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Sustainable groundwater management: How long and what will it take?

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ABSTRACT

Groundwater depletion is arguably one of humanity's greatest sustainability challenges of the 21st century. With Sustainable Development Goals only a decade away, water authorities around the world are in the urgent need for concrete and targeted measures to ensure that communities adhere to groundwater management policies as rapidly and as effectively as possible. In this paper, we combine computational social science, groundwater modelling and empirical data from the World Values Survey to generate future ensembles of hydro-social trajectories under alternative courses of management and social action or inaction. Our simulations shed new light on the role that cultural values can play in shaping the societal trajectories and norms that emerge when resources are either allocated or not sufficiently allocated to monitor compliance, issue fines, engage community leaders, and deter rule-breakers. This study presents a new approach to explore and evaluate the capacity of existing and future management actions to steer groundwater systems towards sustainable trajectories, to forecast the celerity and timing of social transformations at the inter-decadal scale, and to help nations identify the most pertinent management options under institutional, political, social, and/or cultural constraints. The methods presented here are broadly applicable to support strategic decisions that rely on the monitoring, enforcement, and compliance of environmental regulations.

1. Introduction

Groundwater is being rapidly depleted worldwide (Aeschbach-Hertig and Gleeson, 2012; Famiglietti et al., 2011; Richey et al., 2015; Rodell et al., 2009). Much of this depletion is linked to irrigation in agricultural regions (e.g., the Indo-Gangetic Plain, the North China Plain, the North and South Arabian Peninsula, Western Mexico, central USA and the California Central Valley) where major food bowls and population centres are located (Gleeson et al., 2012b; Margat and Van der Gun, 2013). Recent hydro-economic analyses reveal that unsustainable rates of groundwater abstraction threaten water and food security not only locally (Wada et al., 2012), but also globally via international trade links (Dalin et al., 2017).

In most stressed aquifer systems, the preferred option has been to regulate groundwater abstraction by setting and enforcing sustainable allocation limits (Aeschbach-Hertig and Gleeson, 2012; Margat and Van der Gun, 2013; Shah et al., 2003; Theesfeld, 2010). To be effective, these policies require that the "rules of the game" are socially accepted, adhered to and enforced. Adherence to the rules however cannot be assured as water users may choose to either resist, ignore (by omission, purposely or due to misinformation) or violate restrictions imposed on them. Although strict monitoring and penalties may induce people to play by the rules, such show of force can erode trust between water agencies and users (Gelcich et al., 2006; Jones and Andriamarovololona, 2008; Ostrom, 1990; Ostrom and Walker, 2005). In the developing world, where much of the groundwater depletion is happening (Aeschbach-Hertig and Gleeson, 2012; Margat and Van der Gun, 2013), monitoring millions of water users is likely an impractical and expensive solution (Shah, 2009; Shah et al., 2003).

Understanding the drivers of compliance and their sensitivity to

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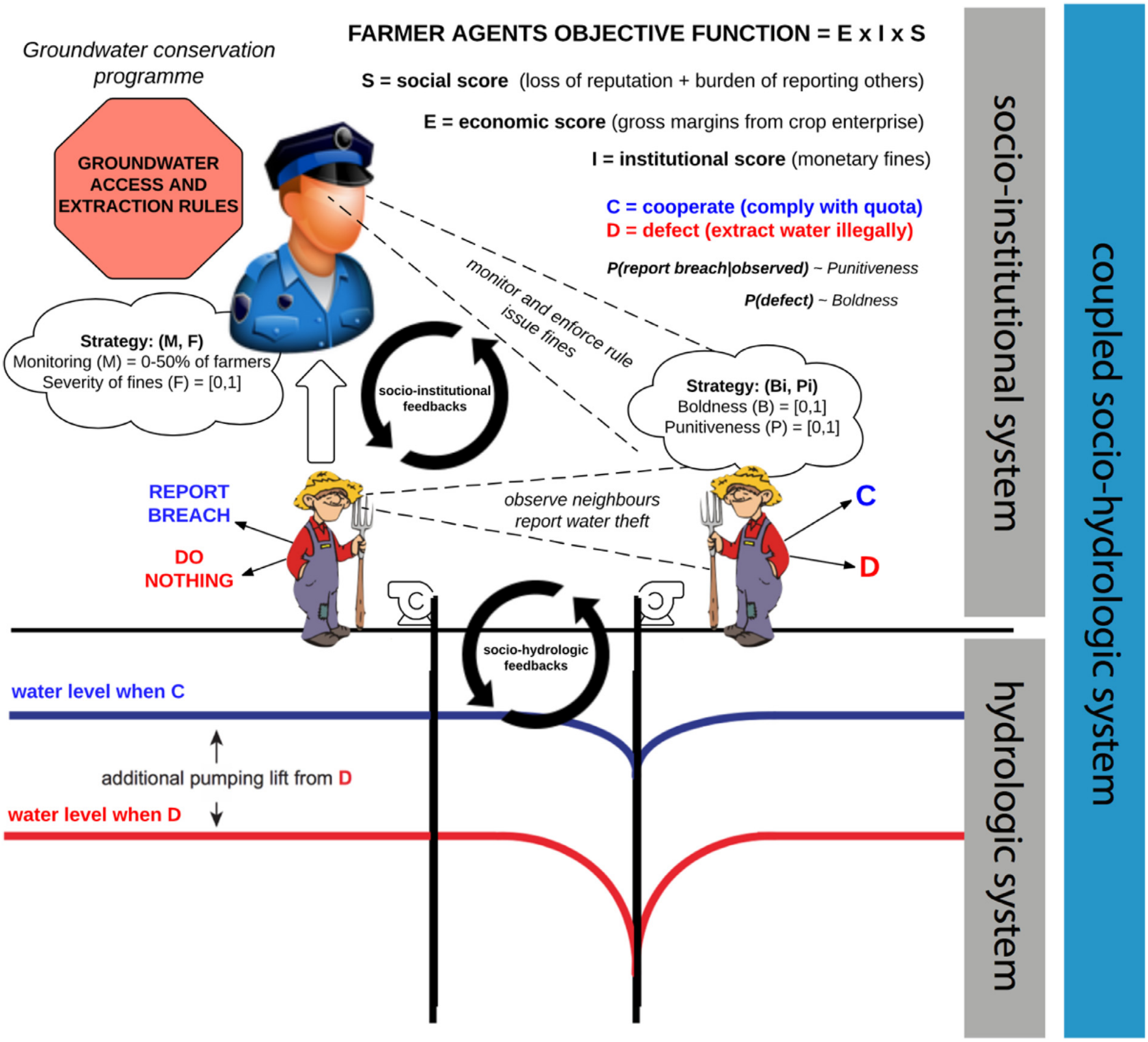

Fig. 1. The coupled socio-hydrologic system conceptualised in the Groundwater Commons Game (GCG). The GCG synthesises human cooperation and collective action theory, into an exploratory modelling framework of intermediate complexity to identify fundamental regulatory and social drivers of compliance with groundwater management policies.

policy instruments and cultural factors remains a major challenge for even the most adept water agencies in developed countries (Margat and Van der Gun, 2013). Empirical surveys and social research typically take years to plan and develop while consuming considerable time, effort and resources in the process. Much of social research on the issue of compliance is site-specific and results derived from it are often difficult to generalise and extrapolate to other regions. Alternative methods of enquiry into the attitudes of water users towards groundwater regulations are needed to gain a preliminary understanding of how hydro-social systems could be steered towards local, national and international socio-environmental objectives. INTERPOL (INTERPOL-UNEP, 2016) reports that 30–50% of the global water supply is illegally obtained, with water theft expected to rise due to drought and climate change (Water Crimes, 2017). If this trajectory continues, the UN (2016) projects a 40% shortfall in water availability by 2030. Reversing this trend requires substantial improvements to compliance and enforcement because no matter how many novel governance tools are designed, it will all be insufficient if compliance and enforcement is absent or inadequate (Felbab-Brown, 2017). The role that adherence to groundwater management will play in the efforts of water agencies to achieve the desired groundwater outcomes can be purposefully explored through computational social science models, which have proven to be a valuable tool for synthesising empirical and theoretical knowledge on human cooperation, cultural values, and social norms (Castilla-Rho et al., 2017).

Previous work introducing the Groundwater Commons Game (Castilla-Rho et al., 2017) ascertained the *long-term efficacy* of groundwater management policies in the context of irrigated agriculture. This work however left a number of open questions for further research, of which elucidating possible future *trajectories towards sustainable groundwater management* is arguably the most important. For hydro-social systems to embark on sustainable trajectories, management policies must trigger both short- and long-term social transformations. These policies will be effective to the extent that they, in the short-term, promote rapid acceptability and internalisation of groundwater abstraction rules, and in the long-term maintain a stable and cooperative social stance towards groundwater regulations. Understanding the timing and speed at which a high degree of regulatory compliance may or may not develop is essential to meet the pressing geo-political and geo-economic challenges associated with water scarcity across the globe (World Economic Forum, 2019). Ensuring optimal compliance with rules limiting groundwater extraction is particularly important in order to respond to present and growing risks of water theft (Matthews, 2017).

How long and what will it take to embark on sustainable groundwater management trajectories? To answer this question, we build and expand on our previous steady-state analysis of the Groundwater Commons Game (Castilla-Rho et al., 2017) by investigating and ensemble of temporal trajectories triggered by three generic management decisions designed to steer the behaviours of resource users, namely: (a) the level of regulatory enforcement (i.e., decisions relating to the resources allocated to monitoring compliance and monetary fines), (b) the monitoring style (random or targeted monitoring), and (c) the adoption of active norm management strategies (engaging leaders and deterring rule-breakers). We investigated four case studies where groundwater is under intensive use—the Murray–Darling Basin (Australia), the California Central Valley (USA) and the transboundary Punjab aquifer (India and Pakistan). These four countries and their trade partners account for about 80% of the total groundwater depletion embedded in international trade of crop commodities (Dalin et al., 2017). They also broadly represent the four cultural typologies or 'ways of life' defined by Cultural Theory (individualist, fatalist, hierarchist, and egalitarian) (Verweij, 2000). When combined with the World Values Survey (www.worldvaluessurvey.org), these cultural typologies provide a robust empirical basis of comparison of human values and beliefs at a global scale.

2. Methods

The coupled socio-hydrology model used for this study is shown conceptually in Fig. 1, Supplementary Fig. 2, and described in detail in Castilla-Rho et al. (2017). The ODD + D model documentation(Grimm et al., 2006, 2010; Müller et al., 2013) with details on the conceptualisation, assumptions, variables, equations, underlying theory, empirical data, and validation based on a field survey of water licensees across three jurisdictions of the Murray–Darling Basin in Australia) can be accessed in GitHub repository of the Groundwater Commons Game (https://github.com/juancastilla/Groundwater_Commons_Game). An overview of the main components of the GCG is provided below.

2.1. Model conceptualisation and complexity

The GCG is an exploratory modelling tool that relies on agent-based simulation (Epstein and Axtell, 1996; Farmer, 2009; Macal, 2016) to formalise social theories of human cooperation and collective action (Axelrod, 1986; 1997; Axelrod and Hamilton, 1981; Gotts and Polhill, 2009; Gotts et al., 2003; Nyborg et al., 2016). The exploratory modelling approach, on the one hand, allows quantitative and qualitative analysis to de done in a controllable way (Castilla-Rho et al., 2015; Epstein and Axtell, 1996) using agent-based simulations as a scientific instrument. Agent-based simulation, on the other hand, captures the evolution of social interactions as they simultaneously impact, and respond to, the availability of groundwater in a common-pool resource situation (Castilla-Rho et al., 2017). In terms of model complexity, the GCG seeks to strike a balance between generic and case-specific details, which would otherwise obscure the general insights needed for comparative global studies. The main aim here is to identify the key regulatory and social drivers of compliance in realistic physical settings. By parameterising the model with relevant economic, institutional, social, and hydrogeological information, the GCG be used to provide advice on local water management issues and guide improvements to compliance and enforcement arrangements.

