

Orientations to navigate the complexity of freshwater resilience in social-ecological systems

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Abstract. Resilience is a widely applied and diversely interpreted concept in freshwater science with applications that span disciplines, analytical frameworks, scales of analysis, and system delineations. This diversity leads to an equally rich variety of resilience insights which are difficult to compare, aggregate, synthesize, and apply in decision-relevant contexts. Here, we seek to support greater critical and reflexive awareness of how freshwater resilience insights are generated by proposing three social-ecological orientations: 1) freshwater resilience as a shared physical and social reality; 2) the necessity of multiple knowledge production systems; 3) the emergence of freshwater resilience through open systems with cross-scale dynamics. We demonstrate the benefit of holding these orientations through four case studies spanning the almond debate of California's Central Valley, the Sahelian paradox, the seasonal flood pulse in the Mekong River Basin, and hydropower in the Amazon Basin. We envision that these orientations can serve as a shared foundation for holistic freshwater resilience research and better understanding of processes that generate resilience insights. To advance beyond perspectives of freshwater resilience that capture only one or few dimensions, we argue that freshwater resilience science should embrace a

sustained commitment to inclusion of multiple perspectives, provision of context-rich descriptions of resilience processes, and transparency in documenting how resilience is conceptualised in the research that produces claims about it.

1 Introduction

40 Resilience is a widely applied and diversely interpreted concept in the social-ecological, sustainability, and Earth system sciences, as well as in policy and practice (Anderies et al., 2023; Cumming and Peterson, 2017; European Union, 2025; Folke et al., 2016; Schellnhuber, 2009; Turner, 2010). Freshwater scholarship represents a broad and substantial contingent of these communities (Rodina, 2019), and major themes in freshwater science have encouraged a wide uptake of the language and concepts of resilience (Falkenmark et al., 2019; Rockström et al., 2014). These encouraging themes include the
45 recognition of non-stationarity in hydrological processes (Milly et al., 2008), the understanding that human activity is the dominant driver of global hydrological change (Abbott et al., 2019; Chandanpurkar et al., 2025; Virkki et al., 2026; Vörösmarty and Sahagian, 2000), and the perspective that freshwater is inseparably embedded in social and ecological systems that reciprocally shape and are shaped by freshwater (Falkenmark, 1977; Folke, 2003; Kaandorp et al., 2026; Ostrom, 1990). While a breadth of freshwater resilience scholarship has generated a rich literature, it has not necessarily
50 generated one that is internally coherent. The variety of disciplinary norms and specialisations, analytical frameworks, scales of analysis, system delineations, knowledge systems, and working definitions of resilience create a mixture of insights that are difficult to compare, aggregate, synthesize, and apply in decision-relevant contexts including science, policy, and practice.

Resilience has typically been defined as the capacity of a system to absorb, adapt, reorganize, or otherwise continue
55 functioning in the face of external shocks (Folke, 2006). Yet, this general definition takes different forms upon application. A catchment hydrologist may study the capacity of a freshwater system (e.g., an aquifer, river, or watershed) to absorb climate or anthropogenic shocks while maintaining key ecological and hydrological functions such as flow regulation, habitat, and storage (Lotcheris et al., 2026; Mao et al., 2017; Zipper et al., 2022) and describe this ability as freshwater resilience. Simultaneously, a water governance scholar might assess the ability of formal or informal institutions to
60 anticipate, adapt, and transform in response to freshwater-related stresses (Clarvis et al., 2014; Moore et al., 2024; Rodina, 2019) and describe these abilities as institutional resilience. A global climate modeller may quantify future precipitation trends under different shared socioeconomic pathways (Schleussner et al., 2021) and describe persistent regional precipitation patterns as resilient under global change, whereas a disaster risk response expert may consider resilience based on their lived experience with community responses to extreme events (Graveline and Germain, 2022; Hochrainer-Stigler et al., 2020). While all these approaches are correct and valid to support finding solutions to different freshwater resilience
65 challenges, yet effective dialogue amongst them remains difficult.

