The controversial debate on the role of water reservoirs in reducing water scarcity

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Abstract
Reservoirs are built worldwide for a higher water supply in dry periods by storing water temporarily in wet periods. Recent socio-hydrology studies hypothesized, by creating “supply–demand cycles”, that reservoirs can lead indirectly to counterintuitive dynamics such as more water scarcity and a higher economic and social vulnerability. This opinion argues that reservoirs are part of co-evolutionary processes with natural, social, and engineered elements and therefore, water scarcity need to be analyzed within socio-political interactions. Aspects such as (a) institutions; (b) governance processes; (c) social–ecological factors; (d) narratives of water scarcity; and (e) powerful economic interests are essential to understand feedback mechanisms between reservoirs and water scarcity and to hypothesize long-term phenomena such as water scarcity. Neglecting these interactions could lead to biased research agendas, misleading conclusions, and adverse effects on the transformation process toward sustainability. Given the complexity of social–ecological systems, the diversity and critical capacity of inter- and transdisciplinary work is crucial to further advance the study of unintended side effects of reservoirs or — more general — the study of socio-hydrology.

This article is categorized under:
Human Water

KEYWORDS
governance, institutions, social–ecological system, socio-hydrology, socio-political context

1 | INTRODUCTION

During the last decades, water abstractions have been rising due to increasing world population, improving living standards, changing consumption patterns, economic growth, and expansion of irrigated agriculture (J. Liu et al., 2017; Mekonnen & Hoekstra, 2016). The resulting water crisis is expected to become more critical in the near future, driven by socio-economic and climatic changes (Kahil et al., 2019), but also due to governance failures (Gupta, Pahl-Wostl, & Zondervan, 2013). Enhancing water supply to alleviate water scarcity has become an important issue in many parts of the world (W. Liu et al., 2019). Among potential adaptation measures, reservoirs have been shown to be increasingly...
important in ensuring water security and facilitating drought management (Ehsani, Vörösmarty, Fekete, & Stakhiv, 2017). Such reservoirs can potentially cover or reduce water deficits during the dry and high-demand season by releasing water stored in the wet season (Wanders & Wada, 2015).

The strategy to increase the storage capacity, which dominated the global water agenda in former times, has been largely phased out but is still pursued, mainly by some emerging or developing countries. Most high-income countries have already reached the limit of their storage capacity and they transitioned to an era of environmental protection and soft-path approaches due to social and political resistance against reservoirs (Gleick, 2003). However, the strategy to increase the storage capacity has become highly relevant again globally due to climate change. Climate change is causing widespread glacier retreat and new water-storage potential of areas that are expected to become ice-free during the course of this century are explored and plans are drawn up for their use (Farinotti, Pistocchi, & Huss, 2016; Farinotti, Round, Huss, Compagno, & Zekollari, 2019; Kellner, 2019). Such reservoirs have the potential to mitigate projected changes in seasonal water availability from melting glaciers by managing runoff. Against this background, the understanding of interactions and feedbacks between engineered (e.g., infrastructures like reservoirs), social (e.g., institutions, governance processes), and natural (water and associated natural resources) elements becomes increasingly important (Brelsford et al., 2020).

Scientists with different disciplinary backgrounds have been examining coupled natural-human systems over decades (Bousquet, Robbins, Peloquin, & Bonato, 2015; Cox et al., 2016), e.g., in the frameworks of water resource management (Pahl-Wostl, Kabat, & Möltgen, 2008), water governance (Gupta et al., 2013), common-pool resources (Ostrom, 1990), political ecology (Blaikie, 1999), or social–ecological system research (Schlüter et al., 2019). In recent years, a growing community of socio-hydrologists have been starting to combine hydrological modeling with feedback mechanisms between physical and social systems in the water cycle (Sivapalan, Savenije, & Blöschl, 2012). Major steps were achieved in incorporating human factors in the analyses (e.g., Davies & Simonovic, 2011; Di Baldassarre et al., 2015). However, they conceptualize social and natural domains separately and couple models using bidirectional feedbacks between the social and physical components (Brelsford et al., 2020). They present water cycles mainly in the form of causal-loop diagrams (Di Baldassarre et al., 2018; Gohari et al., 2013; Kuil, Carr, Viglione, Prskawetz, & Blöschl, 2016) or conceptual frameworks (Di Baldassarre et al., 2013; Di Baldassarre et al., 2015; Di Baldassarre, Kooy, Kemerink, & Brandimarte, 2013), which are very illustrative and easily comprehensible, but running the risk to oversimplify complex interconnections (Gober & Wheater, 2015; Loucks, 2015; Yu, Sangwan, Sung, Chen, & Merwade, 2017). These studies do not integrate institutions and collective decision-making and use a limited view on human action in the form of fairly deterministic rules for the dynamics of variables at the population level or for behavior at the individual level (Brelsford et al., 2020). Social science literature, in contrast, tends to focus on case studies without integrating systematically hydrological outcomes. Interdisciplinary research, which combines two or more disciplines to advance systems knowledge and to find solutions, which are beyond the scope of a single discipline, and transdisciplinary research, which co-produces together with societal actors not only systems knowledge, but also target and transformation knowledge (Schneider et al., 2019), are unfortunately still rare in the field.