2.2. Hydro-social system

The GCG parsimoniously captures the hydro-social interactions of agricultural communities operating under groundwater management programs as they have been implemented in many parts of the world (FAO, 2016; Margat and Van der Gun, 2013; Theesfeld, 2010). The model focuses on the fundamental social, cultural, economic and institutional factors that may influence the degree to which farmers adhere to management policies. In this study groundwater management policies are modelled as water allocations (quotas) imposed on groundwater licenses, enforced by a regulator agent through variable levels of monitoring (m, M) and fines (f, F). Agents (farmers) may either comply (C) with water allocations, or defect (D) (i.e. extract groundwater illegally beyond the allocated quota). When an agent decides to defect, the volume of water extracted illegally is proportional to its internal norm of compliance (boldness B, explained below). Agents can also make decisions about reporting offending neighbours or overlook others' behaviour and do nothing.

2.3. Agent behaviour and interactions

As shown in Fig. 1, each agent represents a farmer, endowed with a two-dimensional strategy (B, P) that guides the agent's decisions. B (boldness) represents the probability that the farmer will defect, and P (punitiveness) represents the probability that the farmer will report a neighbour that takes water illegally (both variables are normalised between 0 and 1). Agents have no foresight and they rely on a simple heuristic rule to update their strategies from 1 year to the next: "*imitate* the strategy of whichever neighbour is doing best, continue *exploiting* the current strategy if better, and *explore* a new strategy occasionally". This heuristic engages the agent population in a process of individual deliberation to determine what to do the following year based on their individual experiences and those of their immediate neighbours. The heuristic is supported by the theory of *bounded rationality* (Gigerenzer, 2007; Gigerenzer and Goldstein, 1996; Simon, 1955), which establishes that decisions are continuously mediated by the circumstances and the environment in which they take place, and that individuals are only partly rational and have limited time and information to make a fully informed decision. Bounded rationality suggests that in most real-world situations, fast and frugal heuristics can do as well, or better than more complex decision-making strategies (Gigerenzer and Goldstein, 1996). In the above conceptualisation of agent behaviour, differences in decision-making by agents can arise from their spatial circumstances and previous experiences, making some more likely to break rules than others (Keane et al., 2008). Our conceptualisation is based on work by Gotts and Polhill (2009) suggesting that farmers are largely influenced toward adopting behaviours by the example of other farmers they know, who are successful.

2.4. Modelling social norms

In our simulations, strategies are repeatedly evaluated on the basis of the social and economic costs and benefits that they accrue to each agent. To carry out this evaluation, agents refer to a simple utility calculation to probe the social and economic implications of their decisions. This calculation combines into an overall performance index (PI): a) an economic score (E) that is directly proportional to the gross margins of crop production, as determined by the irrigated acreage and the pumping costs (which is a function of the depth of the groundwater table); b) an institutional score (I) that represents the proportion (0–100%) of gross margins forgone to pay fines; and c) a social score (S) that represents the loss of reputation and the social costs of reporting offenders; the three score components are parsimoniously aggregated using equal weighting by the equation $PI = E*I*S$ (see ODD + D for details and justification of each component). Agents refer to PI to compare and decide amongst competing strategies (B,P). Overall, the model implements social norms as informal, non-obligatory attitudes towards groundwater management rules (i.e., the boldness and punitiveness levels adopted by each agent). The strength of these norms can be computed as $SN = mean(P) - mean(B)$ with values of $SN = -1$, $SN = 0$ and $SN = 1$ representing a weak, a neutral, and a strong social

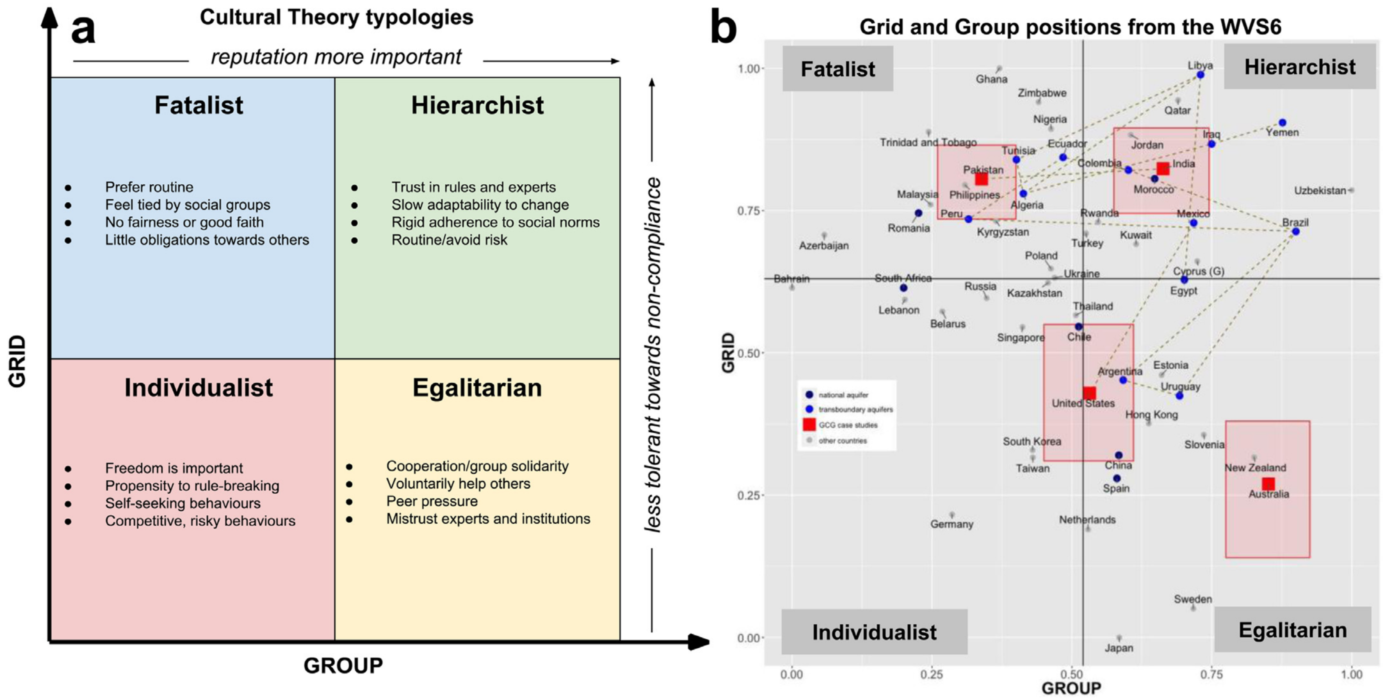

Fig. 2. Global map of cultural typologies based on Cultural Theory and Wave 6 of the World Values Survey (WVS). (a) The four typologies of Cultural Theory and values that characterise each typology. (b) Cultural traits computed from the World Values Survey Wave 6 (2010–2014), adapted from Castilla-Rho et al. (2017).

norm of compliance, respectively.

2.5. *Eliciting agent parameters using cultural theory and the world values survey*

To parametrise agent behaviour—i.e. the ways in which farmers make decisions—we employ Cultural Theory (also known as Grid-Group or Plural Rationality Theory; see Castilla-Rho et al., 2017). Cultural Theory defines four types of rationalities or 'ways of life', defined by two cultural dimensions: grid and group. The group dimension describes how strongly people are bonded together, e.g. low-group people tend to be self-focused and competitive while high-group people have their interests overlapping with the interests of the collective. The grid dimension represents the extent to which people rely on standards (e.g., morals, shame, reputation) for achieving goals. Low-grid people tend to undertake risky behaviours whereas high-grid people display routine and avoid risk. Taken together, grid and group form a two-dimensional cultural map—split into four quadrants—that defines four typologies of human behaviour: individualist, egalitarian, fatalist, and hierarchist (see Fig. 2). The grid and group dimensions of Cultural Theory determine how agents in the GCG construe and evaluate their social interactions (de Vries and Petersen, 2009; Rotmans and de Vries, 1997; see Verweij, 2000; Verweij et al., 2015), i.e. the social score (S) in the performance index (PI = E*I*S), as follows:

- The group dimension [0–1] measures the importance that agents ascribe to maintaining a good reputation: *What is the social cost of being caught breaking the rules?*
- The grid dimension [0–1] measures how tolerant agents are towards illegal groundwater extractions of others: *What is the social cost of being the whistle-blower?*

Currently there are no surveys that measure grid and group characteristics across societies, but they can be indirectly obtained from datasets like the World Values Survey (WVS). The WVS represents the most recent and comprehensive global dataset on cultural values available and consists on detailed questionnaires that have been implemented through face-to-face interviews to over 400,000 respondents in almost 100 countries since 1981. Moreover, the WVS is the only empirical study covering the full range of global variations, from very poor to very rich countries, in all of the world's major cultural zones (www.worldvaluessurvey.org). In this capacity, we applied the methodology proposed by Chai et al. (2009) to isolate questions in the WVS that carry the most useful information about grid and group dimensions across countries. After manually discarding and grouping questions under each of the two cultural dimensions, a one-way analysis of variance (ANOVA) is used to select 20 questions (10 for grid, 10 for group) that provide sufficiently high between-country variation ($P < 0.001$) to highlight differences across societies. Questions for each category are normalized to a scale of 0–1 and then averaged to generate a grid-group score for each country. Finally, the scores are used as weights to compute the social utility (S) that each agent derives from his or her decisions. The social utility function has the form $S = (1\text{-grid})^m \times \text{group}^n$, where m = number of times the agent reports a neighbour that takes water illegally, and n = number of times the agent is see taking water illegally. In practice, this means that the intrinsic cost of reporting non-compliance decreases with increasing group score. Overall, the WVS therefore provides cultural context to our simulations, and allows the parametrisation of agents and their decisions. Fig. 2 shows the grid and group scores computed by(Castilla-Rho et al., 2017) for the 57 countries included in the World Values Survey (Wave 6 2010–2014; n = 90,350; www.worldvaluessurvey.org).

