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Review

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Place for sociohydrology in sustainable and climate-resilient agriculture: Review and ways forward

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Abstract

Given the increasing demand for high-quality food and protein, global food security remains a challenge, particularly in the face of global change. However, since agriculture, food and water security are inextricably linked, they need to be examined via an interdisciplinary lens. Sociohydrology was introduced from a post-positivist perspective to explore and describe the bidirectional feedbacks and dynamics between human and water systems. This review situates sociohydrology in the agricultural domain, highlighting its contributions in explaining the unintended consequences of water management interventions, addressing climate change impacts due to/on agriculture and incorporating human behaviour into the description of agricultural water systems. Sociohydrology has combined social and psychological insights with novel data sources and diverse multi-method approaches to model human behaviour. However, as agriculture and agriculturalists face global change, sociohydrology can better use concepts from resilience thinking more explicitly to identify gaps in terms of desirable properties in resilient agricultural water systems, potentially informing more holistic climate adaptation policy.

Impact statement

As the largest consuming water sector (by far), agriculture is a domain where food and water security are strongly interlinked. Sociohydrology has offered post-positivist approaches to understand the dynamics of human–water relationships. This study highlights the contributions of sociohydrology in the agricultural domain. Sociohydrology has been able to describe how agricultural water management actions have often led to counterproductive, often unintended consequences by integrating human behavioural dynamics, interdisciplinary methods and novel data sources. By incorporating concepts from resilience thinking, sociohydrology can emerge as an approach to understand the susceptibility of agricultural systems and agriculturalists to global change and uncertainties, potentially better informing climate-resilient agricultural policy.

Introduction

Agriculture is key to human survival but has large impacts on resources and the environment globally. Out of the nine planetary boundaries (Steffen et al., 2015), agriculture is a major driver of four boundaries which have been completely transgressed, that is, biosphere integrity, biogeochemical flows, land system change and freshwater use (Richardson et al., 2023). Agriculture also both affects and is affected by climate change – another boundary that has been transgressed (Richardson et al., 2023), thus requiring a reduction of its environmental impacts while adapting it to future climates. Changing earth systems and biosphere further hinder human development and well-being outcomes, such as ensuring just and equitable access to resources while remaining within the planetary boundaries (Steffen et al., 2015; Folke et al., 2021; Rockström et al., 2021).

Given the increasing demand for high-quality food and protein caused by global population growth and changing diets, global food security remains a challenge (Calicioglu et al., 2019). While food availability and total material wealth have improved globally, unsustainable resource exploitation (leading to resource scarcity), pollution and degradation of ecosystem services, and inequitable social-economic and political conditions remain challenges to local and global food systems (Raudsepp-Hearne et al., 2010; Steffen et al., 2011; Zwarteveen and Boelens, 2014; Gordon et al., 2017). FAO (2017) has recognised several global agricultural needs such as addressing climate change and the associated intensification of natural hazards, and eradicating extreme poverty and reducing inequality, for example, in the context of agriculturalists.

Agriculture, food and water security are inextricably linked (Pereira, 2017). Agriculture uses about 38% and 70% of the global land and freshwater resources, respectively (Pimentel et al., 2004; Rosegrant et al., 2009; FAO, 2020). Water footprint of food production (Mekonnen and Hoekstra, 2014; Senthil Kumar and Janet Joshiba, 2019), and blue and green water needs for agriculture (Chiarelli et al., 2020; Wang-Erlandsson et al., 2022) are large. Hence, how we design future agriculture is driven by and affects local water resources, which are limited, spatially dispersed and uncertain under climate change (Matthews et al., 2022).

Water availability and management are complex issues due to the coupling of social and biogeophysical processes, and need to be looked at through an interdisciplinary lens such as hydrosocial, water food energy (WFE) nexus and sociohydrological approaches (Vogel et al., 2015). Hydrosocial approaches apply a political ecology lens and use qualitative methods to unpack social, cultural, political and economic issues in terms of either access or control that emerge from human interactions with its water environments (Ross and Chang, 2020; Haeffner et al., 2021). The WFE nexus can be seen as a top–down quantitative approach to simulate or interpret human–agricultural water relations. It identifies and defines connections between water, food and energy subcomponents and uses them to simulate the trajectories of variables such as water and energy use, as well as food and energy production (Khan et al., 2022). Sociohydrology was introduced from a post-positivist perspective to study and account for the bidirectional feedbacks and dynamics between human and water systems (Sivapalan et al., 2012). It aims at interpreting the coupled evolution of such systems using inter-, multi- and transdisciplinary methods along a spectrum of qualitative and quantitative methods, eventually informing policy (Di Baldassarre et al., 2019). Endogenous human agency has been central to its bottom–up approaches, yet it has mostly limited itself to emergent patterns and not been so much about the agents such as agriculturalists, for example, what properties of a system can sustain climate-resilient livelihoods.