For reservoirs, proposed supply–demand cycles hypothesize that reservoirs can lead to counterintuitive effects. This means that an increasing water supply can generate a higher demand, which in turn can even aggravate water scarcity (Di Baldassarre et al., 2018; Gohari et al., 2013). Furthermore, it is hypothesized that reservoirs can reduce the effort to develop other adaptation measures, and in consequence increase the economic and social vulnerability, which is called the “reservoir effect” (Di Baldassarre et al., 2018). However, while the effort of socio-hydrology to investigate the role of reservoirs in alleviating water scarcity is certainly useful, the perspective that reservoirs are part of co-evolutionary processes with natural, social, and engineered elements has not been sufficiently taken into consideration, even though long-term phenomena such as water scarcity emerge from these processes. Against this background, the short opinion wants to open an important intellectual debate in indicating some starting points for a necessary broader reflection on feedback mechanisms of reservoirs.

2 | THE SOCIO-POLITICAL DIMENSION OF RESERVOIRS

Reservoirs are part of social–ecological systems co-constituted with interactions between humans, social networks, institutions, and political and natural dynamics. Reservoirs as public infrastructures result from co-evolutionary processes at the interface of physical and social systems (Aguilera-Klink, Pérez-Moriana, & Sánchez-García, 2000). They are shaped by institutions and require governance processes, where actors work together to achieve a common goal,
such as regulations about the allocation of water. To understand whether, how and why reservoirs can lead to water scarcity, it must first be scrutinized how water scarcity is understood—for whom, for which use, at what scale, in what timeframe, and in which context. Most assessment approaches for water scarcity apply a single—mainly relative—indicator to quantify water scarcity (J. Liu et al., 2017). Relative scarcity, for example, measures the amount of water available or used relative to another factor such as population or available renewable water resources (Alcamo & Henrichs, 2002; Falkenmark, Lundqvist, & Widstrand, 1989; Kummu et al., 2016). They deal considerably less with the political nature of scarcity. Political scarcity considers inter alia: (i) how water scarcity is shaped by social-ecological factors; (ii) how scarcity is socially constructed (Gerber, 1997; Kaika, 2003), perceived, and “manufactured” to match particular interests (Mehta, 2001); (iii) how narratives of scarcity are used in political discourses about competing water uses (Scoones, 2010); (iv) how historical inequalities as a result of exploitation and elite control have affected regulations about water access and control (Mehta, 2005); and (v) how such regulations consider different groups of people, creating winners and losers in times of water scarcity (Mehta, 2010a, 2010b). Demonstrating the political nature of scarcity does not imply that scarcities are not “real”. I argue that these aspects have to be integrated in the analysis, because they have direct effects on how problems are perceived, solutions conceptualized and supported, and they impact policy and investment behavior.

In light of the above, one important perspective and the overarching argument of this opinion why simplified feedback mechanisms have the potential to overlook important explanatory causal mechanisms is that water scarcity in the context of reservoirs has to be embedded in socio-political interactions. Socio-political elements need to be part of supply–demand cycles representing explanatory mechanisms for long-term dynamics (Figure 1). The opinion can cover just some aspects of the overarching argument and discusses five subordinate arguments hereinafter: (1) Institutions shape human behavior and human-environmental interactions; (2) Governance processes regulate the supply- and demand-side; (3) Social–ecological factors influence water demand; (4) Narratives of water scarcity effect problem understanding and conceptualization of solutions; and (5) Powerful economic interests influence reservoir construction.