2.6. *Coupled socio-hydrologic model*

The hydro-social model was developed using FlowLogo (Castilla-Rho et al., 2015). Within our simulated hydro-social systems, agent strategies and pumping decisions impact the groundwater resource (e.g. groundwater drawdown, change in storage and fluxes), with groundwater conditions feeding back into the social dynamics as variable pumping costs and as inputs for subsequent agent decisions. Unlike traditional scenario-based modelling where the hydrologic and social systems are modelled separately, the two-way coupling in the GCG captures the two-way feedbacks and complexity of the groundwater

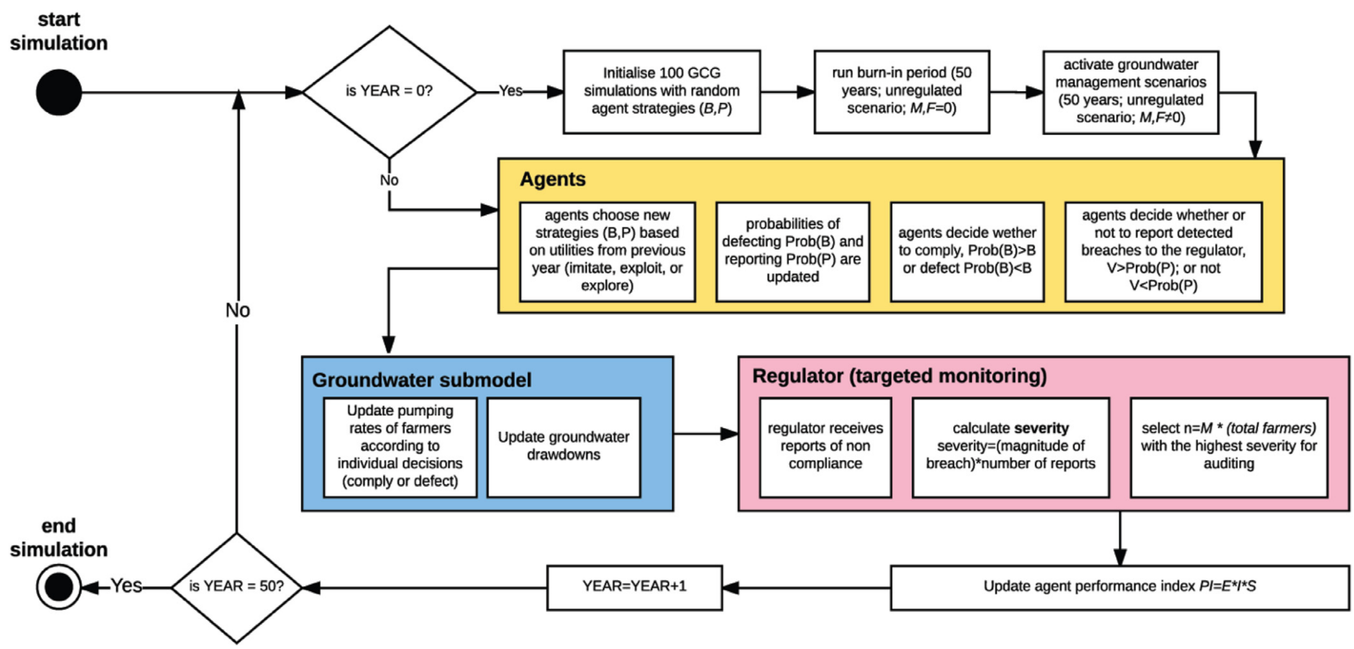

Fig. 3. Scheduling and linkage of hydro-social interactions in Groundwater Commons Game.

management problem in a dynamic way: at each time step, agent decisions simultaneously affect and are affected by the hydrological system (Fig. 3).

The hydrogeology was conceptualised for a 10 × 10 km (10^4 ha) representative subsection of each basin, discretised into 50 × 50 cells, each representing an area of 200 × 200 m (Fig. 4). Hydraulic boundary conditions were defined as no-flow boundary to the North and South (black), and fixed-head at the East and West (blue); setting head values to create a regional East–West gradient of 1/1000 (representing typical conditions in regional aquifer systems). The groundwater source tapped by agents was simulated as a semi-confined sand aquifer of 50 m thickness, with hydraulic conductivity $K = 10$ m/d and storativity $S = 1 \times 10^{-4}$. Agents pump from this groundwater source to irrigate their crops. Model time steps were 6 months. We used a steady-state run

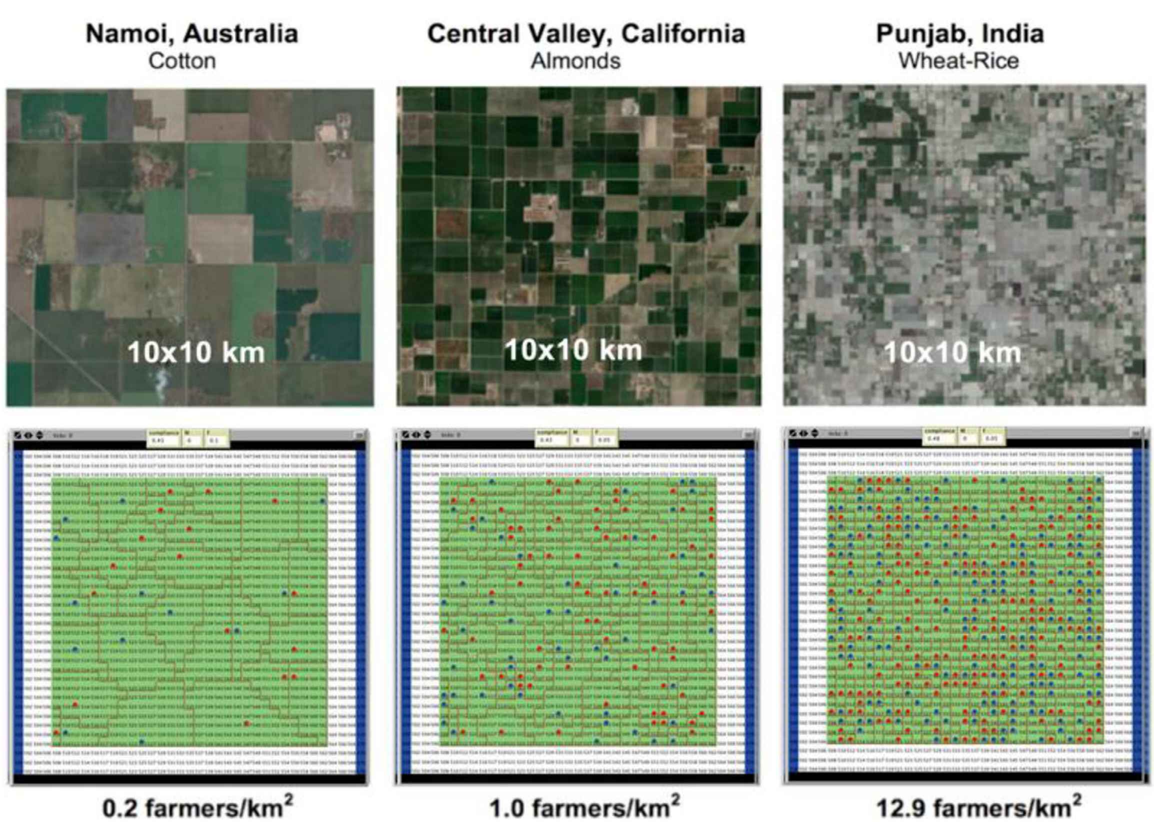

Fig. 4. Conceptual implementation of GCG case studies. Top panels: Spatial configuration and representative patterns of land parcels in a 10 × 10 km area based on Google Earth imagery. Bottom panels: GCG implementation of the three case studies.

with no pumping as the initial condition for each transient simulation of 100 years.

2.7. Case studies

We parametrised GCG simulations for three irrigation areas currently facing unsustainable groundwater demands: the Murray–Darling Basin (Australia), the California Central Valley (USA), and the Punjab (India and Pakistan). These case studies were chosen for their global relevance (Gleeson et al., 2012a; Richey et al., 2015; Rodell et al., 2009; Taylor et al., 2013; Wada et al., 2010, 2012), their cultural diversity (grid-group positions) (FAO, 2016; Margat and Van der Gun, 2013), and the varying size of the populations involved (Fig. 4). Notably, these three areas are also at different stages of implementing groundwater regulations. Australia has instituted a system of water licences and seasonal allocations in the Murray–Darling Basin under state and federal water legislation (e.g. the Water Act of 2007); India's National Water Policies are still several years away from implementation and enforcement (Subhadra, 2015); while California has enacted the Sustainable Groundwater Management Act (2014), but only recently formed multiple localised groundwater sustainability agencies.

Fig. 4 shows the configuration of a typical farming setting for the three case studies based on satellite imagery, and its conceptualisation in the Groundwater Commons Game. We see from this figure a high density of fields and farms in the Punjab in comparison to farmers in the Murray–Darling Basin, with the California Valley showing an intermediate situation. Specific agro-economic data defining these case studies (e.g. water demands, crop yields, revenues, costs of irrigation, etc.) are presented in the model documentation found in the Groundwater Commons Game OpenABM repository (https://www.openabm.org/model/5634/).

2.8. Analysis approach

Simulation experiments were designed as follows:

- After initialising each of the 4 groundwater models, 100 simulations for the coupled socio-hydrologic system were run for each for a period of 100 years. The simulation period was split into two management periods of equal length. The first 50 years (t_0–t_{50}) correspond to a period of minimal management (M = 10%, F = 10%, i.e. 10% of groundwater users monitored and 10% of profits used to pay fines), whereas the following 50 years (t_{50}–t_{100}) represent the transition to the second management period where more stringent groundwater policies are introduced. Allocations were arbitrarily set at 20% of the water that agents need to irrigate their entire area with crops under optimal conditions. This simulates a water limited system in which tighter groundwater management is needed to avoid depletion. Agents that comply with the allocations proportionally cut back on their irrigated acreage (i.e., 20% allocation means they are only allowed to irrigate 20% of the land). This assumes that there is no capacity for farmers to improve the efficiency of their irrigation. Agents that extract water illegally choose to cultivate a larger proportion of land (e.g., an agent with $B = 0.8$ that decides to extract water illegally will irrigate 20% + 0.8 × 80% of land). The decision to irrigate beyond the allocated limit carries a risk of being reported by other agents and receiving a fine by the water authority.
- We considered an arbitrarily maximum monitoring capacity of M = 50% because it is currently unlikely that any water authority will be able to monitor all of the water users present in any catchment. Based on preliminary tests, the four permutations of enforcement powers (m = 10%, M = 50%; f = 10%, F = 90%) chosen were deemed sufficient to map the overall response of the coupled socio-hydrologic system to these variables.
- Institutional parameters were held static over the second management period to isolate and examine the evolution of the internal temporal dynamics (e.g. changes in groundwater levels and farmer decisions) as opposed to the responses to external forces. Agro-economic parameters (e.g., crop price, yields, gross margins, price of electricity for pumping) were held constant at their long-term average for the same reason.
- The grid and group cultural dimensions were subdivided into 16 subclasses using 0.2 increments of grid and group values in the interval [0.2,0.8]. Using these subclasses, the four countries included in our case studies were parametrised as follows:
  - *Australia (Murray Darling Basin)*: Grid = 0.2, Group = 0.8
  - *USA (Central Valley)*: Grid = 0.4, Group = 0.4
  - *Pakistan (Punjab)*: Grid = 0.8, Group = 0.4
  - *India (Punjab)*: Grid = 0.8, Group = 0.6
- For each of the 16 grid-group subclasses, we initialised 100 independent simulations. In each simulation, individual agents were assigned a strategy (B,P) with each variable B and P drawn at random from a [0,1] uniform distribution. No correlation between B and P was assumed. A new seed was set for the random number generator in each simulation.
- For simplicity, and considering that each country would have internal variability of their grid and group scores, case studies were assigned to the closest of the 16 combinations within the grid-group cultural coordinates.

GCG simulations were run on a high-performance computer cluster, with more than 200,000 simulations computed for this analysis.

Simulation results are presented as time series, or trajectories, for specific variables of interest. We report the mean and 95% confidence intervals (CI) of 100 independent simulations at a given point in time. In line with our scientific aims, the main variable of analysis is compliance, defined as the % of agents from the total population that adhere to the groundwater management policy. Besides compliance, we simulated trajectories of four additional state variables: cumulative illegal extraction in GL/10^4 ha (for reference, 1 GL = one thousand million litres, or a volume of about 500 Olympic swimming pools), mean groundwater depletion (in metres below pre-development conditions), and mean boldness and punitiveness of the agent population (0–1). Cumulative illegal extraction trajectories represent the total groundwater storage gains from a specific management decision that would otherwise have been lost to water theft. Groundwater depletion trajectories represent the impact on groundwater conditions and quantify the economic costs of pumping groundwater from a deeper water table at different points in time. Boldness and punitiveness trajectories, when combined, illustrate the rate of growth or decay of social norms (strength of norm = SN = P - B).

