Hydrological Sciences Journal

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/thsj20

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To cite this article: David J. Yu, Melissa Haeffner, Hanseok Jeong, Saket Pande, Juliane Dame, Giuliano Di Baldassarre, Glenda Garcia-Santos, Leon Hermans, Rachata Muneepeerakul, Fernando Nardi, Matthew R. Sanderson, Fuqiang Tian, Yongping Wei, Josepha Wessels & Murugesu Sivapalan (2022) On capturing human agency and methodological interdisciplinarity in socio-hydrology research, Hydrological Sciences Journal, 67:13, 1905-1916, DOI: 10.1080/02626667.2022.2114836

To link to this article: https://doi.org/10.1080/02626667.2022.2114836

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Published online: 10 Oct 2022.

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HYDROLOGICAL SCIENCES JOURNAL
2022, VOL. 67, NO. 13, 1905–1916
https://doi.org/10.1080/02626667.2022.2114836

SPECIAL ISSUE: ADVANCING SOCIO-HYDROLOGY – COMMENTARY

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On capturing human agency and methodological interdisciplinarity in socio-hydrology research

David J. Yu[a,b], Melissa Haeffner[c], Hanseok Jeong[d], Saket Pande[e], Juliane Dame[f,g], Giuliano Di Baldassarre[h], Glenda Garcia-Santos[i], Leon Hermans[j,k], Rachata Muneepeerakul[l], Fernando Nardi[m,n], Matthew R. Sanderson[o,p], Fuqiang Tian[q], Yongping Wei[r], Josepha Wessels[s] and Murugesu Sivapalan[t,u]

[a]Lyles School of Civil Engineering, Purdue University, West Lafayette, Indiana, USA; [b]Department of Political Science, Purdue University, West Lafayette, Indiana, USA; [c]Department of Environmental Science and Management, Portland State University, Portland, Oregon, USA; [d]Department of Environmental Engineering, Seoul National University of Science and Technology, Seoul, Republic of Korea; [e]Department of Water Management, Delft University of Technology, Delft, Netherlands; [f]South Asia Institute, Heidelberg University, Heidelberg, Germany; [g]Department of Geography, Bonn University, Bonn, Germany; [h]Department of Earth Sciences, Uppsala University, Uppsala, Sweden; [i]Department of Geography, University of Klagenfurt, Klagenfurt, Austria; [j]Department of Land and Water Management, IHE Delft, Delft, Netherlands; [k]Department of Multi-Actor Systems, Delft University of Technology, Delft, Netherlands; [l]Department of Agricultural and Biological Engineering, University of Florida, Gainesville, Florida, USA; [m]Water Resources Research and Documentation Centre (WARREDOC), University for Foreigners of Perugia, Perugia, Italy; [n]Institute of Environment and College of Arts, Sciences & Education (CASE), Florida International University (FIU), Miami, Florida, USA; [o]Department of Sociology, Kansas State University, Manhattan, Kansas, USA; [p]Department of Geography and Geospatial Sciences, Kansas State University, Manhattan, Kansas, USA; [q]Department of Hydraulic Engineering, Tsinghua University, Beijing, China; [r]School of Earth and Environmental Sciences, The University of Queensland, St Lucia, Australia; [s]Communication for Development, School of Arts and Communication, Malmö University, Malmö, Sweden; [t]Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA; [u]Department of Geography and Geographic Information Science, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA

ABSTRACT

Socio-hydrology has expanded and been effective in exposing the hydrological community to ideas and approaches from other scientific disciplines, and social sciences in particular. Yet it still has much to explore regarding how to capture human agency and how to combine different methods and disciplinary views from both the hydrological and the social sciences to develop knowledge. A useful starting ground is noting that the complexity of human–water relations is due to interactions not only across spatial and temporal scales but also across different organizational levels of social systems. This calls for consideration of another analytical scale, the human organizational scale, and interdisciplinarity in study methods. Based on the papers published in this journal's Special Issue *Advancing Socio-hydrology* over 2019–2022, this paper illuminates how the understanding of coupled human–water systems can be strengthened by capturing the multi-level nature of human decision making and by applying an interdisciplinary multi-method approach.

ARTICLE HISTORY
Received 27 July 2022
Accepted 3 August 2022

EDITOR
S. Archfield

GUEST EDITOR
(not assigned)

KEYWORDS
socio-hydrology; interdisciplinary multi-method approach; multi-level; multi-scale; human–water relations; organizational complexity

Introduction

As the extent of human activity on Earth and in the water environments accelerates, it is becoming increasingly important to recognize society and water systems as truly interdependent systems and the subtle interactions that shape outcomes (Sivapalan 2015). In coupled human–water systems, multiple water and social processes with different characteristic (temporal and spatial) scales can be relevant, and these processes are often connected in ways that are not obvious (Blair and Buytaert 2016). Local or short-term processes in physical and social domains can be linked to global or long-term processes through a mesh of interconnections. Making sense out of such complexity is already a difficult task, but the challenge multiplies when we begin to consider the fact that humans exhibit agency in decision making (Pande and Sivapalan 2017). That is, humans are capable of making freewill actions and have the potential to act differently in seemingly similar situations because their decisions can be sensitive to contextual factors, such as underlying sociocultural and biophysical conditions (Ostrom 1998, Bandura 2001). In particular, human agency often involves multiple or nested levels of decision making that influence what actions are taken by which actors, e.g. an infrastructure manager's decisions on local water infrastructure is not free from the influences of decisions made by local- and federal-level governments and household-level behavioural traits (Yu *et al.* 2020). This multi-level nature of human decision making, therefore, should be of significance in understanding why a given water resources-related problem occurs in one context but not in another. Hydrology alone is not sufficient to tackle this type of understanding. Multiple disciplinary views and methods from both the natural and social sciences are needed to achieve a fuller understanding of such complex human–water systems (Tress *et al.* 2005).

