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Social tipping points in global groundwater management

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Groundwater is critical to global food security, environmental flows, and millions of rural livelihoods in the face of climate change[1]. Although a third of Earth's largest groundwater basins are being depleted by irrigated agriculture[2], little is known about the conditions that lead resource users to comply with conservation policies. Here we developed an agent-based model[3,4] of irrigated agriculture rooted in principles of cooperation[5,6] and collective action[7] and grounded on the World Values Survey Wave 6 ($n = 90,350$). Simulations of three major aquifer systems facing unsustainable demands reveal tipping points where social norms towards groundwater conservation shift abruptly with small changes in cultural values and monitoring and enforcement provisions. These tipping points are amplified by group size and best invoked by engaging a minority of rule followers. Overall, we present a powerful tool for evaluating the contingency of regulatory compliance upon cultural, socioeconomic, institutional and physical conditions, and its susceptibility to change beyond thresholds. Managing these thresholds may help to avoid unsustainable groundwater development, reduce enforcement costs, better account for cultural diversity in transboundary aquifer management and increase community resilience to changes in regional climate. Although we focus on groundwater, our methods and findings apply broadly to other resource management issues.

Groundwater underpins humanity's resilience to water scarcity in a changing climate[1]. In the past decade, however, thousands of cubic kilometres of non-renewable groundwater storage have been lost to expanding irrigated agriculture in the world's major aquifers[2,8]. Engineering and economic solutions introduced to avert groundwater depletion have been insufficient to balance regional water budgets[2], whereas groundwater laws and policies can take several decades to fully implement, with no guarantees that resource users will adhere to them[9]. In developing nations, the challenge is particularly important, given the sheer number of users competing for the same limited resource. In these regions, farmers have few incentives to self-organize to secure future availability and monitoring individual pumping decisions is often logistically and practically impossible. Compliance with groundwater conservation policies is therefore essential to achieve socially acceptable, environmentally sustainable and economically viable exploitation of aquifers that supply water and food to billions of people[10].

In collective action problems such as these, human behaviour is deeply influenced by social norms[11]. This is especially clear in the case of water management, where norms have been a key ingredient to achieve long-term collaboration between water authorities and users[12,13]. Social norms are typically defined on the basis of expectations, values or behaviour. Because we are interested in the actual behaviour of resource users (whether they comply with rules or not), here we adopt the behavioural definition as described by Axelrod[6] "a norm exists in a given social setting to the extent that individuals usually act in a certain way and are often punished when seen not to be acting in this way". As yet, research on groundwater governance has focused mostly on the design of standard instruments (for example, monitoring, taxes, quotas, fines, and so on) for securing groundwater availability[10]. A remaining challenge is to understand how people behave in response to groundwater conservation instruments and how social norms supporting or hindering compliance emerge from the interactions of resource users.

Three policy-relevant questions arise: What is the relationship between monitoring and enforcement powers and the propensity of farmers to comply with pumping limits? What role do human behaviour, social norms and cultural values have here? And, in which countries is groundwater conservation more likely to succeed? To shed light on these questions, we devised the 'Groundwater Commons Game' (GCG)—an agent-based model[3,14] rooted in principles of evolutionary game theory[15]. The GCG focuses on contextual factors that have been identified as fundamental drivers of human cooperation[16,17] and collective action[7,18,19] in a wide range of settings, namely monitoring and enforcement powers, social norms and cultural values. Although there may be other factors that potentially have a role in shaping compliance (for example, groundwater dynamics, mental models, alternative production models), our exploratory modelling approach intentionally leaves out secondary dynamics to elucidate the essential causative processes that reproduce the emergent phenomenon of interest (compliance). The factors and mechanisms included in the GCG have a primary role in achieving community compliance as shown by empirical work in cooperation and human behaviour[5,20–22]. Exploratory models such as the GCG are particularly powerful for understanding coupled human–physical dynamics when there are many potential drivers and processes operating at different scales[23].

Our aim is to place groundwater conservation in the context of Ostrom's core ideas relating to the conditions under which resource users may cooperate to sustainably harvest a shared resource over long periods of time[7]. Much of the work in the Ostrom tradition, however, has focused on small communities in isolated areas with little direct government intervention[24]. By contrast, here we focused

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on how compliance can emerge in government-regulated systems. In many places (for example, The Murray–Darling Basin Plan in Australia, the Danube River Basin Management Plan in Europe, and the Sustainable Groundwater Management Act in California) regulation is the preferred option, and arguments are growing for increasing government oversight in response to water shortage (for example, the Indus Basin), including as a way to stimulate self-management[9].

Our agent-based 'artificial societies' provide a unique approach to unravel the social, economic and environmental complexities and nuances of the groundwater conservation problem, in ways that would be impossible with field studies[25]. The GCG simulates the interactions of computational agents[4] that mimic the behaviours of groundwater users in an attempt to 'grow' successful groundwater management outcomes in silico. The behavioural model of our agents builds on Axelrod's evolutionary approach to norms[6] and Gigerenzer's work on heuristics and rules of thumb in human decision making[21,26] (see Methods and overview, design concepts, details + decisions (ODD+D) model documentation in Supplementary Methods). Several mechanistic models of compliance and social norms have been developed in the context of tax evasion[27–29] and fisheries management[30,31], yet there has been little or no consideration in groundwater contexts. Here, we synthesize a growing body of knowledge on human behaviour, cooperation, and collective action to elucidate possible determinants and pathways to regulatory compliance in groundwater systems globally.

We endowed our agents with culturally varying parameters derived from, to our knowledge, the largest and most recent international study of human values and beliefs—the World Values Survey Wave 6 (WVS6) (http://www.worldvaluessurvey.org/wvs.jsp)—to understand how culture impacts groundwater conservation at a global scale. We classified nations surveyed in the WVS6 into four broad types of social organization—hierarchist, individualist, fatalist and egalitarian (co-existing with different degrees of dominance in every society)—using grid–group cultural theory[32] (also known as plural rationality theory[33]), a widely used framework in cultural anthropology (see Methods). It is important to clarify that the four categories proposed by cultural theory are heuristics that are meant to illuminate culture patterns at an aggregate level. These cultural groups are not bounded sets for which a single label can be placed, but may encompass characteristics of multiple cultures that further exhibit internal variation. These four rationalities or 'ways of life' are plotted on a graph with two axes (Fig. 1). The vertical 'grid' axis represents the extent to which tradition and moral values influence human behaviour. The horizontal 'group' axis represents the degree to which individuals understand themselves to be incorporated into and constrained by the community. In our model, the grid dimension is used to quantify an agent's tolerance towards non-compliant behaviour (high grid, less tolerant); whereas the group dimension is used to quantify how important it is for an agent to maintain a good reputation (high group, more important). Our agents, much like in the real world, have limited information about groundwater conditions and what others are doing, and they rely on social interactions and heuristics to deal with these uncertainties [21] (Fig. 2a and Supplementary Fig. 5).

To our knowledge, Fig.1 is the most up-to-date representation of grid–group positions of world countries based on the WVS. Qualitatively, these grid–group positions correspond to what one would expect from the ethnographic literature and socioeconomic, geographical, religious and ethnical correlations[34] (see Methods). Quantitatively, grid–group positions derived from the WVS can be statistically tested against data from empirical surveys (parametric, two-sample t-tests). To assess the robustness of our simulations, and lacking the 'ground truth' for every single country in the WVS, we compared GCG input and output data with a unique field survey of water licensees that we conducted across three jurisdictions of the Murray–Darling Basin[35] ($n=672$; see Methods, Supplementary Fig. 4 and Supplementary Table 2). Results for the Murray–Darling Basin based on WVS6 statistics were consistent (parametric t-test; $P<0.001$) with grid, group and compliance measured in the field, providing empirical support and validity to our analysis (see Methods). Fig. 1 has important implications for management of national and international groundwater basins, as it maps the relative arrangement of societal responses to regulation in aquifers, which cross 'intra-' and 'international' jurisdictions[9]. This information may improve the design of groundwater management plans across cultural borders.