2.1 | Institutions

Institutions are laws, rules, norms, and customs shaping human behavior and human-environmental interactions (Ostrom, 2005). They are crucial for governance processes to coordinate resource uses, resolve trade-offs between individual and group interests, and allocate costs and benefits among actors (Cumming et al., 2020; Lubell, 2013; Ostrom, 2005). However, incoherent institutions are among the most critical sources for barriers to adapt water governance to socio-economic and climate change (Kellner, Oberlack, & Gerber, 2019).

Reservoirs are shared infrastructures to direct natural water processes for the benefit of humans that requires collective action of agents who share it (Yu, Qubbaj, Muneepeerakul, Anderies, & Aggarwal, 2015). Collective action refers to “action situations”, where decisions by a group of individuals create outcomes that arise to them or other groups (McGinnis, 2011b). Action situations are shaped by different types of rules, which prescribe what individuals can or must do, the assigned costs and benefits to actions and outcomes, and possible sanctions in case of violation (Ostrom, 1999, pp. 508). They are created by resource users and are embedded in the legal and regulatory framework of local, regional, and national governments (Ostrom, 2011). The effectiveness, sustainability, and coherence of institutions affect the decision-making regarding new reservoirs (arrow a in Figure 1) as well as the governance processes to regulate the water supply- and water demand-side (arrow b).

2.2 | Governance processes

Depending on its inflow, storage capacity and withdrawals, a reservoir can lose its balance. The unsustainable exploitation of water resources and resulting scarcity depend on decision-making in governance processes on how much water should be available and consumed for which use. Effective regulations can control the supply–as well as the demand-side (arrows c and d). However, the governance processes to define effective and sustainable regulations are challenging, because the way in which water is defined, conceptualized, and valued has a political dimension (Gupta et al., 2013). Furthermore, governance processes need sufficient human and financial resources, aligning attention as well as political support (Garcia et al., 2019; Treuer et al., 2017).

Governance processes for the supply-side (arrow c) require the coordination of different—often competing—water uses rooted in different sectors at different scales with different economic interests and power relations (Pahl-Wostl
et al., 2020; Sayles & Baggio, 2017; Shalsi, Ordens, Curtis, & Simmons, 2019; Weitz, Strambo, Kemp-Benedict, & Nilsson, 2017), and between upstream and downstream water users (Anghileri, Castelletti, Francesca Pianosi, Rodolfo Soncini-Sessa, & Weber, 2013; Cody, 2018; Denaro, Castelletti, Giuliani, & Characklis, 2018). Such power plays between involved actors to control water can reinforce existing inequalities and water scarcity for specific groups of actors. Integrated Water Resource Management (IWRM), formalized in the early 1990s, has attempted to integrate water with other policy objectives to respect the reproductive capacity of the resource systems, and to coordinate it in an integrative manner (Biswas, 2004, 2008). The challenge of IWRM is its own definition, which is cross-sectoral, multi-level, and often needs new institutional, governance, and management arrangements (Ingold & Tosun, 2020). This is reflected in the fact that despite its promotion in national and international policy arenas, IWRM has not been implemented on a broad scale (Pahl-Wostl, 2019; Pahl-Wostl et al., 2020). IWRM principles do not overcome the lack of institutional capacity to govern across sectoral boundaries (Benson, Gain, & Rouillard, 2015).

For demand regulations (arrow d), previous studies have shown that external (e.g., drought, population growth) and emergent (e.g., public attention) changes are positively correlated with the implementation of demand regulations (arrows e and f) and water use behavior resulting in lower per capita water demand (arrow g) (Garcia & Islam, 2019; Quesnel & Ajami, 2017).
Other studies demonstrated the interactions of supply- and demand-side regulations. The study of García, Ridolfi, and Di Baldassarre (2020) showed that the storage volume of a reservoir can influence operating rules of a reservoir and adaptive responses. Larger storage capacities can lead to a later recognition and adaptive response to a shortage (arrow h). The example of Melbourne indicates that supply-side measures like the construction of new reservoirs in combination with demand-side approaches (e.g., water pricing strategies, provision of educational material, support for companies to develop water management plans) can result in a reduced urban per-capita water consumption (Ferguson, Brown, Frantzeskaki, de Haan, & Deletic, 2013). They found that significant changes occurred in the cultural-cognitive, normative, and regulative dimensions including “a shift in cultural beliefs for the water profession, new knowledge through evidence and learning, additional water servicing goals and priorities, political leadership, community pressure, better coordinated governance arrangements and strong market mechanisms” (Ferguson et al., 2013, p. 7300).