This requires a review of what sociohydrology has learned that can aid agriculturalists adapting to climate variability, for example, through the understanding of mechanisms underlying adoption of technologies, and what remains to be learned. For example, is sociohydrological understanding of human behaviour underlying adoption, adaptation and water use enough or is there more to translate this to understanding resilient (or not) agricultural water systems? For this, Section "Sociohydrological understanding of emergent dynamics in agriculture water systems" first illustrates how sociohydrology has been able to understand the emergent dynamics (including paradoxes) that arise within agricultural systems. Section "Sociohydrology in addressing climate change" relates this to agricultural water systems facing climate change. Section "Incorporating human behaviour into sociohydrological understanding" examines efforts to endogenise human behaviour in sociohydrology and highlights the need to identify desirable properties of resilient agricultural water systems. Section "Emerging sociohydrological issues: integrating resilience thinking into agricultural water and for agriculturalists" suggests a way forward for future sociohydrological studies to incorporate and address resilience for agriculturalists and in agricultural systems. Section "Conclusions and ways forward" concludes the review.

Sociohydrological understanding of emergent dynamics in agriculture water systems

Agricultural challenges are complex and context-specific, often resulting from the interplay of factors such as population requirements, governance, water scarcity and climate. In many regions, challenges of increasing food production are linked to agricultural water management (i.e., irrigation management and/or a socioecological imbalance between the approach to agricultural development and ecological limits including available water resources) (Pimentel et al., 2004; Pereira, 2017; Turner et al., 2019). Future irrigation management will likely require increased irrigation coverage and improved irrigation efficiency, through central and decentralised infrastructure/measures, particularly in the face of global change projections. The increasing demands for finite water resources in agriculture have led to a focus on the need for shifting towards demand-side management of water in agriculture instead of supply-driven solutions (Di Baldassarre et al., 2018; Garrick et al., 2020). Such infrastructural irrigation solutions can be complemented by improved water management, through measures like using locally adapted crop varieties (e.g., avoiding water-intensive crops in water-scarce areas), water-smart production methods (e.g., soil management and other techniques to minimise water loss through evapotranspiration) and water harvesting (Oweis and Hachum, 2006; Castelli et al., 2019).

Yet, ill-planned implementation of these interventions can lead to negative externalities and unintended and unexpected impacts on hydrological and social systems (Alam et al., 2022). Human adaptation can lead to a "lock-in" towards unintended or undesired states (Pouladi et al., 2022; Prasad et al., 2022). Irrigation investments can significantly alter the availability and allocation of water flows in a given region, leading to hydrological externalities such as reduced runoff, upstream–downstream impacts, decreased groundwater recharge and baseflows (Calder et al., 2008; Bouma et al., 2011; Alam et al., 2022). At the same time, societies can respond to these interventions and new hydrological conditions in unpredictable and nonlinear ways (Zhang et al., 2014; Alam et al., 2022).

For example, improvements in irrigation water-use efficiency have not always resulted in effective or equitable allocation of finite water resources (Perry and Steduto, 2017; Grafton et al., 2018). Rather, such interventions have often led to increased water use instead of the expected reduction (Zhang et al., 2014; Birkenholtz, 2017). This phenomenon is known as the irrigation efficiency paradox (a sub-phenomenon of the Jevons' paradox or the rebound effect), which can be explained by the supply–demand cycle – *'as availability increases, consumption tends to increase'* (Di Baldassarre et al., 2019, 2018).

Sociohydrology explicitly accounts for the changing and adaptive responses of humans and their impact on the environment. Sociohydrological models have investigated many of these externalities, unintended consequences and emerging phenomena (see Table 1 for some examples). For example, Ghoreishi et al. (2021a, 2021b) developed and applied an agricultural water demand model to understand and model the phenomenon of the rebound effect in the Bow River basin in Canada where water conservation strategies to reduce water usage have in fact led to increased irrigation. Birkenholtz (2017) showed that policies supporting drip irrigation to reduce water use paradoxically led to crop intensification and increased groundwater extraction. Ilyas et al. (2021) developed a

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Table 1. Different sociohydrological studies exploring unintended consequences and emergent phenomena