Using the mean grid–group positions of Fig. 1, we parameterized GCG simulations for the Murray–Darling Basin (Australia), the California Central Valley (USA) and the Punjab (India and Pakistan)—three culturally diverse groundwater-dependent regions experiencing long-term depletion, where substantial irrigation water curtailments are needed to stabilize groundwater levels (see Methods). These examples are also broadly representative of the four 'ways of life' of cultural theory. For generality, we considered groundwater conservation policies in their most simple form: seasonal water allocations established on the basis of groundwater allocation plans, which are subsequently enforced through variable levels of monitoring (M) and fines (F). Such plans are used in many parts of the world to foster sustainable groundwater use and protect environmental flows (for example, the Murray–Darling Basin Plan in Australia, the Sustainable Groundwater Management Act in California, and the Danube River Basin Management Plan in Europe). Water allocation systems are often part of a multilevel governance framework, involving consultation and checks and balances in determining agreed levels of water abstraction[36]. Water authorities, however, only have the capacity and resources to monitor a fraction of resource users. Groundwater users may comply with the rules or extract groundwater illegally beyond the allocated limit. Users may also choose to report offending neighbours, or do nothing[37]. In this study, we have sought to obtain results representative of long-term system responses, that is, at the end of a 50-year management period (see ODD+D model documentation in Supplementary Methods). This alludes to the political, legal and economic challenges of implementing water regulations, which, once introduced, become very hard to adjust over time[9].

As shown in Fig. 2, each agent has a unique strategy (B, P), representing its attitude towards groundwater conservation at a given point in time. The 'boldness' dimension of an agent's strategy (B) is the probability that it takes water illegally during the current growing season. The 'punitiveness' dimension of an agent's strategy (P) (akin to the concept of 'vengefulness' in Axelrod's social norms game[6]) is the probability that it reports a neighbour that takes water illegally. In our simulations, strategies undergo an evolutionary process of selection[38], whereby agents use local information and a simple heuristic to decide what to do next: "imitate the strategy of whichever neighbour is doing best, exploit the current strategy if better, and explore a new strategy occasionally"[21]. In this evolutionary process, strategies are continuously being evaluated on the basis of the social and economic costs and benefits that they accrue to each agent. Furthermore, the behavioural definition of a social norm (SN) enables us to quantify its strength as $\mathrm{SN}=\mathrm{mean}(P)-\mathrm{mean}(B)$ (ref. [6]). For example, we can say that a social norm of compliance emerges[14] if the majority of agent strategies evolve to a cooperative state (B~0, P~1, SN~1). The opposite is true for non-compliance when the system state evolves to SN~−1. The chosen strategies trigger pumping decisions that establish a specific level of compliance and impact on the groundwater resource (the drawdown of the water table). Impacts on the groundwater resource then feed back into the social dynamics (the cost of pumping groundwater from a specific depth, see Fig. 2b) for subsequent agent decisions. The agent submodel is coupled to a spatially explicit groundwater-flow submodel that captures the effect of human behaviour on the hydrological system[25].

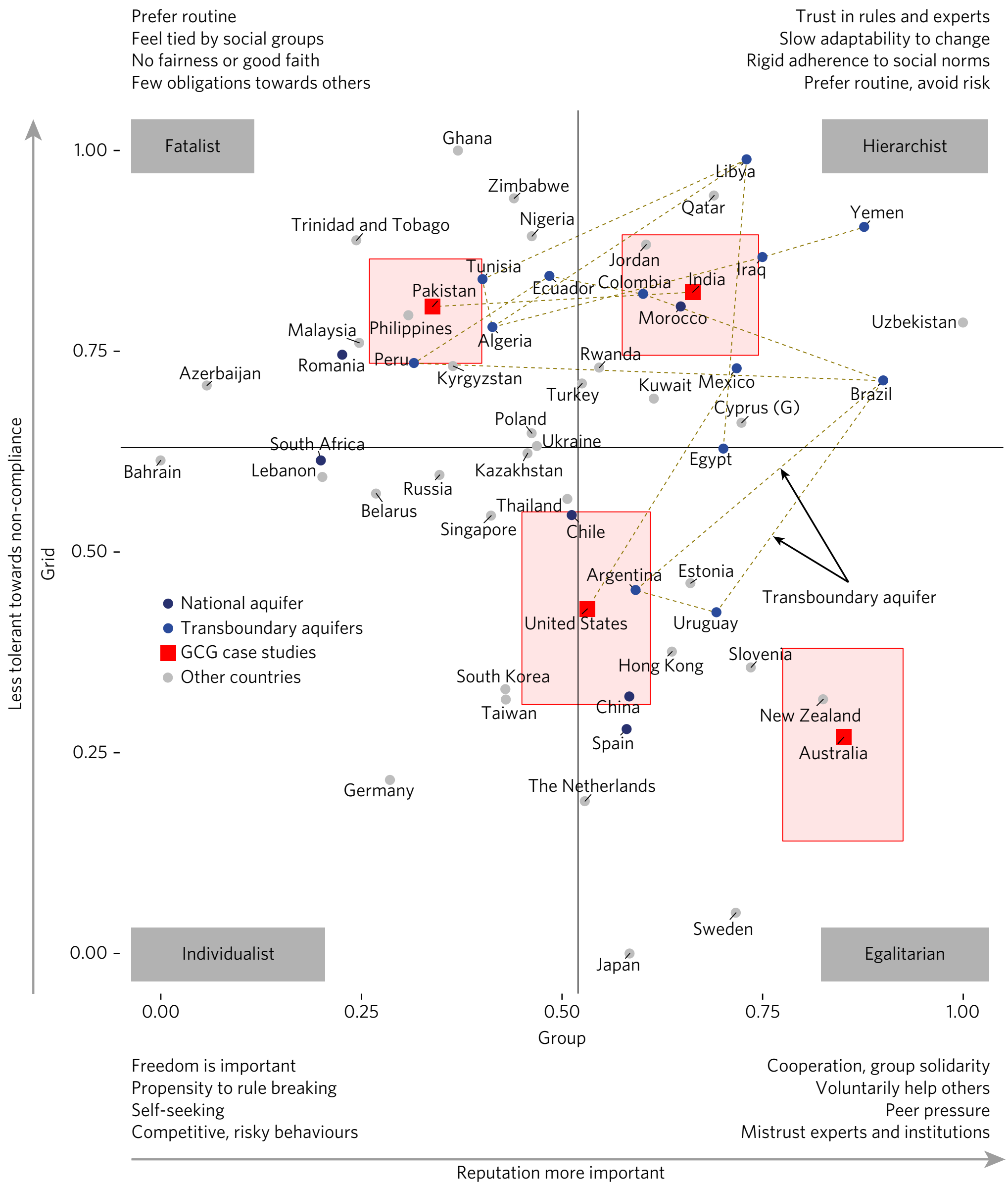

Fig. 1 | Grid–group positions based on the WVS6 reveal the relative positions of nations within the space of possible societal responses to groundwater regulation. Mean scores are shown for each country surveyed in the WVS6 (see Supplementary Fig. 1), normalized by the minimum and mean scores of the country cohort. Grid–group positions are shown for three case studies (red), and countries with transboundary (blue) and national (dark blue) aquifers of agricultural importance[2,8]. Other countries (grey) are presented to emphasize geographic, ethnographic and socioeconomic correlations. Shaded boxes indicate grid and group interquartile ranges, and represent the possible space of intra-national cultural variability in national transboundary aquifers. Dashed lines show major international transboundary aquifer relationships. The horizontal and vertical lines are the grid and group means for all countries surveyed in the WVS6.

Our simulations show that the pathways to groundwater conservation are controlled by tipping points, at which the degree of compliance becomes highly sensitive to cultural values (that is, grid–group positions in Fig. 3a–c) and enforcement powers (Supplementary Fig. 2). The tipping points can be characterized by 'steepness' (the gradient across the grid–group plane) and 'location' (its position within the grid–group plane), and they delineate the boundary between two alternative states of management: conservation and overuse (above and below 50% compliance). Within the socioecological system tradition, this sort of mapping provides valuable qualitative and quantitative insights to establish a system's resilience—that is, the distance to the tipping points[39]. This can be very useful for water authorities around the globe that are trying to determine the level of investment in monitoring and enforcement that is required to achieve stable and resilient groundwater conservation outcomes (that is, the dark-green regions in Figs. 3a–c, Fig. 4 and Supplementary Fig. 2).