Supplementary Fig. 2 shows a sample of time series outputs for one particular parameter set. This figure shows the variability of the simulated trajectories (pre- and post- management intervention), and the impact that more stringent regulation has on the trajectories as a function of time. It is clear from the different time series observed in Supplementary Fig. 2 that some degree of uncertainty is expected in the trajectories due to the stochastic nature of the simulations, which ultimately will impact the accuracy of the metric (mean) summarizing the results. We provide a measure of this uncertainty by showing the standard deviation of the ensemble of trajectories.

2.9. Management scenarios (MS)

Three types of interrelated management scenarios (regulatory measures, monitoring strategies, and active norm management strategies) were chosen for their relevance to groundwater management practice. Supplementary Table 1 provides a summary of the simulated policies, their justification, and the parameter values used.

2.9.1. MS 1: level of regulatory enforcement

We considered the following idealised management scenarios:

1 *mf (lax regulation; low fines and low monitoring):* baseline scenario, where monitoring and fines remain lax over the management period (both set to 10%). This scenario may represent limited political will and low funding, the presence of bribery, corrupt officials, or a scenario where agricultural expansion is promoted (Elshafei et al., 2014; Margat and Van der Gun, 2013).
2 *Mf (low fines and high monitoring):* monitoring can be increased up to 50%, but the economic and/or political context prevent water agencies from imposing onerous fines on illegal users (hence low fines), due to, e.g. push-back from regulated actors and lobby groups, or when reforms to water laws are not politically possible.
3 *mF (high fines and low monitoring):* legal frameworks are put in place to increase the severity of fines. A large proportion of gross margins from crop production ($F = 90\%$) is forgone to pay a fine when an agent is caught pumping groundwater illegally, but the water agency can only monitor 10% of resource users. This may be the case where institutions are dealing with a very large number of users and have limited operational funds.
4 *MF (full enforcement; high fines and high monitoring):* a large proportion of gross margins from crop production ($F = 90\%$) is forgone to pay a fine if an agent is caught pumping groundwater illegally, and the agency has sufficient resources to increase monitoring to 50%.

The definition of the **m** monitoring scenario is based on a survey conducted on water users of the Murray–Darling Basin (Castilla-Rho et al., 2017; Holley and Sinclair, 2015) where 15% of the respondents reported that the regulator conducted an inspection of their property and less than 5% of the respondents reported having experienced compliance or enforcement action by the regulator (hence $\mathbf{m} = 10\%$). Although the **M** scenario might seem comparatively high (50%), current use of real-time data acquisition technologies on water abstractions and the widespread availability of remote sensing products make such high monitoring rates feasible (Bastiaanssen et al., 2005; Holley and Sinclair, 2016).

2.9.2. MS 2: monitoring style

We speculate whether a reactive approach to monitoring and enforcement is actually the most effective way of promoting social norms. To answer this, we used the GCG to simulate the effect of a water authority that systematically investigates reports of alleged breaches, directing the available monitoring resources (time, staff) to audit the most frequently reported agents carrying out the largest water theft (in terms of volume) (Ayres and Braithwaite, 1992; Sparrow, 2011). Then, we compared these results with simulations where we assumed that, although agents submit reports on the offending farmer (agent) and the magnitude of the breach to the water authority, the water authority does not set any particular order in which compliance monitoring is carried out. We used the **MF** scenario for this analysis to demonstrate the difference between the two strategies under most stringent management practice.

2.9.3. MS 3: active norm management strategies

In a previous exercise (Castilla-Rho et al., 2017) we analysed the long-term (static) impact of a group of agents defined as rule-followers promoting a culture of compliance by example (i.e., dedicated citizens with fixed strategies $B = 0$, $P = 1$). Here, we build on that analysis to ascertain how rule-followers influence the temporal dynamics of social norms. We also expanded our analysis to investigate the extent to which rule-breakers can undermine compliance (i.e., a proportion of agents not willing to cooperate or report illegal extractions with a fixed strategy $B = 1$, $P = 0$, that is, opposite to rule-followers). To this end, we seeded different proportions of rule-followers and rule-breakers (0%, 10%, 20%, 40%) into our simulations (randomly in space).

We simulated the trajectories of the hydro-social system under a hypothetical, staged investment approach to address water theft in a system where 20% of the population has been identified as active rule-breakers. This approach represents the efforts of a water authority that, in addition to regulatory measures (monitoring and fines), invests, for example, in water stewardship, citizen education, community meetings, etc. to help legitimise regulatory measures and management policies.

Initially, we assumed that management resources are directed at dissuading rule-breakers (20%, 10% and 0% agents), and once this has been achieved, resources are allocated to engaging citizens to display and promote compliance by their good example (0%, 10% and 20% agents). The progression from 20% rule-breakers to 20% rule-followers notionally represents a stepwise increase in the allocation of management resources. To quantify the benefits that would accrue by implementing this staged approach, we selected baseline values for monitoring (**m,M**) and fines (**f,F**) that we believe are most representative of existing management frameworks (or that could be optimistically implemented) in each case study. For the Murray–Darling Basin and the Central Valley case studies we chose **MF** as a baseline scenario, whereas for Punjab (India and Pakistan), we chose **mF** as baseline scenario given the likely difficulties of monitoring such a large number of farmers.

3. Results

3.1. Enforcement: monitoring and fines (MS1)

Fig. 5a–d summarise the transient response of our simulated coupled hydro-social systems over a management period of 50 years, for each of the case studies and across four enforcement scenarios (**mf, Mf, mF, MF**, see Section 2). Our simulations show that increasing monitoring alone (**Mf**) (i.e. increasing the number of farmers inspected) does not lead to substantial increases in compliance compared to lax regulation (**mf**) (Fig. 5, top row). This result emphasises the complementarity of monitoring and penalties: monitoring that is not backed up by legal frameworks enabling the issuing of strict and substantial monetary fines is not effective, even when the cultural context is favourable (such as in hierarchical societies). For the remaining scenarios (**mF** and **MF**), we find important differences in the way trajectories evolve and their endpoint values.

Hydro-social trajectories evolve in two stages (Fig. 5, top row): an initial stage of rapid response to regulation (*primary response*), followed by a second stage where trajectories gradually slow down towards the endpoint value (*secondary response*). Trajectories having a rapid primary response and a long secondary response (i.e., concave) are most desirable from a management perspective, meaning that compliance emerges rapidly and persists thereafter. The patterns observed in Fig. 5, and based on previous steady-state analyses (Castilla-Rho et al., 2017), suggest that the location of the endpoint value, specifically whether above or below the tipping points (notionally defined here as the region between 40 and 60% compliance), configures the primary and secondary responses and their variability. When the endpoint value is below the tipping point, the secondary response exhibits a relatively slow progression towards that endpoint value (slope ~ 0, Fig. 5a–c). When the endpoint value is above the tipping points (e.g., Fig. 5c–d; **MF**) and beyond the primary response, trajectories exhibit a more rapid increase in compliance. If the regulatory and/or cultural conditions are favourable—for instance, within a hierarchist society subject to comprehensive monitoring and fines—the secondary response becomes nonlinear in time (Fig. 5c–d, noting the difference between India and Pakistan under **MF**). Further, trajectories become more variable and uncertain as the system comes close to or crosses its tipping points (Fig. 5a–c–d, noting the widening of confidence intervals as trajectories approach or cross $\sim 50\%$ compliance). This increase in variance—commonly referred to as "flickering"—is often seen in many

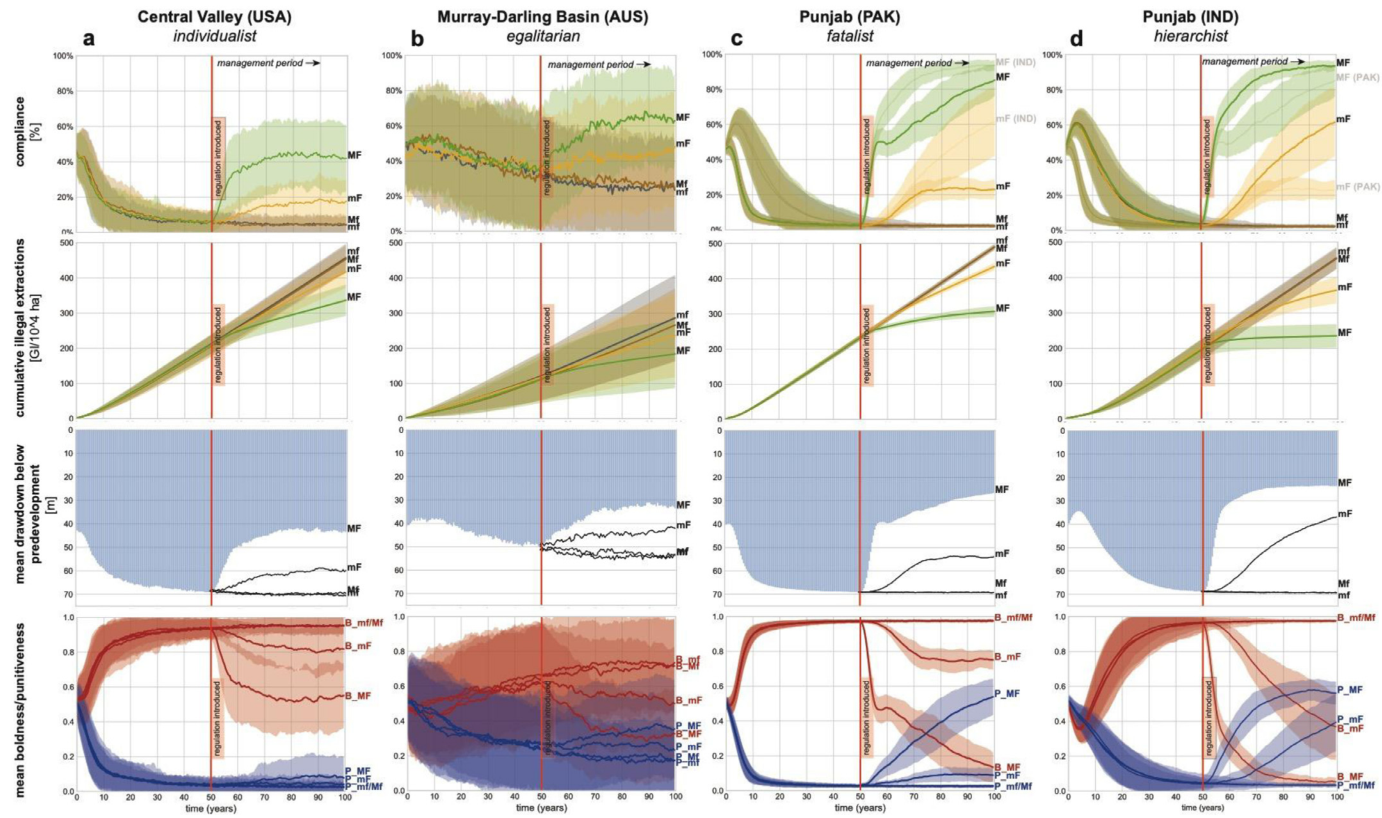

Fig. 5. Hydro-social trajectories in response to monitoring (m, M) and enforcement (f, F) scenarios; (row 1) compliance rates [%]; (row 2) cumulative illegal extractions [GL/10^4ha]; (row 3) mean drawdown below pre-development conditions [m]; (row 4) mean boldness and punitiveness of the agent population. Confidence intervals correspond to the standard deviation of an ensemble of 100 independent simulations.

socio-environmental systems as they approach tipping points (Scheffer, 2009; Scheffer et al., 2009; 2012). This phenomenon is not clearly observed in the Murray–Darling simulations, where trajectories are mainly driven by *group size* effects, as will be discussed in more detail below.