This challenge is not benign: freshwater underpins global sustainability goals (Gain et al., 2016; Jaramillo et al., 2019), senses of place for individuals and communities (Anderson et al., 2019; Scaini et al., 2021), and biophysical processes

that maintain Earth system stability (Gleeson et al., 2020). Resilience insights offer an important knowledge base for actors
70 to decide how to understand, intervene and shape freshwater systems towards desired social and ecological system states.
These insights correspond well with management-relevant concepts, such as thresholds and targets, through explicit
considerations of regime shifts, system state boundaries, and non-linear dynamics. Thus, resilience insights are not only
external descriptions of system behaviour but also active participants that shape possible future system states based on how
these insights are used by actors. While the scientific processes involved in comparing, aggregating, and synthesizing
75 freshwater resilience insights are consequential, they have, to our understanding, received little attention in freshwater
systems science.

In this Perspective, we argue for a more critical and reflexive analysis of the processes and norms through which
freshwater resilience insights are presented and synthesized. Rather than introduce new methods, models, or frameworks, we
consider that transformative advances towards better synthesis of freshwater resilience insights are already possible through
80 mobilising current knowledge and methods. Generating more coherent and holistic assembled bodies of evidence is,
however, a tall order for which there is no single remedy. Yet, we propose here a set of fundamental *orientations* that can
help foster a better integrative understanding of freshwater resilience across disciplines and aid in more holistic evidence
synthesis pertaining to freshwater change.

Firstly, we provide an overview of some existing approaches used to understand aspects of freshwater resilience in
85 social-ecological systems (Section 2). Secondly, we detail the three orientations we argue provide useful context to
communities and studies populating the freshwater resilience literature (Section 3). Thirdly, we demonstrate tangible benefits
of holding these three orientations through a set of four case studies (Section 4). Finally, we conclude with discussing
opportunities and open problems related to working with these orientations (Section 5). We contribute this Perspective as a
research collective of freshwater academics who have been convening informally over recent years
90 (<https://freshwatersystemsworkshop.org/>) and write with a primary audience of physical Earth system and quantitative
social-ecological systems scientists in mind, which are the communities that most authors of this work associate with. Our
goal is to share how adopting these orientations have beneficially shifted our own thinking and ability to work together
across differences in our disciplinarity, scales of analysis, and freshwater systems of study.

2 Freshwater resilience is in the eye of the beholder

95 Freshwater is the bloodstream of the biosphere (Falkenmark and Biswas, 1995) and an intrinsic part of the Earth system
(Gleeson et al., 2020), social systems (Linton, 2010), and social-ecological systems (Falkenmark and Folke, 2002; Sivapalan
et al., 2012). As a result, there is a practically endless set of interactions that can be studied between freshwater and other
processes and systems, and whose resilience may be conceptualised and potentially quantified. While the scope of freshwater
resilience applications may be large, this variety is not unique to freshwater systems and is, rather, a defining characteristic
100 of resilience science. That is, when resilience is not simply used as a metaphor but as a specific and definable attribute, it

must necessarily be conditional to a specific relationship within a specific system and over a specific time scale (Carpenter et al., 2001). Further, there is no comprehensive model for resilience that accounts for the interdependence of resilience processes within systems (Ungar, 2018), and efforts to synthesise resilience insights are limited by the frequent absence in resilience assessments of specifying key features such as the systems of interest, their boundaries, disturbance regimes, or even working definitions of resilience (le Polain de Waroux et al., 2024).

Freshwater resilience in social-ecological systems builds on various disciplines. These include, for instance, water security analysis (Falkenmark et al., 1989; Kummu et al., 2016; Vörösmarty and Sahagian, 2000), Earth system science (Gerten et al., 2005; Gleeson et al., 2020; Meybeck, 2003), social-ecological systems science (Berkes and Folke, 1998; Gain et al., 2021; Ostrom, 2009), systems ecology and resilience theory (Falkenmark et al., 2019; Folke, 2003; Grantham et al., 2019), political ecology and human geography (Boelens et al., 2016; Swyngedouw, 2009), and coupled infrastructure systems (Anderies et al., 2019; Ferguson et al., 2013; Krueger et al., 2022, 2025). Efforts within and between these and other disciplines related to freshwater resilience have generated a tremendous set of approaches, practices, and paradigms, which consider a wide range of focal processes, system boundaries, knowledge systems, and spatial and temporal scales (Fig. 1). Yet, they share a focus on how entities or relationships between them in freshwater systems can persist or transform. Further, the decisions regarding conceptual boundaries and process representations strongly shape how resilience is perceived, conceptualised, and characterised. In this way, we argue that “resilience is in the eye of the beholder”. This fully corresponds with the adage of “resilience of what to what” (Carpenter et al., 2001) and emphasizes that how resilience is defined is strongly shaped by disciplines, methods, and their embedded assumptions.