Group position is a major factor controlling the steepness of tipping points. Countries scoring high in group—where reputation is an important social control[34]—exhibit much steeper tipping points than low-group countries (noting the narrowing of tipping points with increasing group position in Fig. 3a–c). Group size also influence the steepness of the tipping points. Small groups, where users tend to be more dispersed (farmers have few neighbours, see Supplementary Fig. 3), respond almost linearly across the grid–group plane and do not develop particularly high or low levels of compliance (Fig. 3a and Supplementary Fig. 2, Murray–Darling Basin). By contrast, in large groups, where

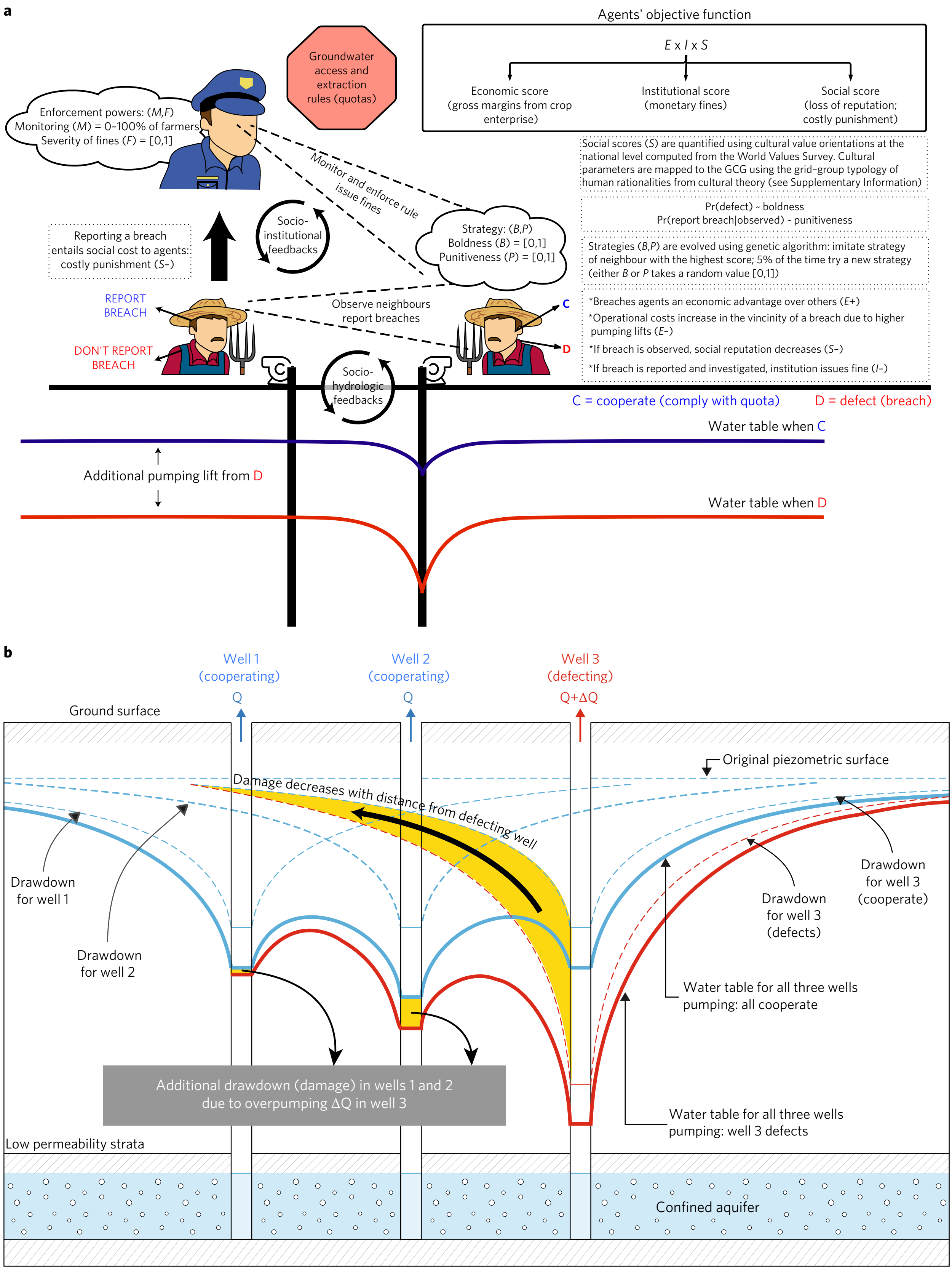

Fig. 2 | The Groundwater Commons Game. a, Farmer agents make pumping decisions based on their cultural values (grid and group position), groundwater conditions (cost of pumping groundwater to the surface), allocation limits and the local socioeconomic context (interactions with neighbours). Agents also choose whether to cooperate (pump the allocated volume as required by the water authority) or to defect (pump more than the allocation to increase profits). **b**, Feedbacks between human behaviour and groundwater availability. Illegal behaviour imposes higher economic costs to other agents, due to the widening, deepening and superposition of pumping cones of depression. Q, pumping rate.