CONTACT Saket Pande S.Pande@tudelft.nl Delft University of Technology, Stevinweg 1, 2628CN, Delft, Netherlands

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Socio-hydrology is an interdisciplinary science of coupled human–water systems that is well suited to take on the challenge outlined above. Socio-hydrology aims to understand the relationships between how human agents process external stimuli and make decisions and how such decisions affect the water environment and society (Konar *et al.* 2019). One of the main achievements of socio-hydrology as a research programme has been exposing the hydrological community to concepts, ideas, and approaches from other scientific disciplines, and social science in particular. But the field of socio-hydrology still has much to explore in terms of capturing the multi-level nature of human agency and how to use an interdisciplinary approach (i.e. combining methods from two dissimilar fields such as hydrology and political science) to develop knowledge. This view is echoed by the invited paper series "Debates – Perspectives on Socio-hydrology," which was organized by *Water Resources Research* in 2015 to provide a scientific forum on socio-hydrology (Di Baldassarre *et al.* 2015, Gober and Wheater 2015, Loucks 2015, Sivapalan 2015, Troy *et al.* 2015). The invited authors commented on a conceptual model of human–flood interaction proposed by Di Baldassarre *et al.* (2015) that simulated the observed pattern of the *levee effect*, the observation that heavy reliance on flood protection structures and the resulting non-occurrence of frequent flooding is often associated with a rise in long-term vulnerability. Human agency in this work is simplified or "lumped" to a single level: the level of society. Depending on the degree of societal memory of floods, the model society adjusts its decisions on investments to flood protection structures and on floodplain settlement. The invited papers offered useful ideas about human agency representation and methodological approaches regarding the levee effect. Loucks (2015) highlighted that human system response to change in water systems can be surprising and is difficult to predict because human decisions are sensitive to contexts. Gober and Wheater (2015) emphasized that, because of the lumped nature of the model's social variables, its representation of social processes is over-simplified. They also suggested additional approaches and theories that can be incorporated to strengthen the model. In a similar vein, Troy *et al.* (2015) underscored the difficulty of validating socio-hydrology models, especially the human system part.

Emerging from the foregoing discussion is a gap in the field: although using lumped social variables and coupling them to physical processes make systems modelling and analysis tractable, they pose challenges to capturing human agency and explaining why some phenomenon occurs in one context and not in another context. Also, because of the heavy reliance on model-based simulations and the inherent complexity of human–water systems, there are difficulties to validating hypotheses (Troy *et al.* 2015). This raises two key themes for further reflection by the socio-hydrology community. (1) How can human–water interactions with multiple levels of decision making and human agency be represented and studied? (2) How can an interdisciplinary multi-method approach be used to better understand such human–water systems? Note that an interdisciplinary multi-method approach here refers to attempts that integrate methods used in two or more disparate disciplines (e.g. combining methods for representing natural system dynamics, experimentally testing human behaviour, and for extracting thematic topics from human conversations, as illustrated by Janssen *et al.* 2010 and Yu *et al.* 2016) as opposed to those that integrate multiple methods used in the same field or closely related fields (e.g. applying time-domain reflectometry and gravimetric methods to determine soil moisture).

Contributing to further reflection on these two themes is the goal of this commentary paper. In approaching this aim, we focus on the papers accepted or published as part of the *Hydrological Sciences Journal*'s Virtual Special Issue *Advancing Socio-hydrology*. We probed the special issue papers to examine recent trends with respect to these two key themes. Although still few in number, we observe more serious attempts to capture multiple levels of social systems and to combine methods from both the hydrological and social sciences to develop a multifaceted understanding of human–water systems. This special issue accepted submission of papers concerning an interdisciplinary approach to socio-hydrology over 2019–2022. These papers, therefore, provide a glimpse into the latest developments regarding our interest.

This commentary proceeds as follows. In Section 2, we discuss human organization as an independent scale of analysis for studying socio-hydrological phenomena, different organizational levels that social units can occupy, and the implications for capturing the multi-level nature of human agency. We then go over how recently published papers in the Virtual Special Issue dealt with this aspect. In Section 3, we describe key aspects that can be used to guide an interdisciplinary multi-method approach to socio-hydrology research. This is followed by a discussion of trends observed in the special issue papers regarding the use of interdisciplinary methods. Lastly, we provide a synthesis and a way forward regarding how to achieve methodological and disciplinary cross-fertilization for theory development in socio-hydrology.

Capturing human agency: space, time, and human organization

Socio-hydrological phenomena often involve physical and social processes that play out across multiple scales and levels in ways that are not obvious. In this section, we discuss why one should consider these processes not only at different spatial and time scales but also at another scale related to human agency to better understand such phenomena. Also, as we shall show in the third section, it is important to know what scales and levels are relevant for the focal variables and theories because they can influence the choice of methods for interdisciplinary research.

Following Gibson *et al.* (2000) and Cash *et al.* (2006), we use the term "scale" to mean a spatial, temporal, or any other analytical dimension that can be used to study a phenomenon and the term "level" to mean the units of analysis at different gradients of specificity on a scale (e.g. monthly and decadal levels in the time dimension). Figure 1 illustrates some of the scales and levels relevant for understanding human–water interactions. However, in contrast to the spatial and temporal

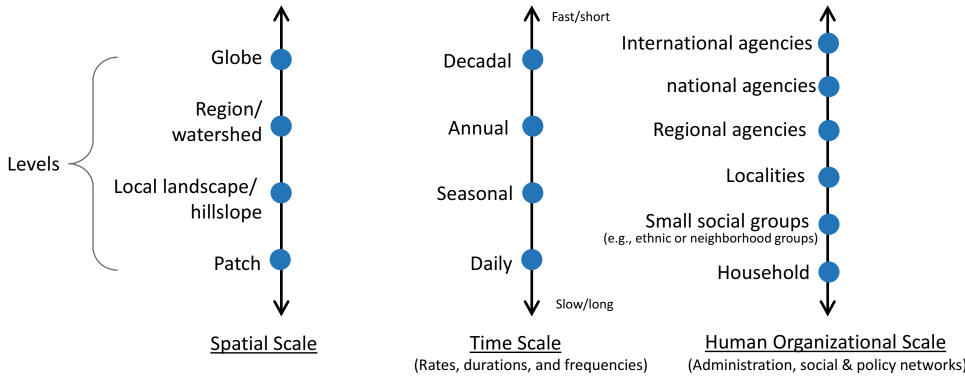

Figure 1. Schematic illustration of different scales and levels that are relevant for understanding human–water interactions.

scales (which are well known and widely explored), a characteristic scale of human social systems – namely, the spectrum of human organizational complexity (the rightmost vertical line in Fig. 1) – is often ignored or abstracted away in studies of coupled human–water systems (Pande and Ertsen 2014). Just like time and space, the spectrum of organizational complexity is an analytical dimension that can be used to study a phenomenon. Varying levels of human organizations – from small social groups (e.g. households, neighbourhood associations, etc.) to local water utilities and government and federal agencies and government – represent different units of analysis within the *human organizational scale*. Although there is a strong correlation between the spatial and human organizational scales, they are not identical. For example, the spatial extents of the European Union and Antarctica are large and comparable, but the latter is much smaller in terms of social complexity. In fact, certain sub-fields of research in the social sciences, such as polycentric governance (Ostrom 2010) and cultural multi-level selection (Waring *et al.* 2015), consider the human organizational scale to be so important that their focus of analysis is centred around how interactions within and around different levels of social systems shape policy outcomes and cultural change.