Cultural values and group size play a crucial role in shaping the rate of change and progression of hydro-social trajectories. The California Central Valley (USA) is an example where individualistic values (Fig. 2) will make farmers less likely to comply and where groundwater depletion is most difficult to avert (Fig. 5a). Over a 50-year management period, full enforcement (**MF**) reclaims approximately 100 GL/10^4 ha of otherwise illegally extracted groundwater and recovers about 30 m of groundwater depletion (Fig. 5a, third row). Strict fines accompanied by low monitoring (**mF**) would only reclaim about 25 GL/10^4 ha and recover 10 m of groundwater depletion. Although social norms do not emerge in either case (for **mF** and **MF**, punitiveness trajectories track below boldness), it is important to note how compliance trajectories are driven by a decrease in boldness and that the punitiveness of agents is subdued (Fig. 5a, fourth row). This shows how social sanctioning can remain largely inhibited in societies that are more tolerant towards nonconformity, that is, where the willingness to comply (economic cost of adopting a lower boldness) is greater than the willingness to sanction illegal behaviour (social cost of adopting a higher punitiveness).

Water users in the Murray–Darling (Australia) hold egalitarian values (see Fig. 2) meaning they are most tolerant towards non-compliance when compared to other nations. Egalitarians are also unique in that reputation is a primary driver of social interaction. Based on agricultural statistics (FAOSTAT, www.fao.org/faostat/), we simulated a farmer population that was one- and two orders of magnitude less than in the Central Valley and Punjab, respectively (Fig. 2d). Our results indicate that management trajectories tend to be unstable and have greater inertia where resource users are few and far between. This is made apparent by the wide confidence intervals and minor changes in compliance, illegal extraction, and groundwater depletion trajectories, which contrasts with the other case studies (Fig. 5a–d). Although the volumetric gains from comprehensive management in the Murray–-Darling are similar to that in the Central Valley (**MF** reclaims approximately 100 GL/10^4 ha of illegal groundwater from the baseline scenario **mf** in both cases**)**, the amount of groundwater depletion that can be avoided is substantially different (30 m in the Murray–Darling vs. 20 m in the Central Valley). This is due to the higher volume of water theft incurred by larger farms and the slower feedback between pumping rates and the costs of pumping for neighbouring farmers in the Murray–Darling case. As in the Central Valley, the activation of norms is primarily due to a decrease in boldness, rather than an increase in punitiveness of farmers (Fig. 5b, fourth row).

The Punjab case study allows us to compare the pure effect of differences between fatalist and hierarchist values without group size as a confounding factor. For the Punjab simulations, the hydro-social system represents a highly connected network of farmers with smaller land holdings (Fig. 4). Such tight systems provide resistance to societal change until the tipping points are crossed and where the decisions of all agents shift in synchrony (Scheffer et al., 2012). This is consistent with the dynamics that emerge in our simulations (Fig. 5c–d). Our results further suggest that communities in the Punjab could embark on sustainable management trajectories (e.g., compliance >50%) within the first decade of management. Under full enforcement (**MF**), these hydro-social systems could cross social tipping points, propelling compliance to almost 90% within 20 years of management. Overall, the temporal dynamics of hydro-social trajectories in fatalist or hierarchist societies (India and Pakistan) stand in stark contrast to those in individualist or egalitarian societies (USA and Australia) where compliance stabilises at 40–60% compliance after 20 years (Fig. 5a–b).

The Punjab case study also allows us to explore the trajectories that would unfold in a shared aquifer, on either side of cultural and political boundaries. Pakistan and India are predominantly fatalist and hierarchist societies, respectively (Fig. 4). Our simulations show that these cultural differences only become apparent after 5 years of management. Under comprehensive management (**MF**), both India and Pakistan follow the same primary response trajectory towards 50% compliance by year 5. Beyond this point, the two trajectories diverge. The most cooperative society (India) exhibits a nonlinear secondary response with a rapid but progressively declining rate of change towards the endpoint value of compliance (~90%, 30 years after management is introduced). In Pakistan, however, the secondary response is linear (Fig. 5c). Under the same management provisions (**MF**), and after 20 years of management, the compliance trajectory of Pakistan (~60%) lags 15 years behind India. From a management perspective, the gap between trajectories followed by India and Pakistan translates to the water authority in Pakistan reclaiming (i.e., preventing people from taking) 25% less illegal groundwater than its Indian counterpart. Although groundwater depletion recovered by the end of the management is almost identical for both nations, the temporal dynamics are very different. This means that the cost of pumping groundwater (all other things equal) is greater for Pakistani farmers (Fig. 5c–d, third row). Without comprehensive monitoring (**mF**)—the most likely case—the two nations follow similar trajectories for over a decade, with contrasting dynamics onwards. In Pakistan, the secondary response of compliance plateaus at 20%, whereas in India there is a steady rise to an endpoint value of about 60% (Fig. 5d). As a result, the Pakistani water authority reclaims 10% less illegal groundwater (Fig. 5c–d, second row) and recovers 15 m less groundwater depletion that the Indian water authority (Fig. 5c–d, third row).

In the Punjab, boldness and punitiveness trajectories (Fig. 5c–d, fourth row) offer insight on how government regulation and cultural values may create conditions for social norms ($\mathbf{SN = P - B}$) and the social sanctioning that supports them **(P),** to thrive **(i.e.,** $\mathbf{SN >> 0}$**).** Although establishing a cause-effect relationship between boldness and punitiveness is challenging(Namatame and Chen, 2016), we hypothesise that it is the social sanctioning of agents that drives the dynamics of the hydro-social system. When a critical mass of agents report water theft in a concerted manner, the following feedback loop is strengthened: illegal extractions are consistently audited, monetary fines are imposed, non-compliance is discouraged, groundwater depletion is prevented, economic profits from crop production are boosted, compliance spreads, and so on. This feedback loop may be strengthened until the point where social norms become internalised (high P and low B become de-facto strategies), propelling the system past the tipping point (Fig. 5c–d). We also find that the rate of change of the population's punitiveness slows down as the rate of change in boldness approaches zero: agents shoulder the burden of reporting others (by increasing their punitiveness) only to the extent that it reduces the likelihood that others break the rules (boldness), or when there is nobody to punish anymore (Fig. 5c–d, fourth row).

3.2. *Monitoring style: targeted vs. random (MS2)*

Systematic, targeted monitoring of water users may have counterintuitive and unwanted effects on the rate at which water theft is detected and deterred (Fig. 6a–d). In all case studies, our simulations suggest that random monitoring (**MF_R**) is more effective at dissuading illegal behaviour than targeted monitoring (**MF_T**). The least difference between the two approaches is observed in the Murray–Darling (Fig. 6b), indicating that the net benefits of random monitoring may not be significant in this hydro-social context. In the Central Valley and Punjab, however, random monitoring makes trajectories more concave (Fig. 6a–c–d): the primary response is accelerated and the onset of the secondary response is advanced in time. In the Central Valley, random monitoring quadruples the primary rate of change and enters the secondary response approximately 15 years earlier (Fig. 6a). In India and Pakistan, the effect is even more significant (Fig. 6c–d). In Pakistan, the secondary response remains linear, whereas in India it becomes nonlinear, meaning that sustainability goals (e.g., illegal extractions close to nil) are achieved after 20 years of management. While the endpoint values of illegal extraction, groundwater depletion, boldness and punitiveness under random and targeted monitoring strategies in India and Pakistan are not markedly different, trajectories differ with significant potential water savings to be gained. This result has important implications for management. In India, for example, a steady-state analysis would have predicted similar outcomes from both monitoring approaches in terms of compliance (see Fig. 6d), whereas our transient analysis shows that the cumulative impacts are very different. This highlights the need for, and value of, using exploratory models like the Groundwater Commons Game to decide amongst possible management strategies. In the Central Valley under random monitoring, the boldness of agents decreases three times faster (i.e., the slope of the primary response), yet it bears no appreciable effect on the punitiveness of agents (Fig. 6a, fourth row). In India and Pakistan, the boldness of agents decreases six times faster, and there is a significant positive effect on social sanctioning.

To better understand and explain the difference between the targeted and random monitoring, we investigated the spatial and temporal evolution of our simulated hydro-social systems under these two strategies. Fig. 7a–b compare the spatial arrangement of farmers, their compliance decisions and monitoring events halfway through the management period (t_{75}). Results show areas where farmers engage in water theft and how effectively monitoring (field inspections) targets these events for the two strategies. From the analysis, it is clear that the random approach does better than a targeted monitoring plan (by breaking long and persistent clusters of black pixels; see Fig. 7c–j). A fundamental assumption of the GCG is that farmer strategies evolve through imitation of their most successful neighbours (Gotts and Polhill, 2009) (see Section 2). In this context, non-compliance foci can emerge and spread locally, but are partially contained by the punitive actions of those around the offending group. These clusters of illegal behaviour will be the focus of non-compliance investigations of an agency adopting a targeted approach (Fig. 7a). However, given the limited resources of any water agency means its staff cannot be everywhere at all times. As a result, vast areas become vulnerable to the emergence and spread of new clusters of illegal behaviour. A water authority that conducts random inspections will probably fail to detect a significant number of breaches, but it has the advantage of distributing its scarce monitoring resources more efficiently and effectively in space and in time. The systemic effect of this nuance is graphically and temporally portrayed in the bottom panels of Fig. 7 (c–f) which show temporal sequences of binary decisions between water theft (black) and compliance (white) prior to and during the management period. The binary sequences clearly show how random monitoring more effectively dissuades farmers from non-compliance (i.e. it tends to break long sequences of black pixels). Temporally, targeted monitoring takes approximately 40 years to dissuade non-cooperative strategies from the population in the Indian Punjab (Fig. 7f). In the Pakistani Punjab and Central Valley non-cooperative strategies are discouraged but never fully eliminated (Fig. 7c–e), whereas in the Murray–Darling the effect is marginal (Fig. 4d). In all four cases, albeit to varying degrees, random monitoring inhibits the formation and spread of non-cooperative norms (Fig. 7g–h–i–j) better than targeted monitoring (Fig. 7c–d–e–f). Growing evidence from other research on human behaviour has also demonstrated that curtailing active policing can reduce illegal behaviour(Sullivan and O'Keeffe, 2017). There are indeed practical disadvantages that come with adopting random inspections: they might leave environmentally-sensitive areas at risk. Hence, random monitoring should be ideally combined with targeted monitoring near groundwater-dependant ecosystems or other vulnerable assets.