### 2.3 Social-ecological factors impact water demand

Analyses on the allocation and demand of natural resources require the considerations of complex social-ecological interdependencies (Berkes, Colding, & Folke, 2002; Ostrom, 2005). Water demand is influenced by factors, such as population and economic growth, lifestyle, and consumption attitudes (arrow i). This opinion highlights only the following three factors affecting supply-demand cycles:

- **a.** From a systemic understanding, human behavior is part of complex adaptive systems, which co-evolves with socio-cultural and biophysical contexts (Schill et al., 2019). More concrete, human behavior has the capacity to adapt to external changes such as higher water supply as well as water scarcity (arrows j and g). Both directions are confirmed by empirical studies (e.g., García & Islam, 2019; Kandasamy et al., 2014).

- **b.** Water reservoirs as many other types of infrastructures shape behavior and enable a certain type of growth (e.g., water demand, population growth, transport demand) (Cervero & Hansen, 2002; Di Baldassarre, Viglione, et al., 2013; Hymel, Small, & van Dender, 2010; Yu et al., 2015). All these areas of research share the same theory that infrastructure can enable growth but does not have a direct causal relationship with this growth. Consequently, reservoirs can enable growth, for instance population or demand increase, but it only occurs if social and economic conditions enhancing growth concomitantly prevail.

- **c.** The trade of agricultural and industrial commodities is associated with a virtual transfer of water used for producing these goods. Many studies have quantified the amount of virtual water exchanged across borders at catchment, regional, intracountry, and the global level (Antonelli, Tamea, & Yang, 2017; Carr, Paolo, Francesco, & Luca, 2013; Faramarzi et al., 2010; Han, Chen, & Li, 2018; Salmoral & Yan, 2018). These studies show that the global water use is often allocated to the production of commodities for global and regional trade, which embodies a large amount of virtual water flows and influences local water scarcity (Hoekstra & Mekonnen, 2016; Vörösmarty, Hoekstra, Bunn, Conway, & Gupta, 2015; Zhao et al., 2015; Zhao et al., 2016). This situation shows that water consumption is often closely linked to the structure of the global economy (Nyström et al., 2019). Consequently, scarcity problems cannot be solved solely at river basin level, because it is “inextricably bound up with the processes that determine where in the world agricultural and industrial production take place and with the written and unwritten rules of global trade” (Hoekstra & Chapagain, 2008, p. xi). This situation begs the question of system boundaries of supply-demand cycles.

### 2.4 Narratives of water scarcity

Narratives of scarcity can be intentionally constructed to support particular interests in political discourses (arrow k). This has direct effects on how problems are perceived, and solutions conceptualized and supported (arrow l) — by state and non-state actors as well as by funding agencies.

The example of Athens demonstrates the political dimension of constructing scarcity with the goal to build more reservoirs. A study by Kaika (2003) shows that the falling level of one of the reservoirs close to Athens was a socio-political rather than a natural process to create a moment of crisis. This situation was used to instill the idea of a water crisis in public deliberations and facilitated — “by casting nature into the role of a source of crisis and water as a scarce
commodity” (p. 927)—a rapid implementation of very controversial political decisions. This resulted in the expansion of reservoir capacity, with the support of the government, construction companies, and the EU through its funding for regional development projects (Kallis & Coccossis, 2003).

2.5 Economic interests influence construction of reservoirs

Reservoirs and water consumption patterns cannot be understood independently from powerful economic interests (arrow m). Building reservoirs, as well as irrigation systems, is a lucrative industry, which by lobbying can influence political choices. Building contractors benefitting from new constructions and water infrastructures are “wellsprings of state power” (Meehan, 2014, p. 2015). For example, China financed 34 large-scale reservoir projects from 2000 to 2015 for USD 9,199 million in Africa (Tang & Shen, 2020).

3 DISCUSSION AND CONCLUSION

Research on water scarcity and reservoirs is topical in times of water crises under global change with major consequences for sustainability. Reservoirs are part of social-ecological systems, which are complex (adaptive) systems that are co-constituted with interactions between humans, social networks, institutions, and political and natural dynamics. As outlined in the last section, ineffective, unsustainable or incoherent institutions; governance processes producing ineffective and unsustainable regulations; power imbalances; virtual water transfers; narratives used purposefully for own interests; and strong economic interests can impact the intended contribution of reservoirs to alleviate water scarcity. These are crucial explanatory interactions why reservoirs could lead to more water scarcity or increase vulnerability and economic damage. They go beyond feedback mechanisms between separately conceptualized natural and social domains, as it is common in socio-hydrology studies (e.g., Di Baldassarre et al., 2015).