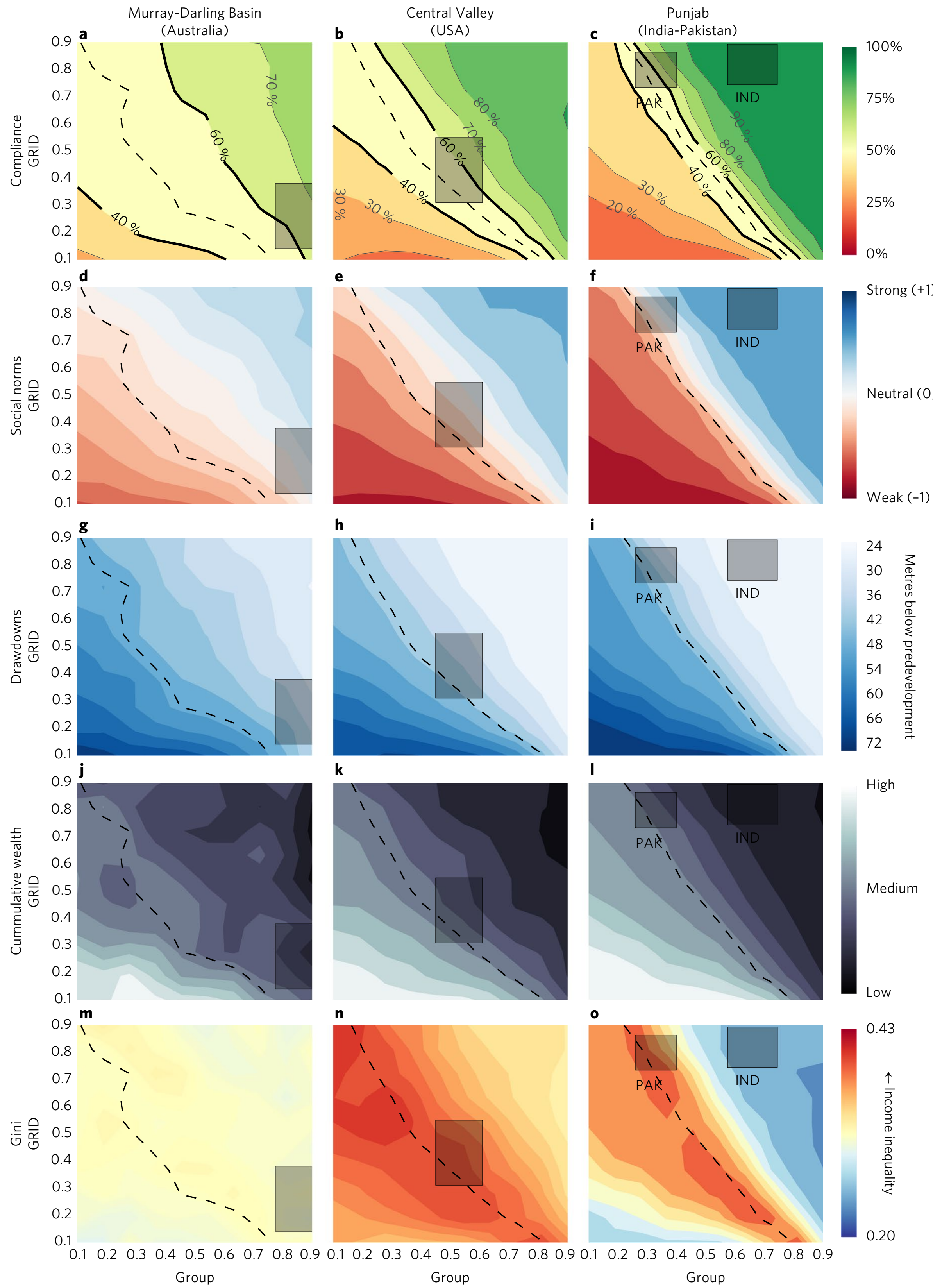

Fig. 3 | Deleterious effects and trade-offs in systems located below or near the tipping points. a–o, Profit-seeking (high cumulative wealth, **j–l**) leads to widespread illegal behaviour (low compliance, **a–c**), norm violation (low SN, **d–f**), resource depletion (large water table drawdowns, **g–i**) and income inequality (high Gini coefficient, **m–o**). Dashed lines indicate 50% compliance, thick solid lines 50 ± 10% compliance. Shaded boxes indicate grid and group interquartile ranges obtained from the WVS6. Axes represent grid (vertical) and group (horizontal) values as defined in the Methods and used to characterize the four ways of life defined by cultural theory. Results (mean of 100 realizations for each parameter combination) are shown for the scenario of strong monitoring and enforcement powers (*M*+*F*+).

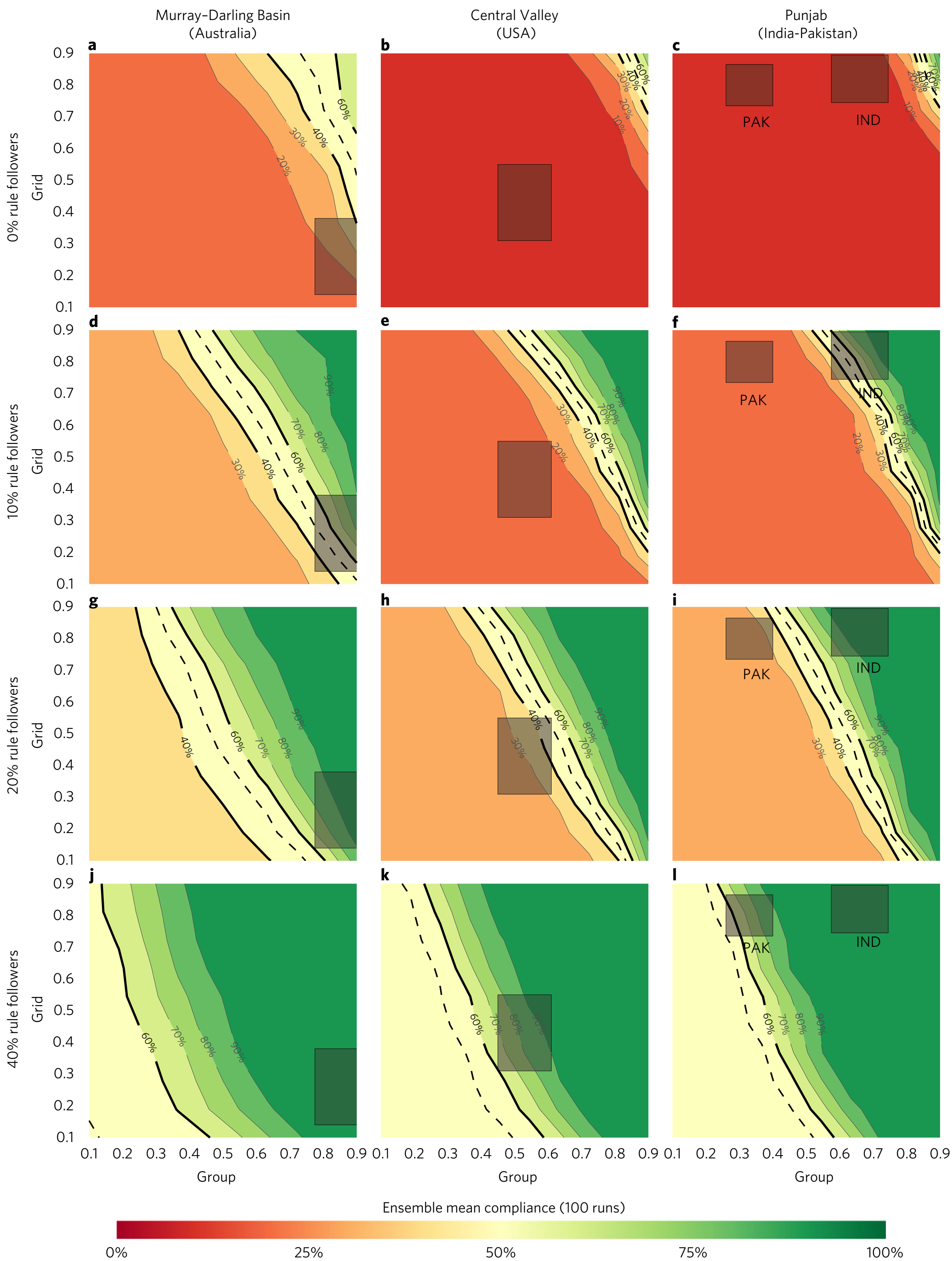

Fig. 4 | Rule followers have a strong positive influence on compliance and groundwater conservation targets. Unlike monitoring and fines (Supplementary Fig. 2), engaging rule followers exerts a strong and positive influence on group behaviour, as revealed by the steepening of the tipping points and the expansion for the conservation state. The scale bar depicts the average compliance value (expressed as percentage of users/agents) out of an ensemble of 100 randomly initiated simulations. Results are shown for a scenario of weak monitoring and enforcement powers (*M*−*F*−).

farmer networks tend to be highly connected (a farmer has many neighbours), tipping points have very steep gradients (Fig. 3c and Supplementary Fig. 2, Punjab). In large groups overuse and conservation also tend to be locally resilient (that is, steep/narrow tipping points surrounded by areas where small perturbations generate small responses; see Supplementary Fig. 2, Punjab).

These findings have three important implications for groundwater systems in the developing world applying or considering to apply groundwater regulation. First, conservation close to the threshold may give a false impression of stability, masking the risk that social norms may be actually approaching a tipping point. Second, overuse close to the threshold could give the false impression that achieving extraction targets would require substantial time and resources, when only a small policy or cultural change may be sufficient. Third, systems that are far from the tipping point will require the investment of substantial resources before any noticeable increase in compliance is observed.

Mapping our GCG outputs onto the grid–group plane and superimposing WVS6 statistics reveals how identical management policies (Supplementary Fig. 2, rows) can have vastly different results in different countries (Supplementary Fig. 2, columns), and how compliance can vary within a given country owing to the grid–group variability at the national level (that is, the range of compliance outcomes within each shaded region in Figs. 3a–c, 4 and Supplementary Fig. 2). This mapping provides a qualitative picture of how cultural values determine whether communities adopt or ignore the rules imposed by institutions[7,40].