Particular phenomena investigated	Paper	Case study region
Jevons' paradox (rebound effect)	Ghoreishi et al. (2021a)	Bow River Basin (Canada)
	Ghoreishi et al. (2021b)	Bow River Basin (Canada)
	Ilyas et al. (2021)	Multiple regions
	Kuil et al. (2018)	Upper Ewaso Ng'iro basin (Kenya)
Lock-in phenomenon	Pouladi et al. (2022)	Urmia Lake (Iran)
	Prasad et al. (2022)	Maharashtra (India)
Rural to urban water reallocation	Garrick et al. (2019)	Global Assessment

system dynamic sociohydrological model to understand and simulate the phenomenon of irrigation efficiency paradox (Jevons' paradox for irrigation efficiency), where increasing on-farm irrigation efficiency does not lead to increased water availability at the basin scale. Similarly, Kuil et al. (2018) showed how the rebound effect can be captured by developing a sociohydrological model framework which links farmers' perceptions of water availability to their crop choice and water allocation in Kenya's Upper Ewaso Ng'iro basin. Pouladi et al. (2022) provided a sociohydrological explanation of the lock-in effect of lake desiccation and soil salinisation of Lake Urmia (Iran), which resulted from interacting anthropogenic and (surface and subsurface) environmental processes, while Prasad et al. (2022) explained lock-in in irrigation from groundwater emerging from 'aspirational' and 'vulnerability' intensification that is mediated by agriculturalists' perception of income risks in horticulture in Maharashtra (India).

Garrick et al. (2019) have pointed out that water reallocations from agriculture to cities have been documented in many regions across the world. Fuelled by growing urban populations, such transfers are shown to have inequitable outcomes both within cities and for rural agriculturalists (Boelens et al., 2018). Such transfers may challenge not only food systems but also especially impact smallholder farmers and their associated livelihoods and cultures. Garrick et al. (2019) indicated that water-use efficiency measures can either be a driver or be adopted as a result of such rural–urban transfers. Such efforts to increase water-use efficiency have often triggered complex power dynamics with impacts on surface water irrigation management where tail-end and smaller farmers are adversely impacted (Hu et al., 2017; Linstead, 2018). Such phenomena are important topics to address with sociohydrology. Table 1 provides an overview of such phenomena related to agricultural water studies in sociohydrology.

Not accounting for such externalities and human–water feedbacks can lead to limited understanding of unsustainable outcomes such as drying of reservoirs and wetlands, groundwater depletion, and water, soil and ecosystem deterioration. Additionally, these negative impacts are often mediated by weak financial capital, knowledge, gender and power relations, leading to affect certain and often poor and marginalised populations disproportionately. Often rich or influential farmers with more access to social, financial and biophysical capital capture more advantages, more subsidies and more benefits, thus exacerbating existing inequalities. Thus before investing, it is crucial to consider potential negative externalities and feedbacks to avoid reinforcing existing inequalities and long-term natural resource degradation.

Sociohydrology in addressing climate change

Climate change is affecting the availability of the water resources vital to agriculture via changes to precipitation patterns (quantity, intensity, types and timing), snowmelt timing and rate, stream flows, groundwater recharge, soil moisture, increased temperature and hence atmospheric water demands and evapotranspiration (Jimenez Cisneros et al., 2014; Ficklin and Novick, 2017; Masson-Delmotte et al., 2021). A reduction in water available for crops is expected (Cook et al., 2020). The increased frequency of intense precipitation and long dry spells and changes in their timing (Breinl et al., 2020) are expected to further increase variability in water availability. Together, these changes are projected to reduce average crop yields (e.g., Hasegawa et al., 2022) and their year-to-year stability (Challinor et al., 2014). Impacts additionally reverberate throughout non-production aspects of local and global food systems (i.e., energy consumption, storage, transportation and food safety). Smallholder farmers can be particularly vulnerable, having limited financial capital, debt cycles and dependence on rainfed agriculture. While climate trends are a challenge for average crop yields and their stability, and hence food security, the impact and extent of such trends and extremes can be exacerbated or alleviated by human decisions and management (Kreibich et al., 2023).

Adaptations to changed growing conditions have been proposed, such as changes in crops and their planting dates, enhanced crop diversification in space and time, drought-resistant crop varieties, water and soil conservation practices, agroecology (i.e., agricultural production drawing on ecological principles and traditional management which may be particularly useful to smallholder farmers) and irrigation application. While these approaches have the potential to reduce the impact of detrimental climatic conditions (e.g., Hasegawa et al., 2022), they might clash with other needs and preferences, or have unintended consequences.

