power generation purposes (see Ahmed and Junmin, 2013; Carmody, 2010).
- Optimising water storage and land use in the UK chalk aquifers to minimise flooding (Macdonald et al., 2012). FlowLogo could

be used to retrofit published ABMs of land-use change (Matthews et al., 2007; Parker et al., 2003) with a groundwater component.

- Defining joint water sharing rules in transboundary aquifer problems such as the Guarani Aquifer System (South America), the Stampriet Kalahari Karoo Aquifer (Africa), or the Colorado River (US-Mexico border) (see Frisvold and Caswell, 2000; Tujchneider et al., 2013). In these cases, FlowLogo models could be used to explicitly represent the different socio-economic drivers, groundwater right systems, and interests in environmental conservation of each state/party.

In these examples, FlowLogo's interactive modelling capability, including the possibility to modify the values of model parameters at run time, could be very useful for participatory modelling. Although not shown here, FlowLogo models can be transformed into participatory simulations using the "Hubnet" architecture with frugal user intervention (Wilensky and Stroup, 1999). This architecture allows stakeholder representatives to switch on or off key agent assumptions or policy levers, as guided by their observations, interests (e.g. crop security and earnings) and responses to 'real-time' changes in the catchment. In the case of groundwater agents, one could start with farmer agents making near-sighted decisions with few interactions, and slowly increasing their foresight and communication with other agents. In the case of policy levers, it would be interesting to interactively control the magnitude of quotas and taxes, or activate/deactivate certain water trading rules. This feature would allow simulating sequences of events that could not be defined by 'a priori' by scenarios. Simulations where stakeholders and managers are given control of such dials during model runs can support workshop-based decision-making (see Gilbert et al., 2002; McIntosh et al., 2011; Voinov and Bousquet, 2010; Zellner, 2008). A case study application using this approach is the subject of ongoing work by the authors.

In terms of computational implementation, FlowLogo allows users to focus on the modelling of a GW-ABM rather than on the technical aspects of model coupling. A benefit of the FlowLogo workflow is that 'designing from scratch' ensures that the user is forced to have a conceptual understanding of the agents being modelled rather than running with pre-existing, and perhaps inappropriate agent behaviour. It is envisaged that the ease of learning and implementing applications in NetLogo will facilitate the adoption of FlowLogo by researchers from many disciplines, giving them access to widely-used social simulation environment. (see An and Wilensky, 2009; Hamill, 2010). Overall, this open-source platform provides a basis for disseminating and replicating GW-ABM research. A series of improvements will be introduced to the model in the near future. The implementation of iterative solutions to the groundwater flow equations, variable-density flow and solute transport, surface water routing, and vertical flow are the subject of ongoing development.

Besides using FlowLogo for scientific analysis of socio-environmental dynamics in groundwater basins we believe its flexibility (i.e., the benefits added by programming in NetLogo language), makes it ideal for water negotiations, public meetings, and also for education in areas ranging from groundwater management to environmental economics, at the undergraduate and graduate levels.

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Appendix A. Supplementary material

Supplementary material related to this article can be found at http://dx.doi.org/10.1016/j.envsoft.2015.08.018.

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