Next, we mapped social (SN), economic (Gini, agricultural profits) and environmental (water table drawdowns) performance indicators across the grid–group plane (Fig. 3d–o). This mapping reveals deleterious effects and trade-offs in systems located below or near the tipping points, where profit-seeking (high cumulative wealth) leads to widespread illegal behaviour (low compliance), norm violation (low SN), resource depletion (large water table drawdowns) and income inequality (high Gini) (Fig. 3d–o). Emblematic of such unwanted trade-offs is the California Central Valley, where lax regulation has fuelled a surge in drilling and pumping activity causing wells to run dry, rapid depletion, diminished environmental flows, aquifer compaction, damage to irrigation infrastructure and farmer debt[41]. Our conceptual framework provides a way to quantify trade-offs among economic, social and conservation goals that are common in groundwater basins around the globe[1,9], but that are difficult to estimate or predict causally.

As shown in Fig. 3a, b, even with strong monitoring and enforcement powers (M+F+), conservation would only be mildly successful in individualist and egalitarian societies (predominantly developed nations). On the other hand, in large fatalist and hierarchist populations (typical of developing nations)—where compliance could hypothetically be as high as 90% (Fig. 3c)—monitoring and enforcing pumping restrictions on millions of private wells would be an extremely expensive and time-consuming endeavour[9,18].

We asked what would happen if management resources were instead focused on increasing the number of rule followers in a community (that is, the systemic effect of a group of individuals behaving purposefully). This may be achieved for instance, through monetary or non-monetary incentives[42], co-management agreements[43], participatory monitoring[13], and/or education and information provision about groundwater management policies and rules[44]. To answer this, we seeded our simulations with an increasing number of agents with fixed strategies $B=0$; $P=1$, located randomly in space. These agents essentially represent dedicated citizens that are not going to defect ($B=0$) and that will selflessly report a non-compliant neighbour ($P=1$) regardless of other people's decisions. We did not impose any constraints on how agents updated their strategies, so they were free to adopt or reject norms ushered by dedicated citizens.

Our simulations ascertain the conditions (grid, group, percentage of rule followers) under which compliance and social norms begin to diffuse within the social network of the farming community. Remarkably, rule followers have a strong, non-linear, positive influence on group behaviour (Fig. 4). For a scenario of low monitoring and enforcement powers (M−F−), only 10%, 20% and 40% of rule followers drive the system past the tipping point in the Punjab, Murray–Darling Basin and Central Valley simulations, respectively. Seeding rule followers has the effect of steepening the tipping points in all three study cases, across the whole grid–group plane (Fig. 4d–f). By contrast, increasing monitoring and enforcement powers (M+ F+) does not have this effect (Supplementary Fig. 2).

These findings suggest that engaging a proportion of rule followers can substantially reduce the costs of groundwater management in large, densely populated groundwater basins in the developing world. In these large, tightly woven network of farmers (see Supplementary Fig. 3), rule followers have a strong influence in social interactions. These people can prevent and contain non-compliant behaviour, amplify the spread of social norms at tipping points[45] and enhance the stability of the conservation state once it has been reached (that is, the dark-green areas in Fig. 4). These dynamics are consistent with how highly connected networks of social, ecological and economic agents respond to perturbations[45], and previous research on the effects of group pressure[46] and herding behaviour[47]. Empirical evidence from countries such as India and Pakistan[13] also point towards the supportive role of rule followers 'leading by example' in promoting joint local action against those that deviate from norms. There is also evidence that a critical mass of rule followers may develop under adverse biophysical conditions[48], or owing to psychologically proximate concerns (temporal or geographically close) about the impacts and risks of drought and resource depletion[49].

What, then, can be done to develop and maintain effective groundwater conservation programs? Our conceptual framework can help answer this question in a number of directions. First, the GCG can be used to qualitatively and quantitatively evaluate the system's position in the grid–group plane, the location and steepness of the tipping points, and the level of effort that will be required to drive the system to the conservation state. Second, our results also point to the opportunity of triggering tipping points by encouraging and rewarding compliance of a critical mass of resource users. In human societies, social norms and cooperation rely on rewards and sanctions, which ensure the compliance of self-interested individuals, on the presence of people willing to perform altruistic acts[50]. In addition, there is also experimental evidence that indicates that rewarding incentives and moralistic sanctions in repeated interactions have large positive effects on cooperation[42]. In this regard, water authorities can do greater good by making strong compliance an advertized goal (for example, by revealing the identity of offenders) and by establishing monetary rewards (for example, tax exemptions) and non-monetary incentives (for example, bonus allocations) for farmers who cultivate a culture of compliance. Third, our results underline the need to build compliance well past the tipping point to ensure system resilience. Once compliance is backed up by social norms, little effort in monitoring and enforcement will be required to uphold sustainable conservation targets. Meeting these targets can substantially increase the ability of communities to maintain agricultural yields through future droughts and changes in regional climate[1].

Recent hydro-economic analyses have shown that groundwater depletion threatens water and food security not only locally, but also globally through international trade links[51]. Economic development, population growth, climate change and rising awareness of the need to allocate water back to the environment, will put increased pressure on irrigation and agricultural systems and contribute to the risk of systemic collapse of global food production. How will governments and farmers adapt to these challenges? It stands to reason that the ability of governments to establish effective groundwater conservation programs and triggering the social norms that support these policies is at the heart of how these challenges will be addressed.

Expanding the GCG in future research to incorporate a larger set of human rationalities is key. For instance, our model could be complemented using the behavioural phenotypes derived by Poncelas-Casasnovas et al.[52], the cultural value orientations of Schwartz[53] or Hofstede's cultural dimensions[54]. The effects of groundwater dynamics (hydraulic parameters, boundary conditions, and so on), mental models (how often new strategies are tested, foresight, hindsight, and so on), alternative production options (for example, choices about which crop to grow or what irrigation technology to adopt) and social networks (their extent and configuration) can be explored with the current version of the GCG with easy user intervention.

More broadly, this study shows how the World Values Survey—heretofore confined to social research—can enrich our understanding of commonalities and barriers to conservation in groundwater hotspots, for which establishing sustainable pumping limits is critical to ensure the livelihoods and food security of millions of people[2,8]. The classification of nations using grid–group positions provides a useful framework to reveal trade-offs and conduct systematic comparisons of alternative management and policy options in multicultural settings. This can be very important, if not necessary, for managing large-scale irrigation systems in transboundary aquifers. Our modelling framework is promising, given that groundwater management is politically challenging, time consuming and expensive to implement and enforce[1,10]. Lastly, because our modelling framework is flexible and can be coupled to any environmental model, our methods can be applied to other resource systems in which regulatory compliance is critical to sustainability, such as fisheries, forests, wildlife and global climate.

Methods

Cultural theory. Cultural theory[32] (also referred to as grid–group or plural rationality theory) was used in this study as a framework to compare social contexts and conceptualize human behaviour according to four broad types of social organization or ways of life (hierarchist, individualist, fatalist and egalitarian). This theory postulates that people are especially concerned with two aspects of social life: grid and group. Grid represents reliance on standards (for example, customs, morals, shame) for achieving goals, with low-grid people having a desire for nonconformity and a belief that nonconformist behaviour leads to individual success. High-grid people rigidly adhere to social norms and they are more willing to punish actions that violate these norms, even if this generates no direct benefits to them[34,55]. Together, grid and group form a two-dimensional representation of cultural types, split into quadrants that define the four aforementioned typologies of human behaviour (Fig. 1). For additional background and justification, see Supplementary Discussion.