For example, the planetary boundaries framework (Rockström et al., 2009) places the biophysical Earth system and its resilience dynamics within its scope but omits consideration of social systems and their dynamics, such as positive social tipping points (Otto et al., 2020). In contrast, community-based participatory research (CBPR) (Roque et al., 2022; Seiferth et al., 2024) accommodates diverse knowledge production modes to enable a holistic view of intertwined processes. CBPR is thus capable of capturing place-based mechanisms of social adaptive capacity (Ruiz-Mallén and Corbera, 2013) but is unable to represent global dynamics and potential drivers of local regime shifts, such as teleconnections. Predominantly quantitative approaches, such as the Food-Energy-Water (FEW) nexus (D’Odorico et al., 2018), may focus on a limited set of key components across multiple systems to enable a comparable level of abstraction and generalization across spatial and temporal scales. Conversely, hydro-social systems research (Nakamura et al., 2025; Ross and Chang, 2020) maintains broad conceptual boundaries when considering the co-constitution of water and society, and resists reduction to a fixed set of components. Instead, it prioritises contextual details over generalisation and typically operates at local to regional scales.

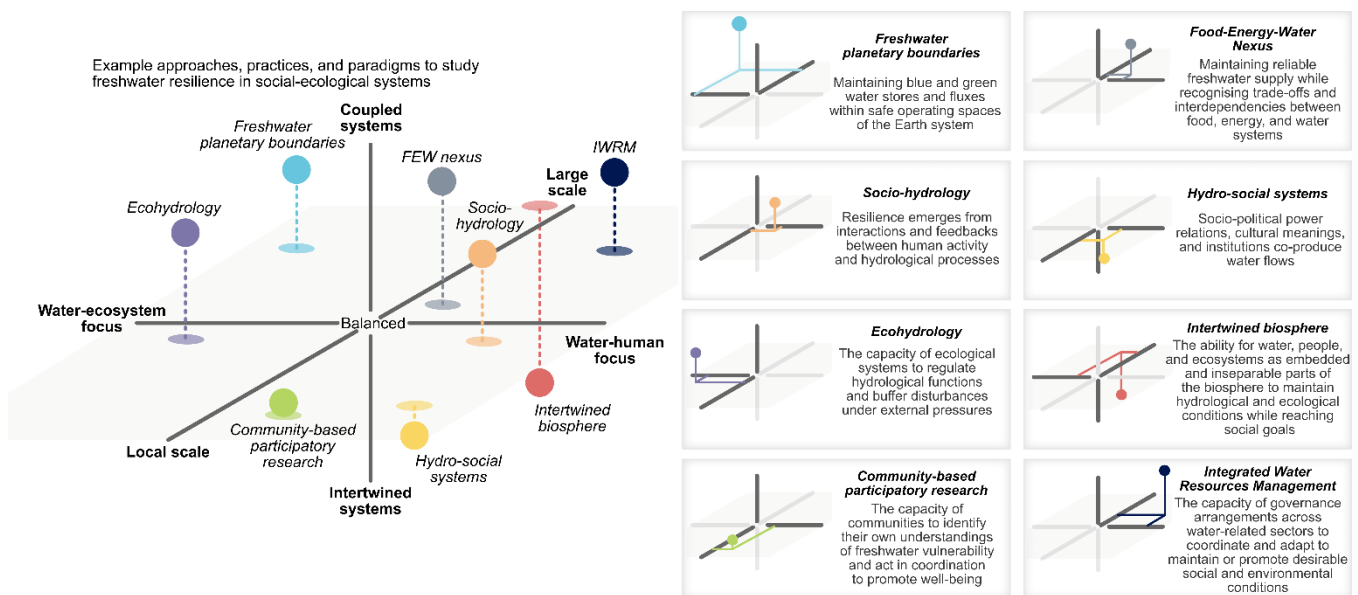


Figure 1: An illustration of some of the approaches, practices, and paradigms that contribute to understanding freshwater resilience. Each entry is represented by a sphere positioned according to three axes: 1) the horizontal axis (x-axis) reflects the balance between water-ecosystem and water-human focus (focus axis), 2) the vertical axis (z-axis) reflects the degree to which systems are conceptualised as coupled or intertwined (mode axis), and 3) the diagonal axis (y-axis) reflects the typical spatial scale of analysis (scale axis). The faded ellipses beneath each circle are a projection of each example's position along the horizontal and diagonal axes. Vertical dashed