It is crucial to realize that human decisions on water can occur at different levels within the nested structure of human social systems and that these level-dependent decisions can be interlinked to shape human agency, e.g. household-level water conservation decisions can affect and be affected by the decisions made at the levels of local and federal governments and water utilities. Consider, for example, the phenomenon of the levee effect (White 1942, Montz and Tobin 2008, Di Baldassarre *et al.* 2013), which has been the subject of multiple socio-hydrology studies (Fig. 2). This phenomenon involves multiple levels and scales of the relevant physical and social processes, including different levels of human organizations. Inclusion or exclusion of this nature may make a difference in explaining why the levee effect occurs in one setting and not in others. Here we cast the three scales introduced in Fig. 1 (spatial, time, and human organizational) onto four variables: flood vulnerability of social units along the spatial scale, flood vulnerability of social units along the time scale, human agency and flood memory along the human organizational scale, and assets or capacity for response along the spatial scale (Fig. 2). Suppose that frequent flooding negatively affects a local city and people, e.g. the system's vulnerability is manifested at the levels of local landscape and seasonal or inter-annual timing

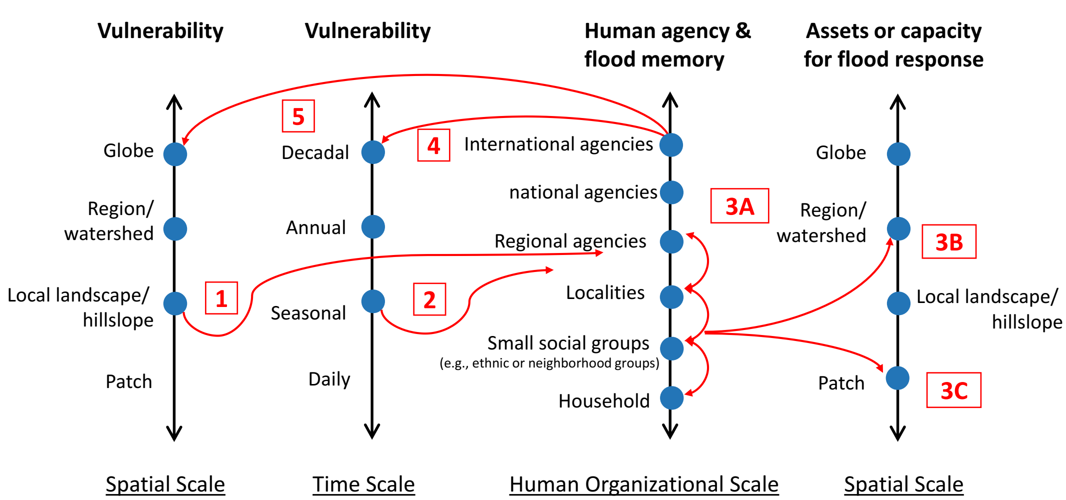

Figure 2. Schematic illustration of human–flood interactions across scales and levels leading to the levee effect with multiple levels of human agency. Here we cast the three scales introduced in Fig. 1 (spatial, time, and human organization) onto four variables: flood vulnerability of social units along the spatial scale, flood vulnerability of social units along the time scale, human agency and flood memory along the human organizational scale, and assets or capacity for response along the spatial scale.

(arrows 1 and 2 in Fig. 2). How would the city and its society respond to this short-term, localized vulnerability? Perhaps one should consider that the preferred decision and flood memory of social units can vary at different human organizational levels. Competitive or cooperative interactions across different levels of social groups can influence outcomes (arrows 3A). One possibility is that the community and its local government organize actions to further raise the levees. But a federal agency and neighbouring communities might oppose that decision because of the transference of the risk elsewhere. Interventions and power dynamics across these multiple levels of human decision making can ultimately shape which trajectory is followed by the affected community – technological society (arrow 3B) vs. green society (arrow 3C).

If the path of green society is chosen, the assets and capacity for flood response would be more decentralized and distributed at the patch level. If the path of technology society is followed, the city's assets and capacity for flood response become more centralized and capital-intensive at the regional or watershed level in space. The resulting stability and the absence of flooding over a long time horizon lead to a gradual decay of societal flood memory and coping capacity. Population density and economic activities increase in the floodplain, possibly attracting manufacturing industries whose goods and services serve areas beyond the city. The end result is an increase in the vulnerability to a rarer flood event in the long run (arrow 4). It also spatially expands vulnerability because most cities are tele-connected through global market systems (arrow 5). Furthermore, it is crucial to note that outcomes of such multi-level dynamics can be sensitive to underlying biophysical or social contexts because of human agency. Abstracting these nuances into a single construct may oversimplify important social processes that shape future social responses. To get at this complexity, one should consider not only these processes at different spatial and time scales but also the multi-level nature of social systems and human agency.

However, the lack of consideration of the human organizational scale has been a key shortcoming of many socio-hydrology studies. Below, we probe how the studies in the current special issue have dealt with or improved upon earlier understanding in this regard.

Multi-level analysis in disaster risk management

Several papers in the special issue considered two or more levels of a scale with respect to phenomena and processes being studied. Alonso Vicario *et al.* (2020) developed a flood evacuation model that includes the linkages between the hazard, the built environment, the population, and the civil protection members. Their model captures multiple levels of the social system and interactions across these levels. For example, an emergency agency and its staff communicate to individuals that they are not allowed to cross the rivers when flooding occurs; individuals react when seeing a flood close to them and change their direction on the roads. Evacuees also may follow other groups of people that are evacuating ahead of them. Vanelli and Kobiyama (2021) argued that socio-hydrology should incorporate disaster risk management. They also observed that although the river basin is an appropriate level of analysis for many hydrological studies, it is not necessarily ideal for socio-hydrological studies. The researcher must be cognizant of the feedback dynamics spiralling up and down scales, or what the authors referred to as the "glocal" scale, to overcome the global–local dichotomy. With the focus on the bidirectional feedback between water systems and society, socio-hydrology has much to contribute to disaster risk reduction.