To exemplify these mechanisms, we consider multiple cases, beginning with irrigation as a measure to climate change adaptation. Irrigation can substantially reduce the impact of projected heat and water stress (e.g., Siebert et al., 2017; Luan and Vico, 2021). Model estimates show that deficit irrigation (i.e., irrigation aimed at stabilising yields and maximising water productivity, but not necessarily maximising yields; Zhang and Oweis, 1999) could be sustainably expanded in approximately a third of currently rain-fed croplands under a + 3 °C warming (Rosa et al., 2020). Yet, the choice of water source for irrigation affects and is affected by the sociohydrological system, requiring difficult decisions. For example, crop yield maximisation and risk minimisation emerged as increasingly hard to reconcile under more extreme climatic conditions, according to a model for sizing small on-farm ponds as sustainable source of water for irrigation.

At the regional scale, the choice of source of irrigation water is not just a question of water availability (Bierkens and Wada, 2019) but also a problem of collective action. An agent-based model (ABM) showed a single farmer can attain the highest average economic return exploiting a communal resource (groundwater) in a community that is otherwise long-view oriented, that is, privileges renewable water sources (e.g., small farm ponds; Tamburino et al., 2020). Nevertheless, the advantage diminished under more extreme climatic conditions. Considering the entire community and the evolution of choices of water source based on previous experiences, an intensification of climatic extremes reduced the fraction of long-view farmers, that is, those relying on renewable water sources instead of nonrenewable groundwater, and caused a worsening of average economic gain and its stability. This is the consequence of nonrational decisions (Di Baldassarre et al., 2019; Schill et al., 2019) and experiential lock-ins (Payo et al., 2016) and might be exacerbated by policies that undermine the sociocultural underpinnings of collective action in traditional societies (Basel et al., 2021).

All in all, climate change and feedbacks between social, hydrological and climate systems (Basel et al., 2022) could enhance the environmental fragility–economic poverty vicious circle (Cheng et al., 2019) and undermine food systems, leading to unintended consequences. These feedbacks and the place for sociohydrological understanding of collective, traditional or individualistic behavioural outcomes are particularly strong when considering smallholder farming. For example, cropping decisions in the Dhidhessa basin (Ethiopia) were influenced by lower sensitivity of crop prices to rainfall variability and farmers' expectations regarding the same, inducing more climate resilience into the system, unravelling the endogenous role of crop prices resulting from the culture of crop diversification and leading to climate-resilient agriculture (Teweldebrihan et al., 2021). In Oaxaca (Mexico), agriculture-dependent Zapotec communities experiencing extended drought self-organised for collective action to implement small-scale managed aquifer recharge (MAR; Basel et al., 2021). Here however, if the individual water-use behaviour is not distinguished from the adoption of technologies such as MAR, it may exacerbate the drought conditions due to overuse of saved water due to misperception of water abundance (i.e., another example of the rebound effect) (Kallis, 2010; Gohari et al., 2013; Di Baldassarre et al., 2019; Basel et al., 2021). Meltwater-dependent irrigated agriculture, which is crucial for livelihood security of mountain communities, also requires adaptive efforts for climate change resilience (Nüsser et al., 2019b). Changes in seasonal snow cover can lead to water scarcity; such situations can be compounded by infrastructural interventions such as dams (Nüsser, 2017; Nüsser et al., 2019a). Collective action or not, adapting to such changes through adoption of 'artificial glaciers', have to be understood in terms of the benefits perceived by farmers, including perceived reduction in water scarcity, perceived risks of crop failure and the possibility to grow cash crops (Nüsser et al., 2019a).

These examples, among many, clearly show the importance of considering not only whether a specific climate change adaptation is technically feasible, but more importantly whether it is also socially and individually acceptable (i.e., in line with perceived risk, attitudes, abilities and preferences), in how without these measures the human–agricultural water systems may evolve to undesirable states. Sociohydrology recognises that humans are the agents of change, whose actions are mediated by their perceptions of risks, cultural norms, perceptions of risks and ownership of resources. These perceptions may vary from person to person, as a result of which individuals in similar environments respond differently in terms of, for example, their use of water (Daniel et al., 2022). Moreover, individuals tend to continually develop their unique lenses to focus, categorise and interpret information (Elliott, 2003) and perceive the world differently based on personal experiences and reflective learning (Kuil et al., 2018). This calls for novel methods based on behavioural theories to improve the understanding of human decision-making that is unique to sociohydrology (Bertassello et al., 2021). Without effective behavioural prediction, efforts to introduce policy and initiatives for innovation to build resilience against global environmental change may turn out to be ineffective (Weersink and Fulton, 2020) (Figure 1).