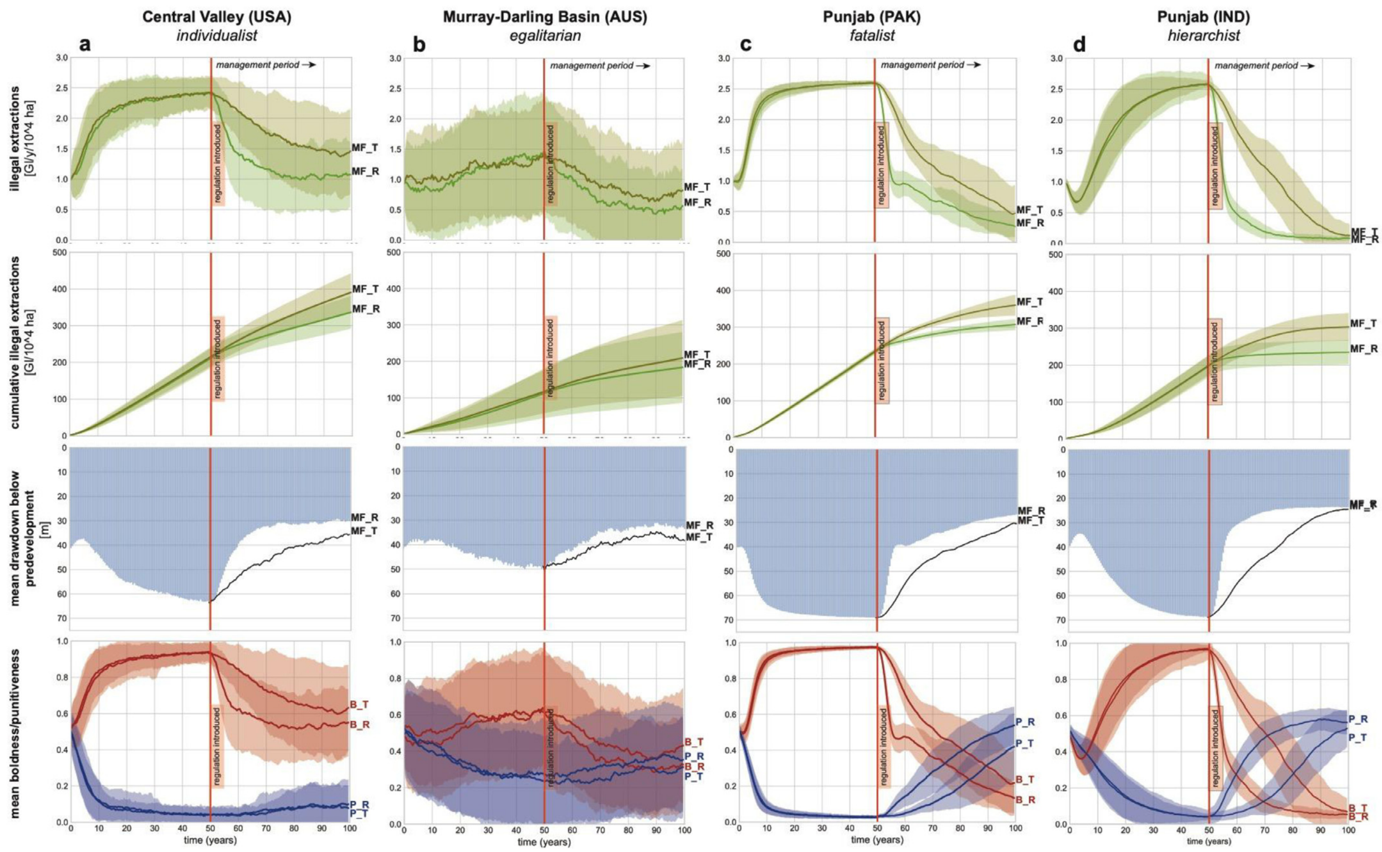

Fig. 6. Hydro-social trajectories in response to targeted (T) and random (R) monitoring strategies. (row 1) annual illegal extraction [GL/10^4ha/year]; (row 2) cumulative illegal extractions [GL/10^4ha]; (row 3) mean drawdown below pre-development conditions [m]; (row 4) mean boldness and punitiveness of the agent population. Confidence intervals correspond to the standard deviation of an ensemble of 100 independent simulations.

3.3. Active norm management: rule followers and rule breakers (MS3)

Finally, we investigated the impacts of individual groups of farmers either promoting or obstructing the consolidation of a social norm of compliance on achieving and maintaining sustainable management trajectories (see Section 2). Fig. 8 shows the impacts of deterring rule-breakers and engaging rule-followers on trajectories that describe the evolution of social norms. Beyond the point where rule-breakers are identified and dissuaded, engaging a minority of rule-followers exerts a strong, positive, nonlinear effect in the rate of change and the activation of a norm (i.e., SN = P − B > 0).

Efforts to deter rule-breakers yield the lowest improvement in compliance in The Central Valley (an individualist society) and Pakistan (a fatalist society) (Fig. 8a). The Murray–Darling (an egalitarian society) offers a slightly more favourable cultural context than the Central Valley due to the greater importance that individuals assign to reputation (Fig. 8b). Based on the steeper slope of their primary responses, the Pakistani and Indian Punjab present the most favourable conditions to foster compliance once engagement of rule-followers is activated (Fig. 8c–d). There are however important differences in the outcomes that could be achieved by deterring rule-breakers in each nation. In Pakistan (a fatalist society), the effect on the primary rate of change and the endpoint value of the social norm strength (SN) is minimal, whereas in India (a hierarchist society) the primary rate of change is 1.5 and 2.0 times faster for a 10% and 20% decrease in rule-breakers, respectively.

Both India and Pakistan may accelerate their trajectories towards sustainable groundwater use by moving past the point of targeting rule-breakers and investing in building a critical mass of rule-followers. Our simulations show that engaging 10% rule-followers is sufficient to propel the primary response to a social norm of about +0.75 over a period of 10 and 15 years in India and Pakistan, respectively. The more hierarchical trait of India helps stabilise social norms throughout the management period, whereas in Pakistan the fatalist trait leads to a secondary response where norms gradually weaken towards a social norm endpoint of about +0.55. Investing additional resources (i.e., from 10% to 20% rule-followers) does not yield substantial improvements in compliance, although it stabilises norms in Pakistan, and shortens the duration of the primary response by about 5 years in both cases. Designing management scenarios which include strategies of how to engage and promote rule followers may thus lead to more rapid attainment of sustainability goals, however, as we have shown here, successful strategies require consideration and understanding of the cultural context in which they will be implemented.

4. Discussion and conclusions

Although our conceptual but empirically-grounded model and its findings can lead to general policy recommendations, they are unlikely to be universally prescriptive. What is likely, however, is that the numerous actions and activities needed to deliver on groundwater objectives will need to include bottom-up approaches where management decisions are designed and implemented by local water authorities (Ostrom, 1990; Poteete et al., 2010). In order to effectively resolve conflicts between groundwater users, and to identify, reduce or eliminate threats to groundwater sustainability, authorities need modelling tools dynamically coupling social, economic, environmental and physical dimensions that will assist in making more proactive, strategic, and evidence-based management decisions. As such, our framework can help design and amend groundwater management programmes, foster more effective use of funds and allocation of staff to enforcement and compliance activities, and synthesise interdisciplinary knowledge on a

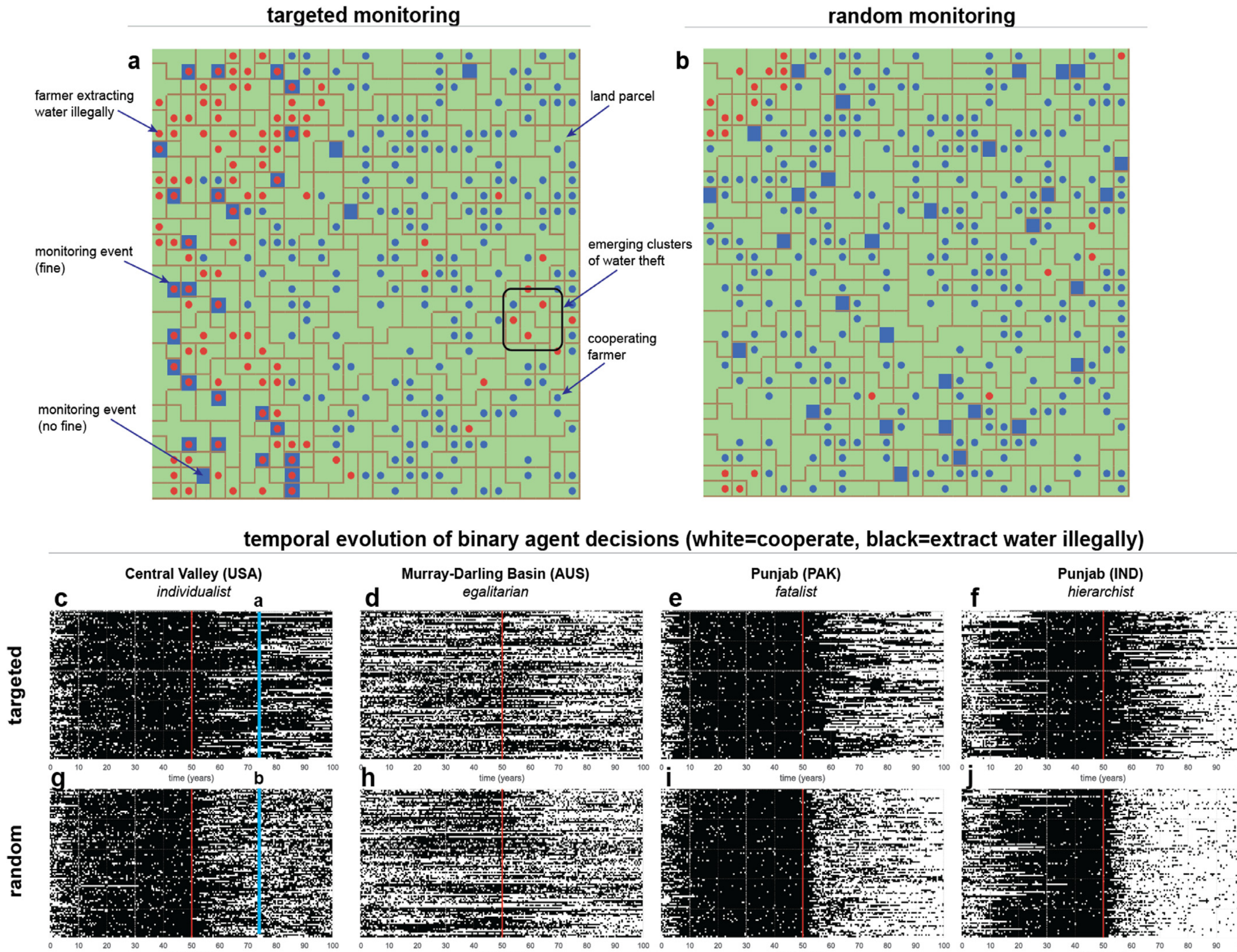

Fig. 7. Spatial and temporal compliance dynamics resulting from targeted and random inspections. Panels (a) and (b) illustrate the spatial distribution of illegal (red dots) and compliant (blue dots) behaviour and inspections (blue squares) for the Central Valley case study after 25 years of management (blue line panels c and g) under the MF scenario. Bottom panels show the temporal sequence of decisions—compliance (white pixels) and noncompliance (black pixels)—for a single agent chosen at random for each of the 100 simulations (i.e., each row in panels c-j correspond to a randomly-sampled agent from the ensemble). To remove sampling bias, we selected, randomly in space, one farmer in each independent simulation and subsequently stacked the binary decision sequences from the 100 simulations on top of each other (i.e. the y-axis represents 100 independent farmers). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

hitherto unprecedented level of analysis.

This study fills an important gap in our ability to evaluate the effectiveness of groundwater management policies, and to forecast the celerity and timing of trajectories towards sustainable groundwater use at the inter-decadal scale. For instance, visualisations of policy landscapes such as the one shown in Fig. 9 can help nations identify the most pertinent management options under current institutional, political, social, cultural and/or funding constraints. Such visualisations may readily support *adaptive decisions*, by enabling water authorities to establish concrete objectives for the next decade and periodically forecast (e.g. every year) whether sustainability targets are likely to be met and make adjustments as necessary. Water authorities may set very specific objectives (e.g., >50% compliance within 10 years of management, blue line in first column of Fig. 9) and subsequently identify and test alternative satisfactory solutions (i.e., scenarios below the blue line) in light of the uncertainty of possible outcomes (Fig. 9, second column). Importantly, policy landscapes like those portrayed in Fig. 9 support the implementation of leading edge environmental management paradigms such as *exploratory modelling* (Bankes, 1993), *adaptive management* (Pahl-Wostl, 2007) and *dynamic adaptive policy pathways* (Haasnoot et al., 2013). Given the baseline conditions and management options considered here, the bottom-line is that major cultural shifts, financial resources and regulatory efforts are required to avoid falling short of meeting targets for groundwater objectives (Holley and Sinclair, 2012; Robertson, 2013). Strategies leading to rapid compliance with groundwater management will strengthen institutions, save large quantities of groundwater, enhance economic growth and reduce poverty in developing countries, and prevent or minimise impacts on water sensitive ecosystems. Finally, our framework can be adapted to support strategic decisions on sustainability targets that rely on the monitoring, enforcement, and compliance of environmental regulations.