Multi-level analysis in water policy and planning

A critical element in the chain of human–water interactions is public policymaking and planning, whereby society formulates its attempts for a coordinated response to observed hydrological phenomena. Kim *et al.* (2021), Oneda and Barros (2021), Philip (2021), and Luan *et al.* (2022) look at this role of planning and policymaking. Kim *et al.* (2021) review the historical trajectories in policymaking over time, observing how water quality and pollution management policies evolved in the past decades, comparing experiences in the state of Oregon, USA, with those in South Korea. In doing so, they observe, for instance, how the early success with point-source pollution control triggered the policies to evolve into attempts to address the more "wicked" problem of non-point source management and, eventually, also beyond conventional pollutants. In their analysis, they pay attention to the multi-level nature of water quality policies, between federal, state, and local agencies in the USA, and through a more centralized political system for water quality management in South Korea.

Luan *et al.* (2022) investigate whether bidirectional feedbacks can be anticipated in planning, including the societal acceptance and implementation of policy interventions aimed at the water system. This also involves the question of multi-level governance, with national or regional plans and their expected uptake by local-level actors. The core focus of the study, though, is on four local communities within one of the provinces in the Vietnamese Mekong Delta. Even at this more local level, results show the differences across districts, and their implications for provincial-level planning.

Philip (2021) centres a very specific policy indicator in her research, the SDG11.3.1 (sustainable development goals) ratio of land consumption rate to population growth rate, and its implications for stormwater management for projected climate change in the city of Hamilton, Canada. The observed values and trends in this indicator are then linked to present land-use planning tools and future developments. This provides an interesting example of how a global policy effort and indicators such as the SDGs, combined with relevant national-, state-, and/or provincial-level actions and policies, transpire at local city levels to track and inform water management efforts and their effectiveness. Oneda and Barros (2021) analyse and compare stormwater management master plans in developed and developing cities, for two cities in Brazil and one city in Portugal. In terms of the interactions, the focus is mostly on analysing the social system response to water system dynamics and challenges. The urban-level analysis is contextualized within the larger hydrological systems and the higher (national-) level legislation and planning systems, but the focus is clearly on the city as the main level of analysis.

Garcia and Islam (2021) developed a water supply planning model that links the evolution of demand to water availability and water stress through the concept of water salience. In this model, water supply and associated infrastructure is at the regional/county level while demand management is at the city level. The case study is Las Vegas Valley Water District, the water distributor. Haeffner *et al.* (2021) argued that socio-hydrology should incorporate a representation justice focus that includes an understanding of how power and politics shape the interaction between humans and water in coupled systems and the composition of the water sector. They analyse interactions between employees and local water agencies over individual careers in the US.

Multi-level analysis of agricultural human–water systems

Khalifa *et al.* (2020) adopted an integrated approach that uses multiple sources of data to analyse the sorghum productivity gap, its temporal and spatial variation and the socio-hydrological determinants affecting the sorghum yield in the scheme. The key findings provide useful insights into potential pathways for sustainable irrigation in the Gezira Scheme and other irrigation schemes that are facing similar challenges. This study crossed several levels: water users at the individual level (smallholder farmers) and the group/community level, or a lumped variable at a population level ranging from community/city to region; water management at the scheme scale; and irrigation systems in large irrigated schemes.

Ross and Chang (2021) developed a system dynamics model (SDM) of a watershed-dependent socio-hydrological system to improve resilience and adaptive capacity to climate hazards. The SDM developed for the Hood River Basin (USA) comprised an upper-climate section that includes snowmelt, a middle section that includes glacial meltwater and precipitation runoff, and a lower-level section that includes irrigation withdrawals and streamflow. The SDM suggests that climate change leads to a decline in available irrigation water in the late summer. A cross-level perspective was included by assessing collaborative water management strategies among irrigators to respond to climate change's influence on streamflow.

Ghoreishi *et al.* (2021) developed an agricultural water demand model that included linkages between individual farmers, socio-economic factors, and agricultural water demand. Their model captured multiple levels of a social system, and interactions across the levels. For example, a farmer's decision about irrigation method, changing crops, and irrigation area was affected by other farmers' decisions and government subsidies; the individual's decision in turn influenced neighbours' decisions through a social network. Carr *et al.* (2021) developed a socio-hydrological model that included linkages between the capacity of local organizations, land use, agricultural practices, and water quality. The model involved cross-level interactions between farmers and local-level water committees. For example, farmers could change their land use and management practices depending on the support given by the local water committees and the regulation from the local Water Police.

Laurita *et al.* (2021) investigated conflictual water allocation between water users (farmers and local communities), which resulted in ecosystem services trade-off between productive services (agriculture) and provision and cultural services (biodiversity conservation, tourism, urban water supply). Interactions involved local farmers and communities directly and the Confederacion Hidrografica del Duero as a regulator. Farmers' satisfaction was linked to their ability to extract water for irrigation, and local communities' well-being was linked to the well-being of the river from which water is diverted and used for irrigation.

Multi-scale analysis

A smaller set of studies in the special issue explicitly considered two or more scales in their analyses. Hossain and Mertig (2020) examine how cross-national relationships and global position structure internal,= or domestic water footprints in 174 countries from 1996 to 2005. Cross-scale interactions are implicitly investigated through the assessment of world-system position on water consumption levels. They find that more developed, advanced countries are able to exploit water resources across the world through virtual water trade. Less developed or underdeveloped countries are thus disproportionately bearing the social and ecological consequences of global water stress, as the global water crisis is externalized from developed to less developed countries. Tamburino *et al.* (2020) develop an agent-based model that simulates a smallholder farming system. The model is calibrated for the Lower Mississippi River Basin and considers corn grown throughout the April–June growing season. They are able to understand the co-evolving relationship between climate, water, and human attitudes over varying time scales. Crop yield, net economic gain, and groundwater table depth evolve over time depending on changing climate conditions and farmers' attitudes.