Incorporating human behaviour into sociohydrological understanding

In earlier sociohydrological works, efforts to endogenise human agency (Pande and Sivapalan, 2017) led to the conception of social state variables such as environmental awareness (van Emmerik et al., 2014) or community sensitivity (Elshafei et al., 2014) (e.g., towards the health of the environment), that are consistent with the values, beliefs and norms sociological theory (Wei et al., 2017). These were incorporated into system dynamics models to explain emergent phenomena of pendulum swings in agricultural systems (Roobavannan et al., 2017). Other models assumed that humans are rational beings able to evaluate options and maximise their well-being in interpreting rise and dispersal of water-scarce societies (Pande et al., 2014).

Several studies have developed dynamic sociohydrological models based on insights from psychology and sociology and applied them in agricultural contexts. Kuil et al. (2018) investigated smallholders' cropping and water allocation choices by developing a sociohydrological model based on the theory of bounded rationality (which assumes that rational behaviour is bounded by practical considerations like the availability of information and time, Simon, 1955). With an application in Kenya's Upper Ewaso Ng'iro, the model simulated the rebound effect and found that while different perceptions of water availability could lead to different cropping patterns, near-optimal similar cropping patterns would also emerge. Studies have also used agent-based models (ABMs) extensively to capture heterogeneities in socioeconomic characteristics and behaviour of farmers (Pouladi et al., 2019, 2020; Kasargodu Anebagilu et al., 2021; Wens et al., 2020, 2022). Agent-based models were developed to explain the catastrophic shrinkage of Lake Urmia (Iran), using questionnaires and field observations based on the theory of planned behaviour (TPB, which consists of attitudes, subjective norms and perceived control shaping a certain behaviour, Ajzen, 1991) and a data mining technique (Pouladi et al., 2020) to generate behavioural rules for farmer agents for performing their agricultural practices. More complex psychological approaches towards behavioural change, built on multiple theories including the TPB, have also been used to explain farmers' socioeconomic characteristics and behavioural perceptions which drive/prevent them towards/from adopting irrigation technologies in drought-prone regions of Maharashtra, India (Hatch et al., 2022).

A further level of complexity is the social structure and its slow evolution as a result of changes in external drivers (e.g., climatic conditions) and internal dynamics (e.g., via adaptation). For instance, social cohesion (via the role of mutualism) emerged as an important force buffering against water availability stresses, in conceptualising a community-managed irrigation system in New Mexico (Gunda et al., 2018). Collective human actions in response to water scarcity may have even led to the rise (and dispersal) of ancient civilisations via technological progress, economic growth and environmental degradation, arising from intrinsic endogenous processes, as is shown by Pande and Ertsen (2014) for the Indus and Hokoham civilisations. Moreover, the inclusion of institutional arrangements can disentangle social processes into rules (norms), behavioural choices towards these arrangements (whether society