lines connect each circle to its ellipse as a visualisation aid to locate the entry's position on the mode axis. These representative but non-exhaustive examples are located as points for visualisation simplicity but in practice are applied across a range along each axis and are plotted here based on subjective perceptions of our authorship group. On the right-hand side, general descriptions of how resilience is defined and approached are provided.

3 Social-ecological orientations to navigate freshwater resilience science

The variety of focuses, modes, scales, and understandings of freshwater resilience (Fig. 1) reveals that no single approach is comprehensive, unbiased, and sufficient to capture the breadth of processes relevant to freshwater resilience insights. For this reason, we argue that more attention needs to be afforded to considering how to work within this rich but messy landscape of diverse assessments. As a first step in this direction, we present here a set of *orientations* that can enable better contextualisation, framing, and synthesis of freshwater resilience insights (Fig. 2). With the orientations, however, we seek to avoid forced integration that would compress or homogenise studies on freshwater resilience but rather attempt to provide a common foundation to enhance mutual understanding and collaboration across research communities. These orientations are presented in conceptual forms here in Section 3, and they are exemplified and summarised using four applied case studies in Section 4 and Table 1 therein.

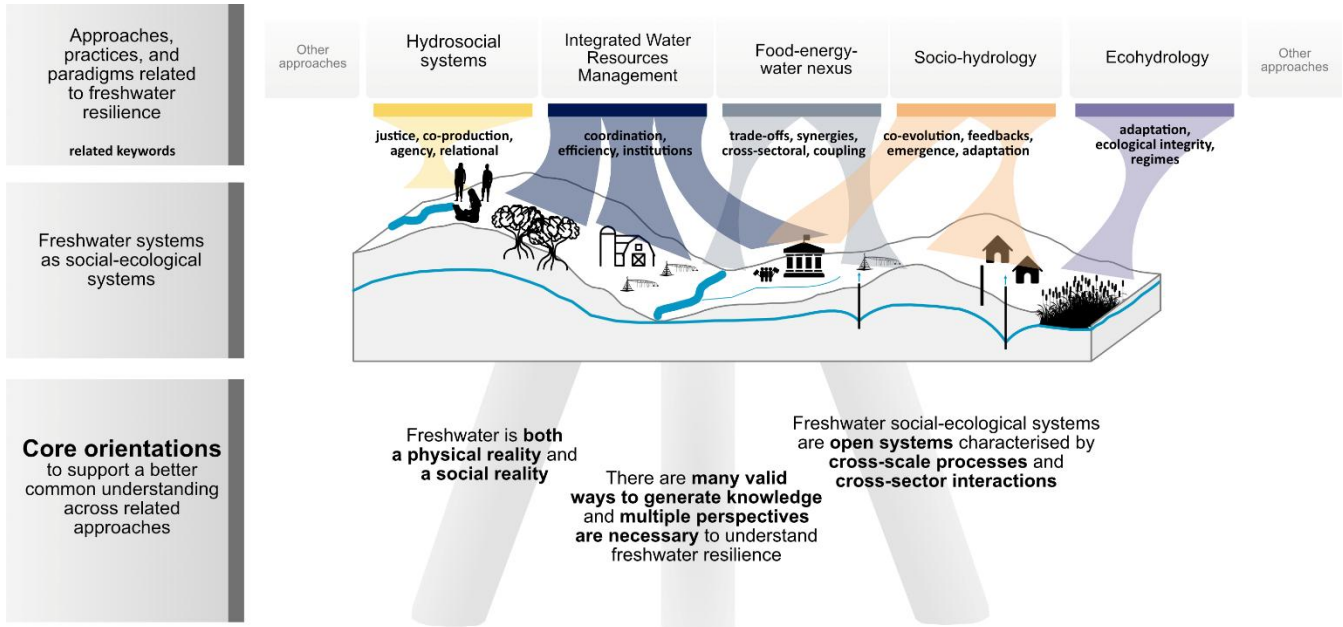


Figure 2: The relationship between freshwater systems (centre of diagram) and an illustrative, non-exhaustive selection of existing approaches, practices, and paradigms that are often applied to generate freshwater resilience insights (top of diagram). Integrative understandings of freshwater resilience in social-ecological systems (centre of diagram) can be facilitated by holding the social-ecological orientations listed below the diagram (three pillars).