Calculation of grid–group scores. Currently there is no large-scale survey that directly measures grid and group characteristics of people, and as such, these scores were obtained from secondary analyses[34,56]. Large-scale survey data used to calculate the grid–group scores were obtained from the World Values Survey (WVS; http://www.worldvaluessurvey.org/wvs.jsp). The WVS is conducted through detailed questionnaires in face-to-face interviews. Questionnaires for the WVS6 (2010–2014) consist of 258 questions administered to about 1,000–3,500 interviewees per country, with a worldwide total of 90,350 interviews. For consistency, qualitative validation and to allow comparisons, we applied the methodology proposed in ref. [34] to compute grid–group scores for the 57 countries covered by the WVS6 (Fig. 1 and Supplementary Fig. 1). The process to calculate grid–group scores from the WVS data can be summarized as follows. (i) Discard questions that are not pertinent to either grid or group. Specific questions regarding political parties, local issues, happiness, life satisfaction, among others, were eliminated because these questions were only pertinent to a specific geographic location and political system and were likely to rest on emotional states in a manner that may be different from questions that represented more straightforward beliefs and values about the larger world. The net effect of this review process meant that 59 questions were retained. (ii) Isolate those questions that carry the most useful information about the grid–group scores. The list of 59 questions was further reduced to 10 grid questions and 10 group questions, on the basis of the highest variations observed across countries, that is, those with the highest F statistic from a one-way analysis of variance (ANOVA). Supplementary Table 1 shows that computed grid–group scores for the selected questions exhibited significantly less variance within societies than between societies ($P<0.001$), meaning that these indices provided sufficiently large variation to highlight differences between countries. The aim of this step was to use the smallest number of questions that give the largest payoff in explanatory power. (iii) Normalize answers to each question onto a scale of 0 to 1. This avoided the inconsistent scaling and scoring of answers for different questions in the WVS. (iv) Average the scores for the questions under each social dimension to generate the final grid–group scores. Scores were computed using equal weights, because there is no theoretically informed a priori reason to assign one question greater importance than another in determining grid or group scores.

The grid (10) and group (10) questions that were used to calculate grid–group scores are categorized in Supplementary Table 1, whereas a summary of raw statistics for grid–group scores are presented in Supplementary Fig. 1. To derive Fig. 1, we normalized the data presented in Supplementary Fig. 1 by the minimum and maximum grid and group country average scores. Grid–group scores were used to evaluate the functional form of the social utility (S) of the GCG agents. S combines the effects of two social concerns: (i) The social costs of reporting non-compliant neighbours; and (ii) The social costs of developing a bad reputation when caught breaking the rules (see Supplementary Methods and ODD+D model documentation).

Validation of grid–group scores. Grid–group scores shown in Fig. 1 were validated on the basis of the previous analysis for the WVS3 and WVS4 in ref. [34]: Socioeconomic correlation was observed between countries with similar cultural characteristics (see relative position of developed versus developing countries in Supplementary Fig. 1a); Geographical correlation was observed for geographically adjacent countries or countries belonging to a specific region (for example, African countries); Ethnicity and religion had an important role in the variation of grid and group characteristics and, for instance, newly independent countries and Muslim countries exhibited similar group scores. For more details, see Supplementary Methods.

Validation of the WVS and GCG results. *Murray–Darling Basin surveys.* Grid–group scores derived from the WVS were statistically tested against data from empirical surveys in the Murray–Darling Basin (Australia). The surveys covered approximately 4,000 water license holders (22% response rate) and were conducted between September 2012 and January 2013 in New South Wales, eastern Australia[35] (Macquarie–Bogan in the central west (CW, $n=1381$); Murrumbidgee/Murray Riverina in the Murray and Murrumbidgee (MM, $n=1258$); Richmond in the north coast (NC, $n=1339$)). These regions were selected purposively to represent a diversity of water sources, locations, authorizations and risk level. These surveys captured water users' views on compliance motivations, experiences with compliance and enforcement by the New South Wales Office of Water, water users' information sources and their knowledge of water regulation. The survey numbers and response rates are summarized in: http://www.connectedwaters.unsw.edu.au/sites/all/files/Water-extraction-in-NSW-stakeholder-views-of-compliance-and-enforcement-survey-report.pdf. To test the validity of the GCG in a real-world groundwater management scenario, we computed grid–group scores (see Supplementary Table 2), monitoring (M), fines (F) and compliance from surveyed data. Results indicated that the grid–group scores computed from the New South Wales surveys did not differ significantly from indices obtained from the WVS6 (parametric t-test; $n_{\mathrm{WVS}}=1{,}477$ and $n_{\mathrm{MDBsurvey}}=672$; two-sided $P=0.12$ for grid and $P=0.65$ for group). Empirical values for monitoring (M), fines (F) and compliance were obtained from survey questions showing consistency with GCG results (see Supplementary Fig. 4). For additional background and justification, see Supplementary Methods.

Main processes/model narrative. The GCG parsimoniously captures the main features of agricultural communities operating under groundwater conservation programs that have been or are yet to be implemented in many parts of the world[9,10,57]. The problem is intentionally designed to be water-limited—rainfall is not sufficient to irrigate crops and an underlying aquifer is used to supplement irrigation demands. The model focuses on the fundamental social, cultural, economic and regulatory forces that may influence whether farmers adhere or not to these policies. The groundwater conservation policy is modelled as water allocations (that apply equally to all agents) enforced by a regulator agent through variable levels of monitoring and fines. These restrictions on groundwater withdrawals constrain the farmers' profits, which have to cut back from the ideal levels of irrigation that maximize crop yields and irrigated acreage. Farmer agents may either comply or extract groundwater illegally beyond the allocated limit; they can also report offending neighbours or do nothing.

Agent decision submodel. The agent's decision strategy was defined by two variables: the propensity to defect (boldness, B) and the propensity to act in a punitive manner (punitiveness, P), with B and P being continuous variables between 0 and 1. The population averages of B and P defined the presence or absence of a social norm (SN). Following Axelrod's definition: a social norm of compliance emerged when $B{\sim}0$ and $P{\sim}1$ became a stable and long-term condition among agents. The emergence of a norm was modelled by allowing farmers to modify their strategies (B, P) on the basis of the evolutionary principles of imitation and exploration. That is, at the end of each growing season, agents look at their neighbours and copy (imitate) the most successful strategy of that year, using a fitness metric as a basis of comparison (we defined this metric as the farmer's performance index, PI, see below). If an agent scores higher than its neighbours, he maintains the current strategy for the following year. With a given probability (mutation), agents change their boldness (B) and punitiveness (P) level to a random value, overriding the imitation mechanism. In other words, agents are allowed to occasionally explore completely new strategies (either *B* or *P*); with 50% chance their value is replaced by a random number drawn from a 0–1 uniform distribution. This heuristic is commonly known as 'best-mean imitation'[58].

Similar to Axelrod's work, we did not impose any constraint or make any a priori assumption or correlation about the boldness (*B*) or punitiveness (*P*) of agents. The evolution of norms of compliance with allocations was simulated as an evolutionary process. The strength of a norm was defined as the difference between the population averages of *B* and *P*. If *B* was markedly higher than *P*, or if there was not much difference between them, a weak norm was obtained (most agents are pumping more water than they are supposed to and not punishing breaches). On the other hand, when agents consistently selected strategies having high *P* and low *B* values, a norm of compliance was obtained. The consequences of agent decisions and interactions were captured and quantified in the farmer's performance index ($\mathrm{PI} = E \times I \times S$, see below and Supplementary Methods). The goal of formulating $\mathrm{PI} = E \times I \times S$ was to construct a simple index to capture the interaction of three broad indicators of farmer success, namely, economic profitability (*E*), good relationships with the water authority or institution (*I*) and prolific social interactions (*S*). Each indicator was represented (quantified) by a utility function. For generality, the functional forms of utility were kept as simple as possible. Supplementary Fig. 7 (top) illustrates the interaction between any two agents, showing the benefits (+) and costs (−) that apply in the neighbourhood of a breach. Another way to think about the dynamics of the GCG is to consider that each growing season, farmers simultaneously play two games: defect-or-not and punish-or-not. The former is driven by the farmers' boldness *B*, the latter by their punitiveness *P*. Supplementary Fig. 7 (bottom) represents the three components of the farmer score (economic, institutional, social) as 'forces' pulling agent decisions in different directions.

The objective of our model is to propose mechanisms that 'pull' the decisions of the majority of farmers towards compliance. The main assumption of our agent's performance index is equal weighting of the three indicators to produce the final index. Equal weighting is the most parsimonious approach, because it avoids introducing complexity (weight coefficients) without clear justification[34]. Practice tends to support this method, unless there are compelling reasons for differential weighting[59].