Achieving an interdisciplinary multi-method research

Socio-hydrology research endeavours depend on the use of diverse perspectives and methods from both the physical and social sciences (Di Baldassarre *et al.* 2021). In an ideal world, researchers can teach themselves multiple relevant methods and theories and apply them as deemed necessary. In reality, however, gaining specialization in any given research method or theory is time consuming and requires significant investment (Poteete *et al.* 2010). This challenge is even greater when a serious cross-fertilization is attempted across dissimilar domains of science, i.e. hydrologists attempting to use the tools and concepts used by social scientists and vice versa. This means that a more probable path to socio-hydrology research is bringing in people with different toolkits and theoretical backgrounds to work together. Herein lies the value of an interdisciplinary multi-method approach: it can help hydrological and social scientists to be savvy about the language and basics of each other's methods. It can help them to be more aware of a variety of forms that a multi-method approach can take, the strengths and limits of such forms, and the degree to which different methods in the natural and social sciences are actually complementary. The need for interdisciplinary methods is also highlighted by several papers in the special issue (Ross and Chang 2020, Wine 2020, Bertassello *et al*. 2021, Hayashi *et al*. 2021, Thaler 2021).

However, it is not obvious to many how to structure an interdisciplinary multi-method approach for effective socio-hydrological research. The challenge lies not in attempting a laundry list of different methods, but in how to judiciously combine different methods in such a way that the methods are compatible with focal variables and theories and that the results and insights from one method help to inform and revisit those from other methods (e.g. Poteete *et al*. 2010). Although there is no straightforward answer, we suggest that there are two key aspects important to guiding one's thinking on how to organize interdisciplinary research.

The first aspect is knowing what scales and levels are relevant for the focal variables and theories under consideration. This is because the scales and levels involved with the focal variables and theories can influence which methods are more fitting than others. For example, if an analyst is interested in developing a system-level understanding using theories like dynamical systems theory and complex adaptive systems thinking, methods such as system dynamics and agent-based modelling are more appropriate than others (Enteshari *et al.* 2020, Pouladi *et al*. 2020, Aghaie *et al*. 2021). Geographic information system (GIS), remote sensing, and archival analyses are necessary for analyses that cover larger spatial and time scales (Lopez-Alvarez *et al*. 2020, Dau and Adeloye 2021, Gaur *et al*. 2021).

Regarding human agency, hypotheses about human decision making at the level of individuals and small groups can benefit from standard data collection methods (e.g. surveys, interviews), high-resolution behavioural studies (e.g. behavioural experiments) and innovative human-driven observational data analytics supported by artificial intelligence, digital technologies and online communities (e.g. social network data mining, remote sensing and image processing). These methods can produce behavioural-level insights on human decisions and preferences. Hypotheses about human agency at larger organizational scales require analytical methods such as big data analysis, case studies, and comparative analysis. The increased interest and extent of citizen science and participatory approaches are demonstrating the scientific value of community engagement enlarging the quantity and diversity of observation's spatial and temporal scale (Etheridge *et al.* 2020, Torso *et al*. 2020, De Filippo *et al*. 2021, Souza *et al.* 2021).

The second aspect is knowing that the starting point of many socio-hydrology research endeavours is identifying a socio-hydrological phenomenon and potential explanatory hypotheses and that it is almost impossible to do true experiments with coupled human–water systems to establish causal inference (i.e. experimentally testing whether a factor X causes a phenomenon Y). Because of this nature, we think there is a recurring methodological pattern in interdisciplinary approaches to studying socio-hydrology (Fig. 3). It begins with the identification of an emergent phenomenon, with rich details and associated key hypotheses based on a case study or comparative analysis of multiple case studies (link 1 in Fig. 3) (e.g. Fornés *et al*. 2021). These case studies are, of course, based on and informed by various data (link 2) collected by diverse methods (e.g. Medeiros and Sivapalan 2020, Palop-Donat *et al*. 2020, Frota *et al*. 2021, Nardi *et al*. 2021, Souza *et al*. 2021).

The observed phenomenon and potential explanatory hypotheses are then tested using either computational experiments or controlled experiments (links 3 and 6). Because it is difficult to do true experiments with real coupled human–water systems, computational and controlled experiments that capture the essential features of real systems are fitting methodological choices. System dynamics and agent-based models are often constructed for computational experiments (e.g. Lyu *et al*. 2020, Ridolfi *et al*. 2020, Homayounfar and Muneepeerakul 2021, Viola *et al*. 2021). These model systems

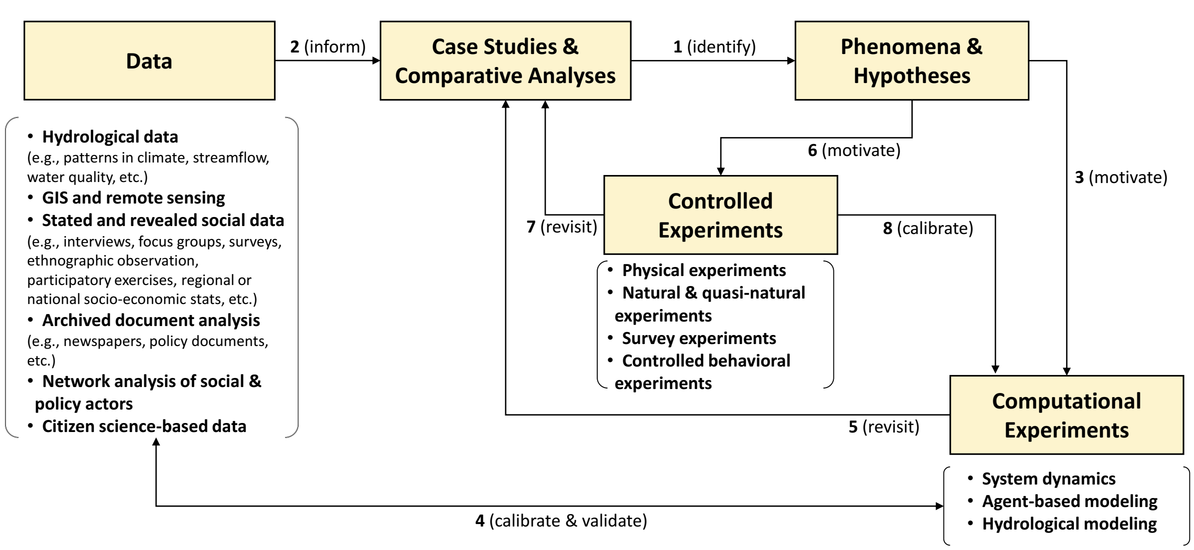

Figure 3. A methodological pattern in interdisciplinary approaches to studying socio-hydrology. GIS: geographic information system.