Our conceptualisation and analysis of groundwater management trajectories may be improved and expanded in a number of directions. Since this paper focuses on the temporal dynamics the frequency of decision making is crucial. How does the frequency in which farmers update their decisions (assumed as yearly in this study) shape the temporal evolution of management trajectories? For instance, would a

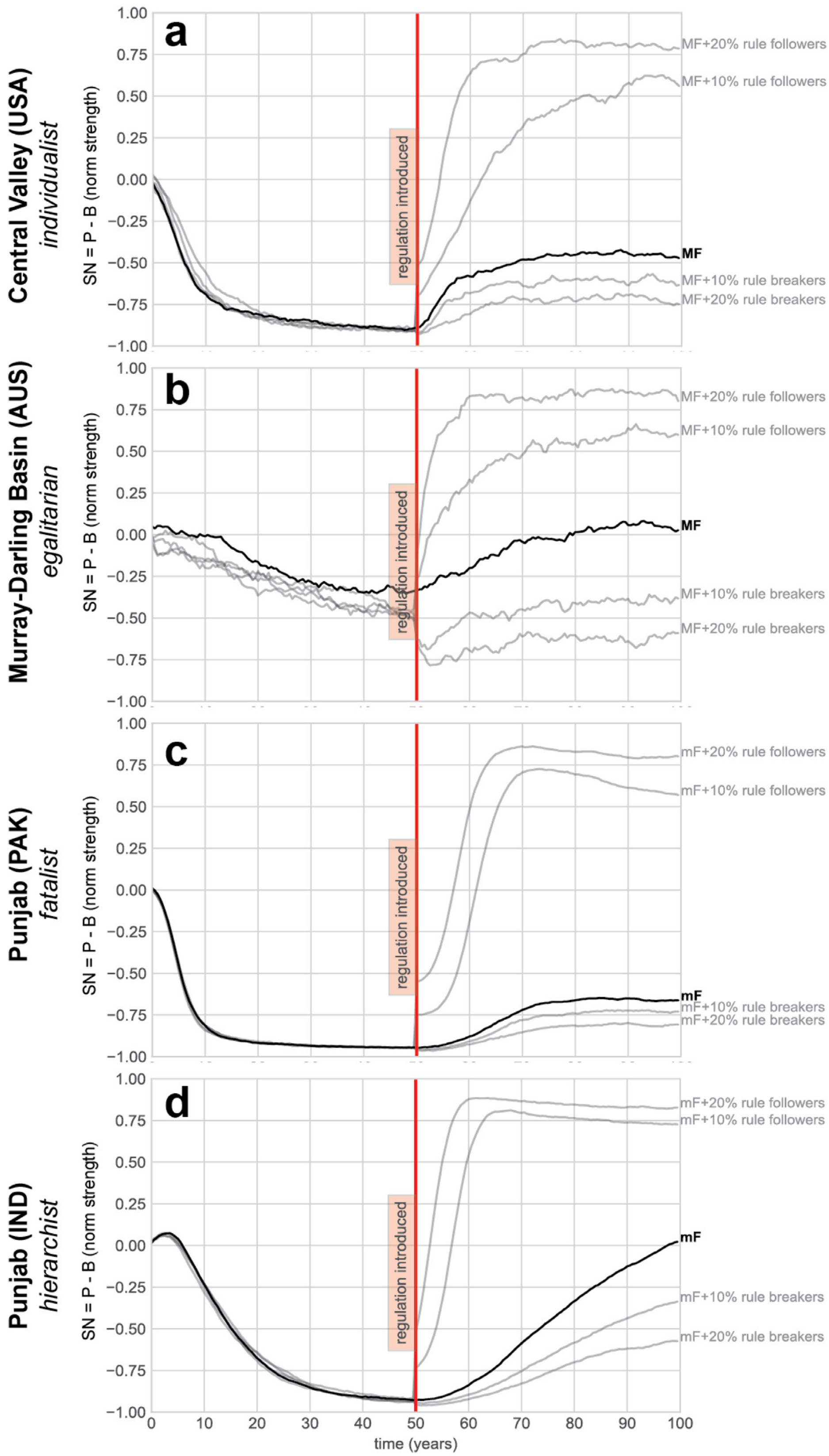

Fig. 8. Strength of social norms (SN = P − B) under progressive efforts to deter rule-breakers (20–0%) and engage rule-followers (0–20%). Results are shown for the most likely management strategy for each case study.

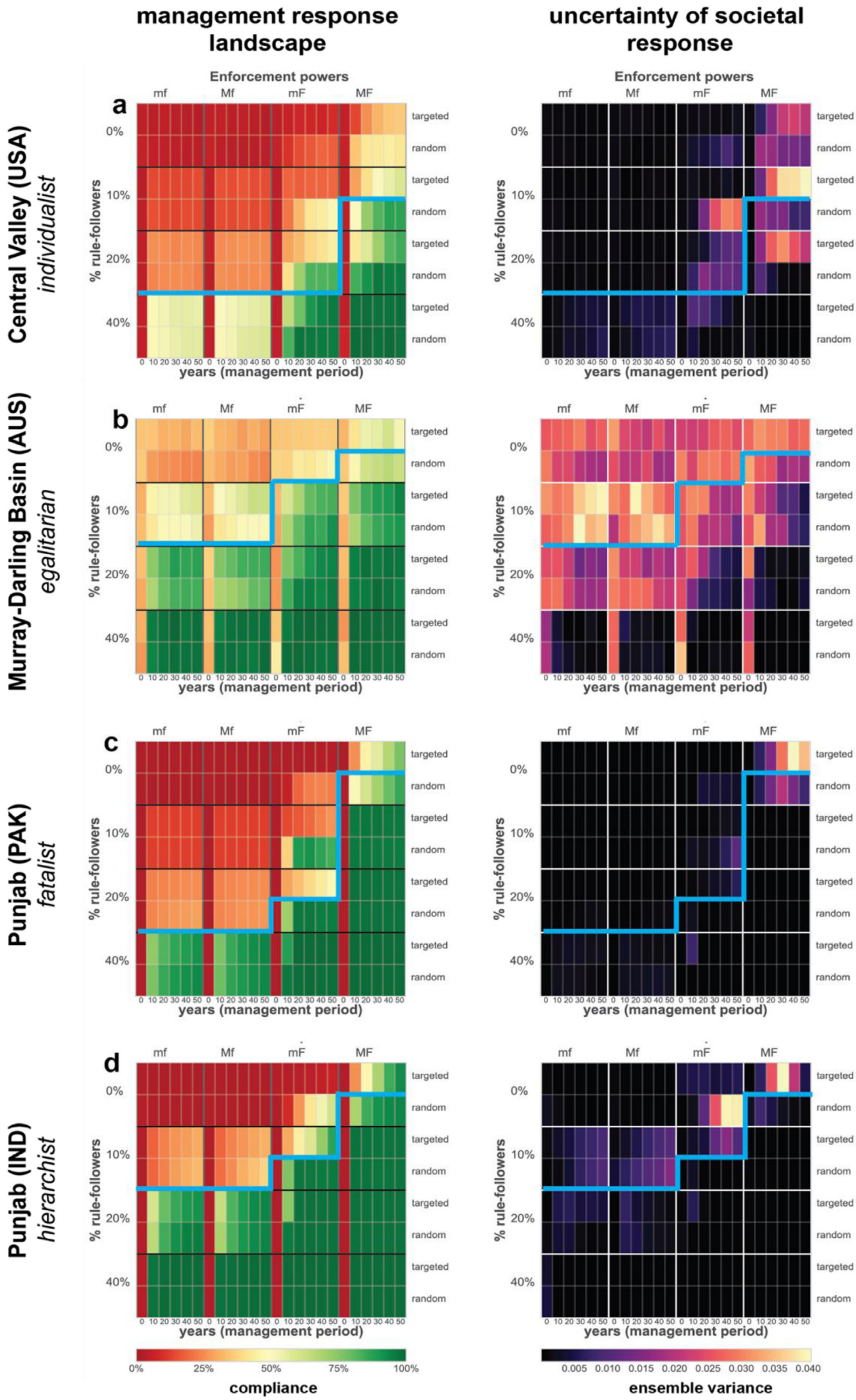

Fig. 9. Management response landscapes of hydro-social temporal dynamics derived from the Groundwater Commons Game.

doubling in frequency halve the time to compliance? or are there non-linear effects to consider? Future research should explore these sensitivities based on empirical data on decision making in different agro-economic contexts. Further experimentation with the GCG should also explore whether specific hydrogeological settings might be more conducive to priming/inhibiting sustainable groundwater use and establish whether specific areas within groundwater basins (e.g. areas prone to larger drawdown) are more likely to develop clusters of water theft. This will require coupling the GCG with more complex groundwater models that incorporate hydrogeological heterogeneity and water quality issues. Other behavioural models (Hofstede, 2003; Poncela-Casasnovas et al., 2016; Schwartz, 2006) could also be incorporated and compared with the four cultural typologies presented here. Linking to the global dimension of groundwater sustainability, our framework could be integrated with agro-economic and macro-scale hydrological datasets to quantify potential couplings and sensitivities to global food security risks (Dalin et al., 2017).

5. Code availability

An updated and fully documented implementation of the Groundwater Commons Game is available to download from the GitHub repository (https://github.com/juancastilla/Groundwater_Commons_Game). Agent-based simulations were conducted in NetLogo. R and Python code developed for statistical analysis and data analysis, and the ODD + D model documentation are also included in the Github repository.

CRediT authorship contribution statement

J.C. Castilla-Rho: Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **R. Rojas:** Formal analysis, Methodology, Supervision, Visualization, Writing - review & editing. **M.S. Andersen:** Methodology, Supervision, Writing - review & editing. **C. Holley:** Funding acquisition, Investigation, Supervision, Validation, Writing - review & editing. **G. Mariethoz:** Methodology, Supervision, Writing - review & editing.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2019.101972.

References

Aeschbach-Hertig, W., Gleeson, T., 2012. Regional strategies for the accelerating global problem of groundwater depletion. Nat. Geosci. 5 (12), 853–861. http://doi.org/10.1038/ngeo1617.

Axelrod, R., 1986. An evolutionary approach to norms. Am. Polit. Sci. Rev. 80 (04), 1095–1111.

Axelrod, R.M., 1997. The Complexity of Cooperation: Agent-Based Models of Competition and Collaboration. Princeton University Press.

Axelrod, R., Hamilton, W., 1981. The evolution of cooperation. Science 211 (4489), 1390–1396. http://doi.org/10.1126/science.7466396.

Ayres, I., Braithwaite, J., 1992. Responsive Regulation: Transcending the Deregulation Debate. Oxford University Press.

Bankes, S., 1993. Exploratory modeling for policy analysis. Oper. Res. 41 (3), 435–449. http://doi.org/10.1287/opre.41.3.435.

Bastiaanssen, W., Noordman, E., Pelgrum, H., Davids, G., Thoreson, B.P., Allen, R.G., 2005. SEBAL model with remotely sensed data to improve water-resources management under actual field conditions. J. Irrigation Drain. Eng. 131 (1), 85–93.

Castilla-Rho, J.C., Mariethoz, G., Rojas, R., 2015. An agent-based platform for simulating complex human–aquifer interactions in managed groundwater systems. Modell. Softw. http://doi.org/10.1016/j.envsoft.2015.08.018.