Freshwater resilience is both a physical and a social reality in which resilience emerges from dynamic interactions among ecological processes, hydrological stores and fluxes, institutions, technologies, knowledge systems, and lived experiences (Linton, 2010; Zwartveen et al., 2017). From a physical science perspective, resilience can be quantified through measurable indicators of hydrological variability, ecological integrity, and system state, their observable thresholds, and regime shifts that signal fundamental changes in system function. From a hydro-social perspective, resilience can be understood as an evolving property of the relationships between people and water that are shaped by culture, power, memory, social relations and meanings of place; these considerations cannot be fully captured through physical metrics. Thus, holistic approaches to freshwater resilience require holding both imperatives in a productive tension (Baird et al., 2024).

There are multiple valid realities of freshwater resilience across physical, social, and cultural contexts. That is, freshwater resilience should rest on a pluralistic ontology (Cornell et al., 2013; Tengö et al., 2014; Yates et al., 2017), meaning that what freshwater resilience is, and what it is for whom, cannot be asserted by any individual framework, methodology, or knowledge system. In line with this ontology, *there are many ways to generate valid knowledge claims about freshwater resilience*. These range from modelling and remote sensing to histories, narratives, and analyses of power; and their relationships and interactions. In intertwined realities, these different ways of knowing co-exist, and holistic approaches to freshwater resilience should not force integration by collapsing them into a single worldview, theory, or

170 model. Acknowledging the existence of multiple ways to generate knowledge thus necessarily requires an understanding that all knowledge is contingent and situated (Zwarteveen et al., 2026).

Freshwater resilience emerges from radically open social-ecological system processes, which are characterized by multi- and cross-scalar dynamics, feedback mechanisms, teleconnections, and cross-sector interactions (Bennett and Reyers, 2024; Levin et al., 2013). While freshwater resilience can build from small spatial scales and be affected by rapid systemic
175 changes, it can also be latently dependent on large-scale (including global) trends that may change at a slow pace but also persist across long timescales. Practically, this means that freshwater resilience cannot be fully understood at any single scale or for any single process or relationship. Further, assessments or interventions fixed to a single scale risk misattributing causes and may fail to anticipate transitions driven by processes operating at different scales or at distal locations.

4 Holistic system descriptions of freshwater resilience enabled through social-ecological orientations

180 We provide four case examples to demonstrate how holding the social-ecological orientations (Fig. 2) may be useful to work with diverse resilience insights in distinct freshwater systems. Furthermore, we summarise how each of the three orientations applies to the four cases in Table 1.

4.1 The almond debate in California's Central Valley

A large share of the global almond supply is cultivated in California, leading to pressures on regional water resources in a
185 hot and dry climate. This highlights how global markets and demand can drive and control the use and consumption of (scarce) regional water resources for the benefit of few consumers and agri-food businesses. Knowledge on this subject is developed through a range of complementary research approaches, in which each contributes a unique perspective. Hydrological modeling and remote sensing are tracking both agricultural expansion and intensification, revealing that almond acreage grew despite ongoing droughts (Alam et al., 2019; Schauer and Senay, 2019). Similar quantitative water-
190 focused approaches include e.g. analysing trade-related virtual water exports and quantifications of the consumptive blue and green water use of almond production, which relate to its water footprint (Fulton et al., 2019; Marston and Konar, 2017). Economically oriented approaches analyze how drivers like prices, water costs, and policy constraints shape almond production and decision-making (Gebremichael et al., 2021). Critical and constructivist perspectives can characterise the same case in very different ways: Reisman (2019), for example, identifies the almond debate in California as a
195 problematization shaped by discourse, power and anxieties about markets, not just as an objective biophysical fact. Studies grounded in political ecology often center around global agrarian capitalism narratives and show how existing policies tend to reproduce existing power asymmetries (Dobbin, 2020).