are simulated to see whether the qualitative behaviour of the model systems is consistent with the observed phenomena. If the target pattern is replicated, then the proposed hypotheses are taken as possible explanations of the observed phenomena until they are falsified (Pande and Sivapalan 2017). Various social and environmental data can be also used to calibrate and validate (link 4) these models. The results and insights obtained from such models can be also used to revisit the case studies (link 5). Meanwhile, controlled experiments that capture the essence of a focal socio-hydrological phenomenon can be conducted to test the identified hypotheses (link 6). For example, physical hydrologic experiments can be used for hypotheses related to physical water process. If the hypotheses concern human behaviour and social dynamics, controlled behavioural experiments and survey experiments can be conducted using human subjects to test hypotheses on how individuals make decisions under different conditions (e.g. McKee *et al.* 2020). The added benefit of such experimental studies is that the resulting data can also be used to revisit the initial case studies (link 7) and empirically ground or calibrate (link 8) the assumptions used in the systems models.

The methods and their linkages discussed above show the phenomena-driven nature of socio-hydrology research and how the scales and levels involved with the focal variables and theories can shape methodological design. Below, we organize the special issue papers in terms of diverse methodological combinations.

Multiple-source approaches

Kim *et al.* (2021) use a semi-structured narrative approach to describe policy development pathways. They distinguish three main historical stages that are described in terms of key policy features (legal aspects, government agencies, resources, civic actors). Information was obtained from document analysis (of policy documents, laws and journal articles), complemented with data on specific variables for the water systems in online databases and provided by the utilities in Oregon and South Korea. Philip (2021) combines data from different sources, including satellite images, to calculate the SDG 11.3.1 indicator values for three different time periods. These land-used and geographical analysis methods then are linked, in an interpretative manner, with more hydrological methods to develop intensity–duration–frequency (IDF) curves for stormwater management. This combination shows that, although the ratio of land use to population growth develops in desired directions, the trends in IDF curves nevertheless signal a need for future action in the city, to effectively employ land-use planning to confront climate change challenges.

Sarband *et al.* (2021) used multiple methods of compromise programming, fuzzy methods and distributed indicators to evaluate localized impacts of water allocation scenarios in Aras basin, Iran. Their use of distributed instead of lumped indicators enabled better determination of regional priorities and spatial tradeoffs of water allocation scenarios. Veloso *et al.* (2022) used the Carampangue River basin in Chile as an instrumental case study to investigate the interplay between preparedness and psycho-social attributes of communities exposed to river floods. They combined multiple research methods and integrated a hydrological analysis of floods with the results from a survey, social cartography, semi-structured non-participant observation, and semi-structured interviews.

Case studies, interviews, surveys, and spatial and statistical modelling

Mondino *et al.* (2020) applied multiple methods in their study: case study, comparative analysis, statistical analysis, and longitudinal survey/analysis. Case studies are used to motivate the analysis and questionnaire survey. They also comparatively analysed the two case communities. Longitudinal surveys and statistical analysis are done to understand over-time changes in the risk perception of people in the two communities. In their case study analysis of the Dhidhessa River Basin, Teweldebrihan *et al.* (2020) conducted a household survey in three study villages (n = 120), as well as key informant interviews and a focus group discussion. Secondary data (official statistics, including census data and population data) complement the analysis. The focal level is the study villages in the basin. In addition, the authors take into account a government resettlement programme as a main driver for migration.

Khalifa *et al.* (2020) used a combination of methods including case study, field survey, remote sensing, GIS, statistical modelling and statistical analysis. Case study was used to analyse an agriculture scheme. Field survey was used to understand socio-economic status and field practices of smallholder farmers that contribute to crop yield gaps. Remote sensing was used to analyse spatial and temporal variation in productivity gaps. The spatial and temporal variations of variables such as productivity level, precipitation and soil properties were analysed using GIS. Statistical modelling was used to understand the relationship between crop productivity, farmers' field practices and farmers' socio-economic status, as well as the relationship between crop productivity and physical variables such as water availability and soil properties.

Participatory approaches

Torso *et al.* (2020) applied participatory action research (PAR) and Indigenous research methodologies (IRM) in their study of hydrosocial systems in Idaho, USA, that are affected by mining. They apply the concept of *hydrosocial territories*, as developed by Boelens *et al.* (2016), to frame the impacts of mining and the politics surrounding it, and describe the judicial complexities of the community–university partnerships that were developed in the study. In a reflective paper on how these methods were implemented, Torso *et al.* (2020) concluded that both PAR and IRM led to a more inclusive and equitable research process whereby sharing data in a reciprocal relationship between the researchers and the community members was prioritized. This led to a better contextual understanding of power dimensions and appreciation of relational knowledge paradigms, as well as promotion of community capacity building.

Etheridge *et al.* (2020) employed public participation in two coastal communities affected by sea-level rise, hurricanes and flooding in North Carolina, USA. Both involved community-level social systems and lake watershed/island water systems. In the first study area, the participatory mapping at a public meeting was used to define the watershed boundary and determine pump locations. In the second study area, citizen scientists collected data on groundwater levels and surface water levels over a period of three months. In addition, a cost comparison between citizen science data collection and non-involvement of the community was calculated.

Case studies and agent-based modelling

Ghoreishi *et al.* (2021) combined an agent-based human sub-model and a lumped water sub-model. The human sub-model simulated the adaptation of new irrigation systems, crop patterns, and area to be irrigated based on interactions and coevolution between farmers' decisions. The water sub-model calculated agricultural water demand using the Food and Agriculture Organization (FAO) Penman-Monteith method. Multiple methods were used to represent and highlight the stochastic (agent-based modelling) and deterministic (lumped hydrological modelling) nature of social and hydrological systems, and could, in turn, capture the heterogeneity of farmers' decision making in their communities, as well as demonstrate its impact on agricultural water use.