Given the complexity of social-ecological systems and the diversity of disciplinary and inter- and transdisciplinary knowledge, no single framework will be best or sufficient for such an analysis (Schlüter et al., 2019). Such research typically goes beyond the scope of an individual research project. It needs to be embedded in larger collaborative research projects to integrate the critical capacity and diversity of inter- and transdisciplinary work. (Schlüter, Orach, et al., 2019). However, generalization and theorizing will remain challenging due to complex causation, social-ecological intertwinedness, changing contexts, and context dependence (Ferraro, Sanchirico, & Smith, 2019). In response to that challenge, meta-analysis of case studies emerged in recent years (e.g., Oberlack, Tejada, Messerli, Rist, & Giger, 2016). They aim to move from case-oriented to variable oriented research, but they provide little insights about interactions between variables. This gap is addressed in “model centered” meta-analyses, which focus on the identification and formalization of causal explanations (i.e., models) developed in published case studies (Villamayor-Tomas et al., 2020). Another approach to overcome this challenge are the so-called middle-range theories, defined as contextual generalizations describing causal mechanisms by “explaining a well-bounded range of phenomena, as well as the conditions that trigger, enable, or prevent these causal chains” (Meyfroidt et al., 2018, p. 53). They could provide a path toward generalized knowledge of reservoir systems and support progress to enhance a sustainable integration of reservoirs in social-ecological systems to reduce water scarcity. Schlüter, Orach, et al. (2019), for example, present “an iterative and collaborative process that combines generalizing from case studies with agent-based modelling as an abductive methodology to successively build and test explanations rooted in complexity thinking” (p. 44). They recommend using a more inter- and transdisciplinary approach by integrating theoreticians, empirical researchers, modelers, and practitioners in this kind of research processes.

However, specific interdisciplinary reservoir studies are still rare to date. Kellner and Brunner (2021) used the Networks of Action Situations approach (Lubell, 2013; McGinnis, 2011b) rooted in the Institutional Analysis and Development framework (McGinnis, 2011a; Ostrom, 2005, 2011) to combine quantitative and qualitative methods. They analyzed how hydrological and socio-economic conditions, institutions, political dynamics, and path-dependencies lead to a governance gap between upstream reservoir planning and potential downstream water scarcity using a case study in the European Alps. Hopefully, also the following not reservoir specific examples stimulate how to integrate socio-political aspects into socio-hydrology studies: Herrfahrtd-Pähle et al. (2020) analyzed socio-political aspects of water governance transitions. They used a multi-level approach, which was based on analyses of secondary data documented in the literature as well as reports. Treuer et al. (2017) and Garcia et al. (2019) analyzed urban water management and
combined standardized quantitative measures with contextual qualitative data and produced structured, data-driven narratives. The narratives aimed to understand policy change and how policy actors influence change. Brelsford and Abbott (2017) used a novel method for decomposing multiple drivers of consumption to analyze whether a decline in per-capita consumption in Las Vegas is the result of water policies or other exogenous changes. Brelsford et al. (2020) proposed to go beyond searching for evidence of feedback mechanisms and instead focus more on understanding successful responses, which have been used to address challenges and how they were affected by institutional structures, socio-economic contexts, and ecological conditions. The knowledge can be complemented by transdisciplinary approaches to co-produce knowledge how to prevent unintended side effects of reservoirs. This approach enables collaborations among various disciplines and societal actors, requires self-reflectiveness, and focuses on real-world challenges (Schneider et al., 2019).

I assert that a more inter- and transdisciplinary approach is needed to further advance the study of unintended side effects of reservoirs or —more general— the study of socio-hydrology. In particular, I argue that reservoirs are part of co-evolutionary processes with natural, social, and engineered elements. Therefore, a more integrated understanding is crucial of how institutional, social, and economic activities shape social and ecological outcomes. Neglecting these interactions could lead to biased research agendas, misleading conclusions, and adverse effects on the transformation process toward sustainability.

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CONFLICT OF INTEREST
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