Economic submodel. Prior to regulation, it was assumed that farmers irrigate crops at full nominal water requirement (Supplementary Table 3). For simplicity, it was also assumed that farmers did not engage in deficit irrigation, meaning that under pumping restrictions they were forced to reduce their irrigated acreage. It was further assumed that if a farmer cooperates, he/she only irrigates a fraction of land equivalent to the pumping allocation (that is, if the allocation is 20% of the full license, the farmer irrigates 20% of his land); whereas if a farmer defects, he/she pumps a fraction of illegal water proportional to his/her boldness (for example, for a 20% allocation, a defecting farmer with boldness $B = 0.1$ would irrigate $20\% + 80\% \times 0.1 = 28\%$ of his land; one with boldness $B = 0.8$ would irrigate $20\% + 80\% \times 0.8 = 84\%$ of his land). The economic utility function was calculated as: $E = \text{gross margin} = \text{income} - \text{variable costs}$ (US$ per ha) (Supplementary Fig. 10). Gross margin budgets (Supplementary Table 3) were calculated using reported and published agro-economic statistics for Bollgard II R cotton in the Murray–Darling basin (2015 Australian Cotton Production Manual, http://www.cottoninfo.com.au/publications), almonds in the southern Central Valley (UC Davis Agricultural and Crop Economics; http://coststudies.ucdavis.edu), and the wheat–rice rotation in the Punjab[60,61]. Gross margins were calculated as total revenue minus total costs, not including the energy costs of pumping groundwater. Pumping costs were calculated and incorporated into the agent's objective function at simulation runtime using depths to the water table from the groundwater submodel, based on the equation for power consumed by a centrifugal pump set: $\mathrm{PC} = P_e g(\mathrm{WR})H/\eta$ where PC is the pumping cost in US$ per ha, P_e is the price of electricity in US$ per kWh, *g* is gravity, WR is the crop's water requirement in ML per ha, *H* is the dynamic pumping lift of the pump in m, and η is overall efficiency. It was further assumed that decisions were only related to water pumping and not to crop choice. Farmers may indeed choose to switch to a different crop when allocations are reduced. Yet, this option is not always available nor feasible to water users as certain crops are long-term investments that require many years to reach their optimal profitable yields. Soils and climate can also limit crop choice. Specialization can also play an important part in cases where farmers have heavily invested in crop-specific machinery. Including crop choice, soil and climate factors, and specialization into our model was not our goal, as this would have added an additional layer of complexity and made our goal of revealing factors that trigger compliance more difficult. For this reason, the current version of the GCG only considered a strictly limited subset of variables that were relevant to our research questions. This chosen subset of variables/drivers, however, are essentially those identified by previous studies as key drivers of human cooperation[5,6,11,21].

Institutional submodel. Groundwater allocations were implemented as a system of non-transferable entitlements or water rights. The focus was exclusively on the role of social norms, thus trading of these entitlements was not considered, as this would incorporate an additional and unnecessary level of complexity into the analysis. Farmer agents were given the option of behaving opportunistically by pumping more water than the allocated limit (that is, the cap imposed by the water authority). The consequences of their decisions were modelled with an institutional utility function, *I*, which notionally represented the proportion of gross margins forgone to pay fines when an agent was caught breaking the rules (Supplementary Fig. 9). The institutional utility function was defined as $I = 1$, if an audited farmer cooperated, or $I = 1 - F$, if an audited farmer was caught defecting, where an *F* of 0–1 indicates the severity of fines implemented by the water authority. The larger *F* is, the greater proportions of profits need to be used to pay a fine.

Social submodel. The social utility function *S* was defined as a means to provide a numeric representation of individual benefits and costs that agents derive from their interactions. *S* was constructed on the basis of the following requirements (Supplementary Fig. 8): *S* allowed agents' utilities to be put on a common scale and compared; *S* followed a Cobb–Douglas functional form that is commonly used in welfare economics and the construction of social indices (see, for example, Happy Planet Index, http://happyplanetindex.org and the Human Development Index, http://hdr.undp.org/en); the intrinsic cost of reporting non-compliant neighbours decreased with increasing grid score[34] and increased each time the agent chose to report a non-compliant neighbour; and the intrinsic cost of developing a bad reputation decreased with increasing group score[34] and increased each time the agent was seen by others to be extracting water illegally. Each season, agents faced the decision of whether to cooperate with the allocations (pump a fraction of their entitlement as required by the water authority) or to defect (pump more than the allocation). Each opportunity to defect came with a probability of neighbouring farmers seeing that breach and reporting it to the water authority. This opportunity was represented by the probability of punitiveness Prob(*P*). Prob(*P*) was drawn from a random uniform distribution on the interval 0–1, at every turn for each agent. When $P < \mathrm{Prob}(P)$, an agent chose to punish a defector. Similarly, the probability that an agent will defect was defined as Prob(*B*). If $B < \mathrm{Prob}(B)$, the probability of defecting is higher than the agent's boldness and therefore it decides to defect, otherwise it cooperates. The social utility function was defined using the following relationship: $S = \mathrm{grid}^m(1-\mathrm{group})^n$, where m = number of times an agent reports a neighbour that takes water illegally; n = number of times an agent is seen taking water illegally. In this functional form of *S*, grid and group are the normalized (0–1) mean grid group scores from Supplementary Fig. 1.

Groundwater flow submodel. The coupled agent-based groundwater model was developed using FlowLogo[25] (Supplementary Fig. 6), a software platform developed by the authors specifically for this purpose. The groundwater submodel represented a 10 × 10 km basin, discretized into 40 × 40 cells. The dimension of each cell was 200 m. Model boundary conditions were defined by a no-flow boundary to the north and south, and constant head boundary cells to the east and west; setting head values to create an east–west gradient of 1/1,000 representing typical conditions in regional aquifer systems. Underlying this basin was a semi-confined sand aquifer of 50 m thickness, hydraulic conductivity $K = 10\,\mathrm{m\,d^{-1}}$ and storativity $S = 1 \times 10^{-4}$. The model was transient with a time step of six months. We used a steady-state run with no pumping stresses as the initial condition for each simulation.

Code availability. A fully documented implementation of the Groundwater Commons Game is available from the OpenABM library (https://www.openabm.org/) of the 'Network for Computational Modelling for SocioEcological Science' (CoMSES). The model can be freely downloaded at: https://www.openabm.org/model/5634/version/1/view. Agent-based simulations were conducted in NetLogo. R and Python code used for statistical analysis and data analysis, and the ODD+D protocol model documentation are included as supplementary files in the OpenABM repository.

Data availability. World Values Survey data and documentation can be freely accessed and downloaded at: http://www.worldvaluessurvey.org. Data and documentation specific to our Murray–Darling Basin surveys are available upon request from C.H. (c.holley@unsw.edu.au). All other data and analyses are available from the corresponding authors upon reasonable request.

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Author contributions

J.C.C.-R., R.R. and G.M. conceived the research ideas and designed the study; C.H. conducted and analysed the Murray–Darling Basin water license surveys; J.C.C.-R. implemented the model, performed the computational experiments, designed figures and analysed the World Values Survey data. J.C.C.-R. and R.R. wrote the manuscript. All authors contributed to the analysis, interpretation, and editing of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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☐ Initial submission ☐ Revised version ☒ Final submission

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Experimental design

1. Sample size

Describe how sample size was determined.

WORLD VALUES SURVEY WAVE 6:
All samples from this dataset were used.

MURRAY-DARLING BASIN SURVEYS:
There are a large number of water users in New South Wales (NSW). As of June 2011, there were over 7000 surface water licences and 71 000 groundwater (bore) licences managed under the Water Act 1912 (NSW) and over 24 000 surface and groundwater licences under the Water Management Act 2000 (NSW). At 30 June 2011, 58 per cent of Water Act 1912 (NSW) licences had been converted to tradable Water Access Licences under the Water Management Act 2000 (NSW). These water users draw on a diversity of water sources (unregulated surface water, regulated surface water and groundwater) for a variety of purposes (e.g. stock and domestic and irrigation). Furthermore, water users themselves vary greatly in terms of property size, land use (e.g. grazing, horticulture), and other characteristics (e.g. membership of irrigation schemes, industry associations, water user groups). Given this diversity, it was decided that a quantitative survey was the best approach to try and capture relevant data. The survey was conducted in three catchments/regions:
• Macquarie-Bogan in the Central West (CW).
• Murrumbidgee/Murray Riverina in the Murray and Murrumbidgee (MM).
• Richmond in the North Coast (NC).
These regions were selected purposively to represent a diversity of:
• Water sources (regulated rivers, unregulated rivers and groundwater).
• Locations (MM and CW are both inland, while NC is coastal).
• Authorisations (e.g. licences, approvals and stock and domestic).
• 'At risk' water sources as defined for the National Framework for Compliance and Enforcement Systems for Water Resource Management.