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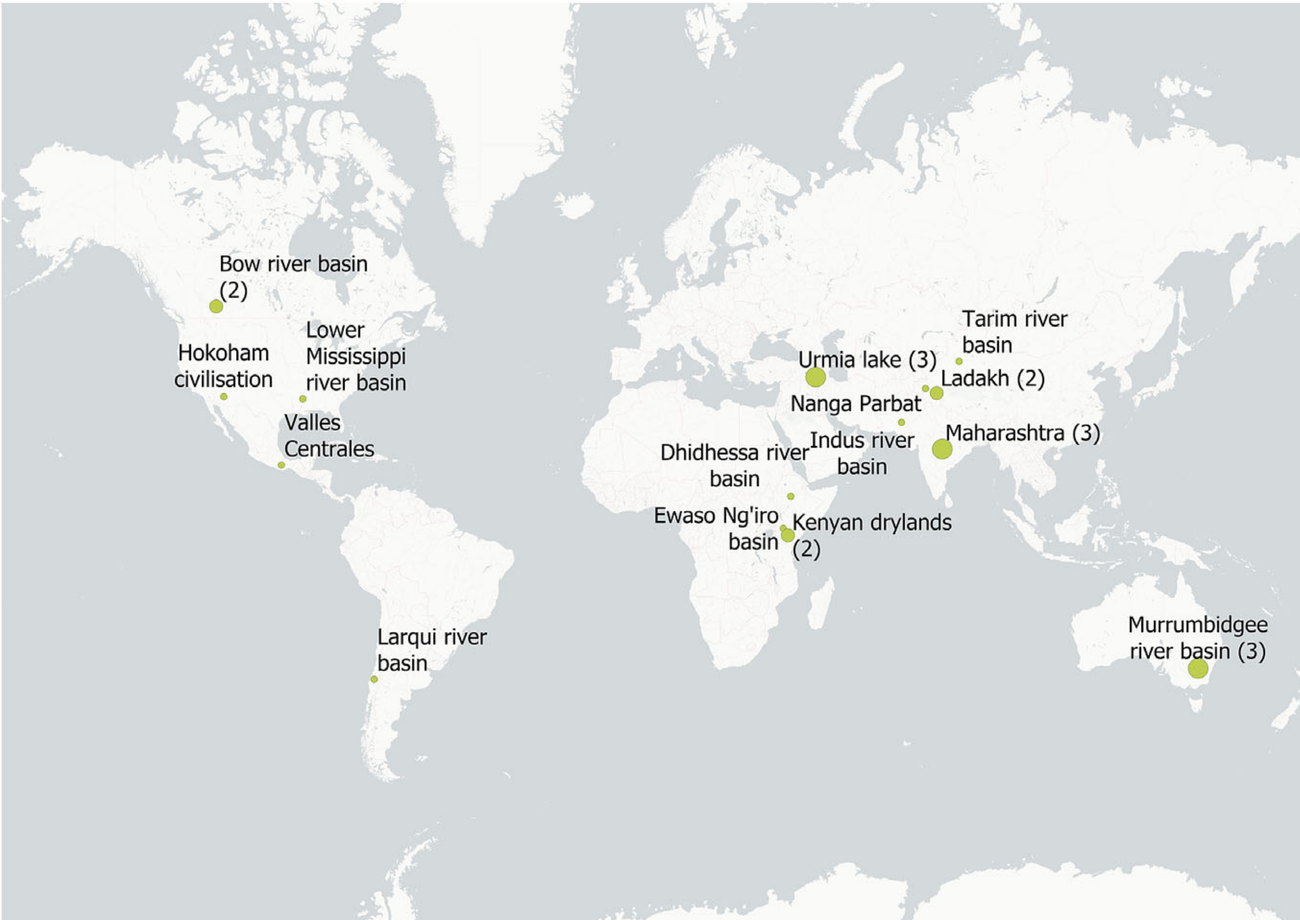

Figure 1. Different case studies related to agriculture investigated by sociohydrological research covered in this review. The size of the bubble indicates the number of publications associated with the particular region (which is mentioned in brackets, if >1).

abides by them or opposes them) and situational factors influencing decision-making (like social memory) (Konar et al., 2019).

Such sociohydrological studies suggest that human agents such as agriculturalists often tend to not make rational or optimal decisions, particularly while facing uncertainty in terms of biophysical and socioeconomic circumstances (Tittonell et al., 2010; Richard Eiser et al., 2012; Howley et al., 2015). In particular, their motivations to adapt or adopt agriculture water practices and technologies can extend beyond purely economic (profit) considerations. These extend towards social, psychological and cognitive factors, for example, perception of risk, that may influence their individual behaviour, and cultural or institutional factors that may condition what farmer may perceive to be a normal practice (Konar et al., 2019; Weersink and Fulton, 2020; Nair and Thomas, 2022). This has been demonstrated in examples on low-adoption of wells and irrigation measures (Sampson and Perry, 2019; Nair and Thomas, 2022), among others. Moreover, rather than being a binary (yes/no) decision, adoption-related decision-making is a multistage process, starting with awareness (of the existence of the technology/solution), followed by evaluation (of using the technology), adoption and revision/dis-adoption based on further changes in circumstances (Weersink and Fulton, 2020). While economic considerations are important during the later stages of the adoption process, social and cognitive factors may be more influential during the earlier stages (of awareness and evaluation).

While these studies have been geared towards understanding human–agricultural systems better, there is scope to consider aspects that could make such systems more resilient against global environmental change (Penny and Goddard, 2018). The body of knowledge generated by incorporating human behaviour informs us about how agriculturalists may adopt good agricultural interventions. The gap which remains is to identify the set of interventions that would make the system resilient for agriculturalists. Sociohydrological studies have highlighted, for example, that the Murrumbidgee River basin was more resilient due to its diversified economy and therefore was able to transition to a less-water-intensive economy within the basin. However this proved to be difficult for desiccated lake basins (like Aral Sea) whose economy singularly depended on agriculture (Pande et al., 2020). This alludes to 'diversity', one desirable property (of many) exemplifying resilient systems. The following section discusses the way forward for understanding what resilience could mean to agriculturalists.