Castilla-Rho, J.C., Rojas, R., Andersen, M.S., Holley, C., Mariethoz, G., 2017. Social tipping points in global groundwater management. Nat. Hum. Behav. 1 (9), 640–649. http://doi.org/10.1038/s41562-017-0181-7.

Chai, S.-K., Liu, M., Kim, M.-S., 2009. Cultural comparisons of beliefs and values: applying the grid-group approach to the world values survey. Beliefs Values 1 (2), 193–208.

Dalin, C., Wada, Y., Kastner, T., Puma, M.J., 2017. Groundwater depletion embedded in international food trade. Nature 543 (7647), 700–704. http://doi.org/10.1038/nature21403.

de Vries, B.J.M., Petersen, A.C., 2009. Conceptualizing sustainable development. Ecol. Econ. 68 (4), 1006–1019. http://doi.org/10.1016/j.ecolecon.2008.11.015.

Elshafei, Y., Sivapalan, M., Tonts, M., Hipsey, M.R., 2014. A prototype framework for models of socio-hydrology: identification of key feedback loops and parameterisation approach. Hydrol. Earth Syst. Sci. 18 (6), 2141–2166.

Epstein, J.M., Axtell, R., 1996. Growing Artificial Societies: Social Science from the Bottom Up. The Brookings Institution.

Famiglietti, J.S., Lo, M., Ho, S.L., Bethune, J., Anderson, K.J., Syed, T.H., et al., 2011. Satellites measure recent rates of groundwater depletion in California's Central Valley. Geophys. Res. Lett. 38 (3) L03403–n/a. http://doi.org/10.1029/2010GL046442.

FAO, 2016. Global Diagnostic of Groundwater Governance — Thematic Papers. fao.org.

Farmer, J.D., 2009. The economy needs agent-based modelling. Nature.

Felbab-Brown, V., 2017. Water Theft and Water Smuggling: Growing Problem or Tempest in a Teapot? Brookings.

Gelcich, S., Edwards-Jones, G., Kaiser, M.J., Castilla, J.C., 2006. Co-management policy can reduce resilience in traditionally managed marine ecosystems. Ecosystems 9 (6), 951–966. http://doi.org/10.1007/s10021-005-0007-8.

Gigerenzer, G., 2007. Gut Feelings. Penguin.

Gigerenzer, G., Goldstein, D.G., 1996. Reasoning the fast and frugal way: models of bounded rationality. Psychol. Rev. 103 (4), 650–669. http://doi.org/10.1037/0033-295X.103.4.650.

Gleeson, T., Alley, W.M., Allen, D.M., Sophocleous, M.A., Zhou, Y., Taniguchi, M., VanderSteen, J., 2012a. Towards sustainable groundwater use: setting long-term goals, backcasting, and managing adaptively. Ground Water 50 (1), 19–26. http://doi.org/10.1111/j.1745-6584.2011.00825.x.

Gleeson, T., Wada, Y., Bierkens, M.F.P., van Beek, L.P.H., 2012b. Water balance of global aquifers revealed by groundwater footprint. Nature 488 (7410), 197–200. http://doi.org/10.1038/nature11295.

Gotts, N.M., & Polhill, J.G. (2009). When and how to imitate your neighbours: lLessons from and for FEARLUS.

Gotts, N.M., Polhill, J.G., Law, A.N.R., 2003. Agent-based simulation in the study of social dilemmas. Artif. Intell. Rev. 19 (1), 3–92. http://doi.org/10.1023/A:1022120928602.

Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., et al., 2006. A standard protocol for describing individual-based and agent-based models. Ecol. Modell. 198 (1–2), 115–126. http://doi.org/10.1016/j.ecolmodel.2006.04.023.

Grimm, V., Berger, U., DeAngelis, D.L., Polhill, J.G., Giske, J., Railsback, S.F., 2010. The odd protocol: a review and first update. Ecol. Modell. 221 (23), 2760–2768. http://doi.org/10.1016/j.ecolmodel.2010.08.019.

Haasnoot, M., Kwakkel, J.H., Walker, W.E., Maat,, ter J., 2013. Dynamic adaptive policy pathways: a method for crafting robust decisions for a deeply uncertain world. Global Environ. Change 23 (2), 485–498. http://doi.org/10.1016/j.gloenvcha.2012.12.006.

Hofstede, G., 2003. Culture's Consequences. SAGE Publications.

Holley, C., Sinclair, D., 2012. Compliance and enforcement of water licences in NSW: limitations in law, policy and institutions. Australas. J. Natl. Resour. Law Policy 15 (2), 149.

Holley, C., Sinclair, D., 2015. Water Extraction in NSW: Stakeholder Views and Experience of Compliance and Enforcement. National Centre for Groundwater Research and Training Connected Waters Initiative Research Centre UNSW Australia, pp. 1–88.

Holley, C., Sinclair, D., 2016. Regulation, technology, and water: buy-in as a precondition for effective real-time advanced monitoring, compliance, and enforcement. Geo. Wash. J. Energy Environ. Law, 7 (1), 52–293. http://doi.org/10.1146/annurev-lawsocsci-110615-084651.

INTERPOL-UNEP. (2016). *Strategic Report: Environment, Peace and Security – A convergence of Threats*.

Jones, J., & Andriamarovololona, M.M. (2008). The importance of taboos and social norms to conservation in Madagascar. *Conservation* ….

Keane, A., Jones, J.P.G., Edwards Jones, G., Milner Gulland, E.J., 2008. The sleeping policeman: understanding issues of enforcement and compliance in conservation. Anim. Conserv. 11 (2), 75–82. http://doi.org/10.1111/j.1469-1795.2008.00170.x.

Macal, C.M., 2016. Everything you need to know about agent-based modelling and simulation. J. Simul. 10 (2), 144–156. http://doi.org/10.1057/jos.2016.7.
Margat, J., Van der Gun, J., 2013. Groundwater Around the World. CRC Press.
Matthews, K., 2017. *Independent Investigation into NSW Water Management and Compliance*. industry.nsw.gov.au.
Müller, B., Bohn, F., Dreßler, G., Groeneveld, J., Klassert, C., Martin, R., et al., 2013. Describing human decisions in agent-based models – ODD + D, an extension of the odd protocol. Environ. Modell. Softw. 48, 37–48. http://doi.org/10.1016/j.envsoft.2013.06.003.
Namatame, A., & Chen, S.-.H. (2016). Agent based modelling and network dynamics.
Nyborg, K., Anderies, J.M., Dannenberg, A., Lindahl, T., Schill, C., Schlüter, M., et al., 2016. Social norms as solutions. Science (New York, NY) 354 (6308), 42–43. http://doi.org/10.1126/science.aaf8317.
Ostrom, E., 1990. Governing the Commons. Cambridge University Press.
Ostrom, E., Walker, J., 2005. Trust and Reciprocity. Russell Sage Foundation.
Pahl-Wostl, C., 2007. Transitions towards adaptive management of water facing climate and global change. Water Resour. Manag.
Poncela-Casasnovas, J., Gutierrez-Roig, M., Gracia-Lazaro, C., Vicens, J., Gomez-Gardenes, J., Perello, J., et al., 2016. Humans display a reduced set of consistent behavioral phenotypes in dyadic games. Sci. Adv. 2 (8) e1600451–e1600451. http://doi.org/10.1126/sciadv.1600451.
Poteete, A.R., Janssen, M., Ostrom, E., 2010. Working Together. Princeton University Press.
Richey, A.S., Thomas, B.F., Lo, M.H., Reager, J.T., Famiglietti, J.S., Voss, K., et al., 2015. Quantifying renewable groundwater stress with grace. Water Resour. Res. 51 (7), 5217–5238. http://doi.org/10.1002/2015WR017349.
Robertson, S., 2013. A regulatory framework for monitoring and enforcement of water access rights in Western Australia. UW Austl. L. Rev. 37, 215.
Rodell, M., Velicogna, I., Famiglietti, J.S., 2009. Satellite-based estimates of groundwater depletion in India. Nature 460 (7258), 999–1002. http://doi.org/10.1038/nature08238.
Rotmans, J., & de Vries, B. (1997). Perspectives on global change: tThe targets approach, 1–479.
Scheffer, M., 2009. Critical Transitions in Nature and Society. Princeton University Press.
Scheffer, M., Bascompte, J., Brock, W.A., Brovkin, V., Carpenter, S.R., Dakos, V., et al., 2009. Early-warning signals for critical transitions. Nat. News 461 (7260), 53–59. http://doi.org/10.1038/nature08227.
Scheffer, M., Carpenter, S.R., Lenton, T.M., Bascompte, J., Brock, W., Dakos, V., et al., 2012. Anticipating critical transitions. Science 338 (6105), 344–348. http://doi.org/10.1126/science.1225244.
Schwartz, S.H., 2006. A theory of cultural value orientations: explication and applications. Compar. Sociol. 5 (2), 137–182.
Shah, T., 2009. Climate change and groundwater: india's opportunities for mitigation and adaptation. Environ. Res. Lett. 4 (3), 035005. http://doi.org/10.1088/1748-9326/4/3/035005.
Shah, T., Roy, A.D., Qureshi, A.S., 2003. Sustaining Asia's groundwater boom: an overview of issues and evidence. Nat. Resour. Forum.
Simon, H.A., 1955. A behavioral model of rational choice. Q. J. Econ. 69 (1), 99–118. http://doi.org/10.2307/1884852.
Sparrow, M.K., 2011. The Regulatory Craft: Controlling Risks, Solving Problems, and Managing Compliance 12. Brookings Institution Press, pp. 649–667. http://doi.org/10.1080/13501760500160151.
Subhadra, B., 2015. Water: halt India's groundwater loss. Nature 521 (7552) 289–289. http://doi.org/10.1038/521289d.
Sullivan, C.M., O'Keeffe, Z.P., 2017. Evidence that curtailing proactive policing can reduce major crime. Nat. Hum. Behav. 1 (10), 730–737. http://doi.org/10.1038/s41562-017-0211-5.
Taylor, R.G., Scanlon, B., Döll, P., Rodell, M., van Beek, R., Wada, Y., et al., 2013. Ground water and climate change. Nat. Clim. Chang. 3 (4), 322–329. http://doi.org/10.1038/nclimate1744.
Theesfeld, I., 2010. Institutional challenges for National Groundwater Governance: policies and issues. Ground Water 48 (1), 131–142. http://doi.org/10.1111/j.1745-6584.2009.00624.x.
UN, 2016. UN High Level Panel on Water Action Plan.
Verweij, M. (2000). Transboundary environmental problems and cultural theory: the protection of the Rhine and the Great Lakes, 1–272.
Verweij, M., Senior, T.J., Domínguez D., J.F., Turner, R., 2015. Emotion, rationality, and decision-making: how to link affective and social neuroscience with social theory. Front. Neurosci. 9 (123), 169. http://doi.org/10.3389/fnins.2015.00332.
Wada, Y., van Beek, L.P.H., Bierkens, M.F.P., 2012. Nonsustainable groundwater sustaining irrigation: a global assessment. Water Resour. Res. 48 (4), W00L06. http://doi.org/10.1029/2011WR010562.
Wada, Y., van Beek, L.P., van Kempen, C.M., Reckman, J.W., Vasak, S., Bierkens, M.F., 2010. Global depletion of groundwater resources. Geophys. Res. Lett. 37 (20) L20402–n/a. http://doi.org/10.1029/2010GL044571.
Water Crimes, 2017. European Report on Water Crimes.
World Economic Forum, 2019. World Economic Forum: Global Risks Report 2019 2019. http://doi.org/10.1016/S1361-3723(19)30016-8.