Alonso Vicario *et al.* (2020) combined GIS, hydraulic modelling, agent-based modelling, behavioural theories and expert judgement. In the GIS and hydraulic modelling, and in part of the agent-based model, local-level water-related variables are modelled. In another part of the agent-based model, individual-level variables are represented. Multiple methods are used because this was required to obtain precise flood maps (hydraulic model) that were afterwards combined with social components to test flood evacuation strategies (agent-based modelling). Michaelis *et al.* (2020) developed and implemented an agent-based model of human–flood interactions. They focused on the dynamic role of individual and governmental decision making on flood-risk management. A case study of the Po River (Italy) is used to illustrate potentials and limitations of the model.

Case studies, interviews, and dynamical systems modelling

Buarque *et al.* (2020) analysed human–flood interactions in the city of Sao Carlos (Brazil) by combining observations with system dynamic modelling. Neupane *et al.* (2021) explored the potential impact of land-use change on flooding in Columbia, South Carolina, USA, using a hydrological model. Carr *et al.* (2021) combined a case study, interviews, literature analysis, and socio-hydrological modelling. The case study and interviews were included to gain a fuller understanding of water quality and water quality management responses. Bringing together information from the literature was essential to bridge the gaps in data from the case study. Socio-hydrological modelling was chosen to develop a semi-quantitative "cause and effect model," that could show how the system could respond to increases or reductions in support, resources, and capacity. The collection of methods was critical for developing a more complete understanding of the system being studied.

Laurita *et al.* (2021) conducted a case study based on stakeholder analysis, hydrological modelling, and ecosystem services quantification. A stakeholder analysis was performed using semi-structured interviews and an actor-linkage matrix in order to identify the main actors involved in the recharge project and to define the dynamics that relate to them. Hydrological modelling was performed to calculate the local-level water balance, and a service provision index was used to quantify local ecosystem services. Multiple methods helped in analysing a local water allocation problem by combining social and hydrological inputs, while accounting for ecosystem services.

Synthesis and a way forward

This commentary is motivated by two thematic questions that present both a challenge and an opportunity for the field of socio-hydrology. How can one represent and study multiple levels of human agency and decision making that often underlie human–water interactions? How can one do interdisciplinary research that combines multiple different methods from the hydrological and social sciences? Based on the *Hydrological Sciences Journal* Virtual Special Issue *Advancing Socio-hydrology*, we probed these two themes and generated tentative insights. We highlighted that, although the spatial and temporal scales are well appreciated by the hydrological sciences community, the same cannot be said about the human organizational scale and how social processes along this dimension influence outcomes. We argued that the spectrum of human organizations should be treated as another key analytical dimension and that consideration of this dimension might hold clues to explaining why a socio-hydrological phenomenon occurs in one context but not in others. We also highlighted that, because of the complexity inherent in such systems, multiple disciplinary views and methods from the hydrological and social sciences are likely to be needed to develop understanding. To help guide one's thinking on how to organize such interdisciplinary research, we sketched a core structure in the interdisciplinary approaches to studying socio-hydrology.

In addition, we outlined the special issue papers in terms of scales and levels of analyses and use of multiple methods. Our summary shows that a sizable portion of the special issue papers employed different concepts and methods from other scientific disciplines – social sciences in particular. We also see applications of two or more methods or consideration of cross-level processes in some studies (although those concerning the human organizational scale are still rare). This suggests that socio-hydrology as a community research programme is on the right track in terms of embracing interdisciplinarity for studying coupled human–water systems. It also implies that socio-hydrology is currently undergoing a long arduous

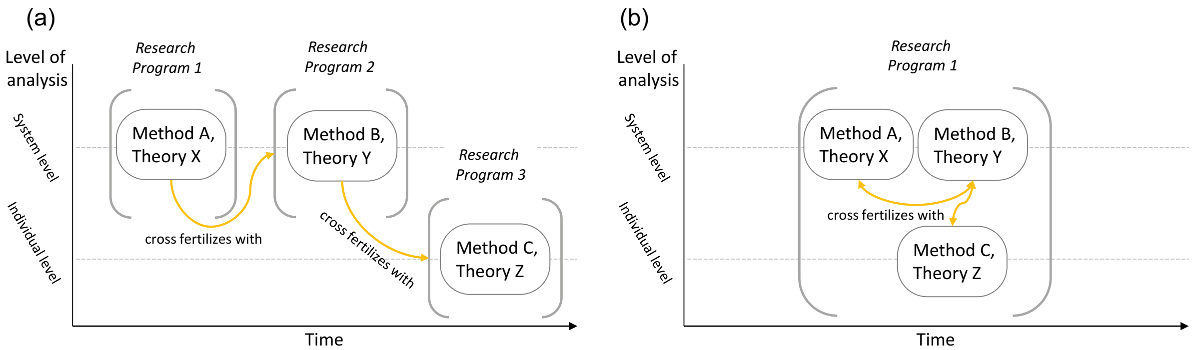

Figure 4. Two ways of methodological and disciplinary cross-fertilization for theory development. In the sequential mode (a), findings from one method or discipline used in a research programme are taken up by subsequent research programmes for cross-fertilization. In the parallel mode (b), a single research programme combines multiple methods and disciplinary ideas in an integrative way from the beginning for cross-fertilization.

process of building scientific consensus. As indicated by historian of science Naomi Oreskes (2004), "scientific consensus" about a frontier subject develops over a long time horizon (e.g. 30–40 years) as many scholars produce varying results using different ideas, data, and methods. Although confusion can occur initially, a consensus may emerge over time as data become better and findings become more concordant. The breadth and variation in the ideas and methods used in the special issue papers can be viewed as natural manifestations of this long process of building a consensus.

As a synthesis and a way forward, we now take a broader perspective to discuss how disciplinary and methodological cross-fertilization can occur for theory development in socio-hydrology. In the closely related field of social-ecological systems research, benefits and examples of such cross-fertilization have been demonstrated (Janssen and Anderies 2013). Scholars from different disciplines using different methods have all contributed to advancing knowledge of complex social-ecological systems that might have been unattainable otherwise (Poteete *et al.* 2010). In particular, as illustrated by Fig. 4, such cross-fertilization generally occurs in two ways through studies conducted at different levels of analysis in the space, time, or human organizational scales – *sequential* and *parallel* modes (Poteete *et al.* 2010). We suggest that these two modes of cross-fertilization are also highly relevant to socio-hydrology and can inform the community research programme of socio-hydrology on how the works of diverse groups can collectively lead to theory advancement.