Emerging sociohydrological issues: Integrating resilience thinking into agricultural water and for agriculturalists

Resilience, the capacity of systems to function and develop with change and uncertainty is a vital need for agricultural systems (Morecroft et al., 2012; Ward, 2022). While resilience concepts may be inherent to sociohydrology, there is much scope to incorporate key resilience attributes (diversity, redundancy, connectivity, adaptive learning and inclusivity and equity) more explicitly while conceptually framing sociohydrological problems (Penny and Goddard, 2018; Rockström et al., 2023), potentially improving interpretations of unintended consequences.

Diversity (e.g., biodiversity and diversified livelihoods) increases system flexibility through the ability to respond in multiple ways to systemic changes or external shocks (Rockström et al., 2023). Redundancy ensures system functioning and reduces the chances of single-point failure (Rockström et al., 2023). Diversity and redundancy work in tandem so that multiple functionally similar system elements respond differently to disturbances to enhance resilience (Penny and Goddard, 2018). Sociohydrological studies could more explicitly incorporate diversity and redundancy attributes to test hypotheses such as the effect of too little or too much diversity on system resilience (Penny and Goddard, 2018).

Connectivity relates to how resources, information, species or people interact within systems and higher connectivity can facilitate knowledge transfer, learning and enhance resilience (Penny and Goddard, 2018; Rockström et al., 2023). While sociohydrological models have incorporated connectivity through the flow of capital (Pande and Savenije, 2016), migration of people (Elshafei et al., 2014) or pathways of processing information (Kuil et al., 2018), intra-community connectivity can be further explored through agent-based analyses of social networks (Penny and Goddard, 2018).

Learning can be both individual and collective (social or institutional) and has been conceptualised as a multilayered iterative process (Medema et al., 2014). Single-loop learning, focussing on correcting errors by changing behaviour, is evident in how Pande and Savenije (2016) model smallholder farmers to adjust their actions based on their capital (Medema et al., 2014; Penny and Goddard, 2018). Double-loop learning, which includes an examination of the underlying values and policies within a system to facilitate such corrections, can be seen in community sensitivity studies where societies change their underlying behaviour from environmentally exploitative to restorative (Elshafei et al., 2014; Medema et al., 2014; Penny and Goddard, 2018). Similarly, while learning (generation of new knowledge) and consequent experimentation (by farmers in their decision-making) has been explored in some studies (Kuil et al., 2018), such dynamics can be further explored in the context of adoption or behavioural change.

Equity and inclusion, via participation (i.e., engaging relevant stakeholders in managing and governing systems), is key to resilience due to its role in collective action and cooperation and can be shaped by power dynamics (Leitch et al., 2015; Hahn and Nykvist, 2017). Inclusive and equitable value chains with social safety nets for vulnerable sections can enhance resilience (Rockström et al., 2023). Without addressing and transforming historical inequities, rapid shifts from top–down approaches to more holistic ones will not result in increased resilience and successful adaptation. This is applicable to both water used by agriculturalists and in agriculture. Adding power dynamics as inputs that vary water manipulation can lead to understanding alternative outputs that affect people based on their sociodemographics.

Referring to water used by agriculturalists, accessibility refers to the ability of people to access the physical, economic and information means to attain nearby water safely and without discrimination, including the ability of people to participate in water decision-making. Unfortunately, discrimination undermines attempts for universal access. Some people are prevented from accessing water because of their race, ethnicity, nationality, income, gender, ability, age or other social categories. For example, in an investigation of arsenic contamination in Bangladesh, Sultana (2007) drew attention to the numerous ways through which gender, intersecting with social class, age and geographic location, influenced water access, control and exposure to water. Yet, at least in low-income countries, women often control water reliability in rural areas through water hauling (Zwarteveen, 1997; Meinzen-Dick and Zwarteveen, 1998; Were et al., 2008). At least one study found that women leaders invested more in drinking water resources than men (Chattopadhyay and Duflo, 2004). Despite the global advances made in gender equity, women commonly feel excluded and underrepresented in decision-making around water (Haeffner et al., 2017). As water becomes less of a service and more of a commodity to be bought and sold on the open market, households need purchasing power to access water (Bakker, 2001). However, water prices have outpaced inflation (Cardoso and Wichman, 2022). Water affordability refers to the price households pay for water but is also related to the costs of extracting, treating and delivering water since these costs are often passed down to end users through tariffs. Water unaffordability has become more prevalent in high- and low-income countries alike (Mack and Wrase, 2017; Vanhille et al., 2018). Water pricing, too, is socially differentiated from rural users sometimes paying more for trucked or kiosk water than urban users relying on pipes (Haeffner et al., 2017; Pihljak et al., 2021). Moreover, a governmental solution such as raising prices to encourage water conservation may have the desired effect for affluent households but increase water insecurity for low-income households (Savelli et al., 2021). Instead, a sociohydrological perspective has the potential to enable us to identify the areas that are missing or ignored and contribute to advancing current models of measuring water poverty. In the case of agricultural water, while processes of inclusion (or financial exclusion of smallholders based on power dynamics) have been implicitly explored by models (Elshafei et al., 2014; Pande and Savenije, 2016), the mechanisms of how participation can transform social preferences into environmental decisions can be understood and incorporated more explicitly in sociohydrology.