Across all three regions smaller stock and domestic water users were also included. Taking water under a basic landholder right has historically been subject to little oversight by regulatory agencies. For example, water taken for stock and domestic use is not required to be metered. While such uses have a minimal impact individually on overall water consumption, they may cumulatively have a much more significant impact (with 100,000s of stock and domestic water users across the state).

GROUNDWATER COMMONS GAME SIMULATIONS:
100 stochastic agent-based simulations were performed for each combination of parameters. This number was chosen based on preliminary tests, visual inspection and convergence of system trajectories (model outputs). Preliminary tests showed that 50 realisations are adequate, but we conservatively chose 100. We swept the whole parameter space of the model:

81 combinations of grid-group parameters, see ODD protocol
4 combinations of monitoring and enforcement powers
4 scenarios of rule-followers

100 realisations each
=129,600 simulations

2. Data exclusions

Describe any data exclusions.

MURRAY-DARLING BASIN SURVEY:
Taking into consideration resource and practical constraints, the survey began with a raw list of 4500 licence and approval holders (approximately 1500 from each of the three regions, chosen to include a full range of water users from large entitlement holders extracting water for commercial use to people extracting water solely for stock and domestic purposes). The list was refined to create a more targeted survey list, including ensuring multiple works/licence holders would only receive one survey and removal of any repeat or incomplete addresses, as well as entries pertaining to local/state governments and commercial companies outside of NSW (who were unlikely to have the desired knowledge and experience with on property water use). A final survey list was sent to 1381 CW, 1258 MM and 1339 NC properties (totalling 3,978). The survey numbers and response rates are summarised here on page 14: http://www.connectedwaters.unsw.edu.au/sites/all/files/Water-extraction-in-NSW-stakeholder-views-of-compliance-and-enforcement-survey-report.pdf

In terms of the data gathered being representative, there may be differences between respondents and non-respondents to mail surveys such as the one conducted in the Murray Darling Basin. Statistical comparisons of the property and social background data could not be made because the area covered by Australian Bureau of Statistics statistics does not match the surveyed areas and sourced population. While a lower response increases the likelihood that non-respondents to the survey are significantly different to respondents, response rates by themselves are not good indicators of non-respondent bias, and it is impossible to completely correct for all non-respondent bias.

3. Replication

Describe whether the experimental findings were reliably reproduced.

The study is based on social surveys, therefor there is no replication

4. Randomization

Describe how samples/organisms/participants were allocated into experimental groups.

GROUNDWATER COMMONS GAME SIMULATIONS:
To account for uncertainty and stochasticity, we report the mean and standard deviation of 100 independent realisations. In each realisation, agents are initialised with a strategy (B,P), with each component independently drawn at random from a [0,1] uniform distribution. No correlation between B and P is assumed. When an agent chooses to try a new strategy (the strategy mutates and the agent chooses to explore a new strategy), either B or P (with 50% chance) is replaced by a random number drawn from a [0,1] uniform distribution. The seed of the random number generaton in NetLogo is reset in each realisation.

MURRAY-DARLING BASIN SURVEY:
Randomization was not conducted.

5. Blinding

Describe whether the investigators were blinded to group allocation during data collection and/or analysis.

MURRAY-DARLING BASIN SURVEY:
Blinding was not done.

Note: all studies involving animals and/or human research participants must disclose whether blinding and randomization were used.

6. Statistical parameters

For all figures and tables that use statistical methods, confirm that the following items are present in relevant figure legends (or in the Methods section if additional space is needed).

n/a	Confirmed	
☐	☒	The exact sample size (n) for each experimental group/condition, given as a discrete number and unit of measurement (animals, litters, cultures, etc.)
☐	☒	A description of how samples were collected, noting whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☒	☐	A statement indicating how many times each experiment was replicated
☐	☒	The statistical test(s) used and whether they are one- or two-sided (note: only common tests should be described solely by name; more complex techniques should be described in the Methods section)
☐	☒	A description of any assumptions or corrections, such as an adjustment for multiple comparisons
☐	☒	The test results (e.g. P values) given as exact values whenever possible and with confidence intervals noted
☐	☒	A clear description of statistics including central tendency (e.g. median, mean) and variation (e.g. standard deviation, interquartile range)
☐	☒	Clearly defined error bars

See the web collection on statistics for biologists for further resources and guidance.

Software

Policy information about availability of computer code

7. Software

Describe the software used to analyze the data in this study.	WVS and Murray-Darling basin datasets were processed using the R software. The Groundwater Commons Game was developed using the open-source software NetLogo

For manuscripts utilizing custom algorithms or software that are central to the paper but not yet described in the published literature, software must be made available to editors and reviewers upon request. We strongly encourage code deposition in a community repository (e.g. GitHub). *Nature Methods* guidance for providing algorithms and software for publication provides further information on this topic.

Materials and reagents

Policy information about availability of materials

8. Materials availability

Indicate whether there are restrictions on availability of unique materials or if these materials are only available for distribution by a for-profit company.	N/A

9. Antibodies

Describe the antibodies used and how they were validated for use in the system under study (i.e. assay and species).	N/A

10. Eukaryotic cell lines

a. State the source of each eukaryotic cell line used.	N/A
b. Describe the method of cell line authentication used.	N/A
c. Report whether the cell lines were tested for mycoplasma contamination.	N/A
d. If any of the cell lines used are listed in the database of commonly misidentified cell lines maintained by ICLAC, provide a scientific rationale for their use.	N/A

Animals and human research participants

Policy information about studies involving animals; when reporting animal research, follow the ARRIVE guidelines

11. Description of research animals

Provide details on animals and/or animal-derived materials used in the study.	N/A

Policy information about studies involving human research participants

12. Description of human research participants

Describe the covariate-relevant population characteristics of the human research participants.

MURRAY-DARLING BASIN SURVEY:
There are a large number of water users in New South Wales (NSW). As of June 2011, there were over 7000 surface water licences and 71 000 groundwater (bore) licences managed under the Water Act 1912 (NSW) and over 24 000 surface and groundwater licences under the Water Management Act 2000 (NSW). At 30 June 2011, 58 per cent of Water Act 1912 (NSW) licences had been converted to tradable Water Access Licences under the Water Management Act 2000 (NSW). These water users draw on a diversity of water sources (unregulated surface water, regulated surface water and groundwater) for a variety of purposes (e.g. stock and domestic and irrigation). Furthermore, water users themselves vary greatly in terms of property size, land use (e.g. grazing, horticulture), and other characteristics (e.g. membership of irrigation schemes, industry associations, water user groups). Given this diversity, it was decided that a quantitative survey was the best approach to try and capture relevant data. The survey was conducted in three catchments/regions:

- Macquarie-Bogan in the Central West (CW).
- Murrumbidgee/Murray Riverina in the Murray and Murrumbidgee (MM).
- Richmond in the North Coast (NC).

These regions were selected purposively to represent a diversity of:

- Water sources (regulated rivers, unregulated rivers and groundwater).
- Locations (MM and CW are both inland, while NC is coastal).
- Authorisations (e.g. licences, approvals and stock and domestic).
- ‘At risk’ water sources as defined for the National Framework for Compliance and Enforcement Systems for Water Resource Management.

Across all three regions smaller stock and domestic water users were also included. Taking water under a basic landholder right has historically been subject to little oversight by regulatory agencies. For example, water taken for stock and domestic use is not required to be metered. While such uses have a minimal impact individually on overall water consumption, they may cumulatively have a much more significant impact (with 100,000s of stock and domestic water users across the state).