In the sequential mode of cross-fertilization, findings from one method or discipline are revisited from another methodological or disciplinary perspective for new clues and synthetic ideas (Fig. 4(a)). This connection usually occurs across two or more independent research programmes over time. The rationale is that, while findings from one method can be difficult to explain or treated as anomalies given the theory of the time, they can be confirmed using another method or better explained by applying different research views at a later time. A fitting example of the sequential mode of cross-fertilization in the context of socio-hydrology is the body of knowledge on the levee effect or the safe-development paradox (White 1942, Montz and Tobin 2008). Case studies and comparative analysis of small-N cases led scholars to posit that the non-occurrence of flood events through structural measures is often associated with amplified long-term vulnerability to flooding in the long run (Burton and Cutter 2008, Ludy and Kondolf 2012, Bohensky and Leitch 2014, Di Baldassarre *et al.* 2015). The key contribution of these local-level studies is identifying that this observation may not be an anomaly but rather a recurring, system-level pattern. Subsequently, their insights motivated early socio-hydrology studies that constructed and analysed system-level models at higher levels of spatial and time scales to uncover underlying mechanisms responsible for the phenomenon (Di Baldassarre *et al.* 2013, Viglione *et al.* 2014). A key model construct employed in these studies to represent human agency and to connect human and water system is a single societal-level memory of floods. The resulting system-level insights catalysed further modelling studies that infused different disciplinary perspectives and modelling approaches, including a replicator equation capturing informal social norms and collective action around shared public infrastructure (Yu *et al.* 2017) and agent-based models that capture the aspects of institutional arrangements and government roles (Abebe *et al.* 2019, Haer *et al.* 2020). Meanwhile, place-based and historical studies emerged to place the concept of social memory and the levee effect on a firmer theoretical foundation (Leong 2018, Fanta *et al.* 2019, Mondino *et al.* 2020). These studies conducted longitudinal surveys, historical document analysis, or interviews and content analysis to generate empirical insights. New, emerging methods are also used to develop insights at higher levels of the spatial or time scales that were unattainable using conventional methods. For example, one study analysed satellite night-time images to examine the relationship between human proximity to rivers and the occurrence of flood events (Mård *et al.* 2018). As can be seen, findings from one method or discipline regarding the levee effect phenomenon were sequentially taken up by other studies that used different methods or disciplinary views to further the knowledge of the phenomenon.

In the parallel mode of cross-fertilization, a single research programme is planned from the beginning to combine complementary methods and to bring together scholars with different disciplinary and methodological backgrounds (Fig. 4 (b)). The advantage of this parallel approach is that methodological and disciplinary cross-fertilization opportunities can be thought out from the early research design stages and controlled throughout the project. An example of this mode of cross-fertilization is, perhaps, a National Science Foundation-sponsored research project (award number: 1913665) that two of the authors of this commentary participate in. This project aims to understand how actors across all levels of decision making in a complex watershed system, from reservoir operators to floodplain residents, make decisions in response to increasing hydrological extremes and quicker shifts between wet and dry periods. Its focus is on understanding how such multiple levels of decision making may lead to cognitive biases or systematic errors in judgement in terms of water-supply and flood-control decisions. Due to the interdisciplinary nature of the research, this project incorporated multiple methods and disciplinary views from both the social and hydrological sciences and brought together hydrologists, political scientists, and systems scientists under a single research programme. It is designed to combine a top-down hydrological model and a generic stylized model of reservoir operation to systemically investigate the feedback system of public infrastructure providers, resource users, and the dynamics of water scarcity in a stylized catchment. In parallel, theories and approaches of political economic analysis are applied to understand how governing rules and informal norms shape the decision making of actors situated at multiple levels of decision making in a complex watershed system. Following a political economic analysis framework (Ostrom 2011, Siddiki *et al.* 2019), water resources-related policy and planning documents of a study area are analysed, in conjunction with interviews with stakeholders, to extract knowledge on how water infrastructure and various social actors situated at different levels of social systems are interlinked via management rules or protocols of action (e.g. Olivier 2019).

Finally, a caveat should be mentioned: a multi-method approach is not a panacea for studying all coupled human–water systems in all cases. Combining multiple methods does not guarantee methodologically better research, and the practical challenges associated with the approach can be substantial and should not be underestimated. Indeed, there can be a number of challenges (Poteete *et al.* 2010). For example, it can be infeasible to combine certain methods because relevant data may be simply unavailable. Even if data become available, it can still be difficult to apply an interdisciplinary multi-method approach because considerable effort is needed up front to build competency in using and combining different methods. Thus, a more likely path is to bring in people with different toolkits and theoretical backgrounds to work together. Also, certain methods can be incompatible because of significant differences in sample data or underlying assumptions. Care is needed when matching methods for complementarity. For example, ethnographic studies or qualitative fieldwork and social media-based big data analysis can be incompatible because there may be little overlap in their study sample populations (e.g. rural indigenous people may not actively use social media). Despite the practical challenges above, our view is that an interdisciplinary multi-method approach is almost a necessity if we are to achieve theory advancement in the study of human–water systems. We can attain a more multi-faceted understanding by combining multiple disciplinary perspectives and methods from both the natural and social sciences. Hydrologists need to be an essential part of this convergence.

Acknowledgements

Thanks are due to the authors of the Virtual Special Issue of the *Hydrological Sciences Journal Advancing socio-hydrology* for their inputs and to the Co-Editor Stacey Archfield and the reviewers for their comments and suggestions.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This paper was partially supported by a Collaborative National Science Foundation grant award titled *Cross-Scale Interactions & the Design of Adaptive Reservoir Operations* (award number: 1913665).

ORCID

David J. Yu http://orcid.org/0000-0001-9929-1933
Melissa Haeffner http://orcid.org/0000-0002-7976-3769
Hanseok Jeong http://orcid.org/0000-0003-0587-6629
Saket Pande http://orcid.org/0000-0003-3061-3185
Giuliano Di Baldassarre http://orcid.org/0000-0002-8180-4996
Leon Hermans http://orcid.org/0000-0002-5294-9045
Fernando Nardi http://orcid.org/0000-0002-6562-3159
Matthew R. Sanderson http://orcid.org/0000-0002-5946-6556
Yongping Wei http://orcid.org/0000-0002-4266-4433
Josepha Wessels http://orcid.org/0000-0003-2682-035X
Murugesu Sivapalan http://orcid.org/0000-0003-3004-3530

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