Traditional societies may have had certain desirable attributes that lead to climate-resilient outcomes (Berkes et al., 1995; Usher et al., 2021). These are often linked to culture and other informal institutions that govern water use in a sustainable manner. However, culture and institutions are slow moving variables that take generations to change and only influence individual decision-making and collective actions via norms (Pande et al., 2020).

Policies developed and implemented without adequate prediction of behaviour, or including different perspectives (across gender, or of upstream and downstream residents) in a participatory manner, can be ineffective (Baker et al., 2015; Chen et al., 2016; Weersink and Fulton, 2020). Resilient systems are diverse with inbuilt redundancies, but positivist approaches in hydrological sciences have historically been focussed on efficiency which often has to be introduced at the expense of redundancies or diversity in the system (Morecroft et al., 2012). Sociohydrology, with its post-positivist approaches, can potentially play a significant role in informing such policies by understanding complex system dynamics (including attributes linked to resilience), offering alternatives to sustainable intensification or enhanced irrigation efficiencies (Scott et al., 2014).

Martínez-Valderrama et al. (2023) recommend complex policy mixes aimed at reducing the water supply–demand gaps (also considering climate change) via actions at many levels (rural vs. urban; structural vs. nonstructural; local vs. global), highlighting the effectiveness of a "cocktail of solutions" approach over single solutions. Sociohydrology similarly offers multilevel and multiple-source approaches to conceptualise and assess agricultural water and climate policies, such as narrative approaches combined with document analysis and other sources of water system information to describe policy pathways at different governance levels and scales (Yu et al., 2022). Furthermore, more robust and representative sociohydrological modelling incorporating resilience aspects can be used to simulate scenarios arising from different policies with added realism, evaluate potential unintended consequences and test alternative scenarios to iteratively inform policy development.

Conclusions and ways forward

Sociohydrology, as an interdisciplinary field, is placed well to understand and describe the interlinkages between agriculture, water and food security. This review examined how sociohydrology can explain the emergent dynamics of agricultural systems, account for climate change impacts due to/on agriculture and incorporate human behaviour into the description of agricultural water systems. Sociohydrological models have investigated the unintended consequences of water management interventions in agriculture (such as rebound or reservoir effects), highlighting the importance of accounting for such emergent phenomena to avoid unsustainable outcomes, degradation of natural resources or reinforcing existing inequalities. Sociohydrology also highlights why climate adaptation measures need to consider unintended consequences as well as individual behaviour (of individuals and communities), particularly for smallholders affected disproportionately by climate change impacts. Farmers can make apparently nonrational agricultural decisions due to their unique perspectives and experiences, bound by practical considerations. In this regard, sociohydrological models have considered social and psychological insights and have used novel data sources and diverse multi-method approaches to model human behaviour.

Sociohydrology has been used in understanding policy development for agriculture by investigating demand management measures, technology adoption and incentives for behaviour change to improve water-use efficiency and sustainable intensification. However, identified as a gap, this review proposed that sociohydrology can incorporate resilience thinking more explicitly to understand susceptibility of agricultural systems and agriculturalists to global change and uncertainties (in human–water systems) and possible unintended consequences resulting from agricultural policy. By accounting for technical approaches, earth sciences and the complexity of human behaviour, such interdisciplinary understanding can better inform agricultural policy, from conceptualisation (to initially identify and potentially avoid unintended consequences) to appropriate modifications (based on changes in the contexts of water, human behaviour or institutions).

This review thus positioned sociohydrology in how it has been incorporating social–scientific perspectives in agricultural water systems, identified key gaps in terms of desirable properties that are missing in current models to interpret climate resilience and consequently to develop policies which can enable more accessible, equitable, affordable and holistic solutions for improved resilience and successful adaptation.

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