The Californian almond production exemplifies that freshwater is a hybrid system that is equally a physical and a social reality. The availability of blue water resources in California is increasingly threatened by climate change, for example
200 through prolonged droughts and a declining water supply from the Sierra Nevada (Belmecheri et al., 2016; Mann and Gleick,

2015). But it is also a social realm where human water use and the exceptional economic value of almonds drive the reliance on groundwater for irrigation (Gebremichael et al., 2021; Mall and Herman, 2019). The system is further shaped by bi-directional cross-scale interactions; global decisions are increasingly driving local impacts since global markets, trade agreements, and demand influence and indirectly control the use of regional water resources. At the same time, a small number of large agribusinesses and private investors secure water resources and drive large land-use transformations (Reisman, 2019), often externalizing resulting environmental burdens onto local communities.

4.2 The Sahelian paradox

The "Sahelian paradox" describes a counterintuitive pattern in which runoff and river discharge have increased across parts of the Central Sahel despite prolonged meteorological drought and only partial recovery in rainfall (Descroix et al., 2009; Le Roux et al., 2026; Mahe et al., 2005). Rather than a hydrological anomaly, this paradox reveals a deeper issue. Intense, short-duration rainfall events generate more surface runoff that enhances greenness, which is captured by remotely sensed indicators, without improving soil infiltration (Epule et al., 2018; Pase et al., 2025).

Local knowledge offers a critical counterpoint to remote sensing. Farmers consistently report that "wetter is not better", describing rainfall as more erratic, intense, and less usable for agriculture (Porkka et al., 2021). This alternative perspective captures processes, such as intra-seasonal variability, soil crusting, and rapid runoff, that neither satellites nor standard hydrological models directly measure. As farming expands and soils degrade, rainfall increasingly runs off rather than infiltrates, raising flood risks instead of supporting crops (Elagib et al., 2021; Le Roux et al., 2026; Pase et al., 2025). Local agricultural practices like Zaï pits and half-moons reflect a different relationship with water, one that aims to slow it down, work with the soil, and rebuild moisture over time. In doing so, these practices reveal soil-water feedbacks that remote sensing cannot resolve, but resilience in agriculture management and climate adaptation relies upon (Lèye et al., 2021; Partey et al., 2018; Zougmore et al., 2023). Moreover, the impacts of floods and droughts are uneven. Land tenure, water rights, and political power determine who gains access to irrigation and who is exposed to displacement and damage (Pase et al., 2025). Hence, viewing freshwater resilience solely through a technical lens is insufficient. It is inextricably linked to social and cultural relations, colonial legacies, and governance structures (Pase et al., 2025).

These local dynamics interact with climate change. Increases in extreme precipitation under climate change leads to more blue water dominated landscapes (i.e., larger shares of rainfall turn into runoff rather than transpiration) in the Sahel (Heselschwerdt et al., 2026). Moreover, in transboundary basins, such as the Niger and the Nile, flood waves are growing stronger and can arrive weeks after rains have ceased (Elagib et al., 2021; Pase et al., 2025). These flood pulses reach landscapes where degraded soils have diminishing capacity to absorb them, amplifying flood risk even where vegetation appears to recover. Inept local and regional water management, combined with conflicts between herders and farmers, further worsen water scarcity (Denisova & Kostelyanets, 2024).

4.3 The flood pulse in the Mekong

A core biophysical feature of the Mekong River is a large seasonal flood pulse (Adamson et al., 2009). Each wet season, monsoonal rainfall causes water to rise, spread across floodplains, and recede. This flood pulse acts as the metronome that has historically coordinated and structured everyday life, supporting smallholder production, determining fishing practices, shaping transport and settlement, simultaneously synchronising food production, labour, and livelihood strategies (Tiwari et al., 2023). In Tonle Sap, Cambodia, people quite literally live with this pulse, adapting homes and routines to the lake's annual expansion and contraction (Arias et al., 2013; Keskinen, 2006). Flood pulse dynamics become proverbs that not only dictate when to mend nets, or when the first reliable rains arrive, but also guide fishing practices and technologies attuned to specific fish, currents, and water levels (Tran et al., 2025). The seasonal calendars, proverbs, and craft knowledge embedded in floodplain communities represent a distinct and valid way of knowing the river, built from generations of observation and practice (Tran et al., 2025).

However, widespread hydropower development has resulted in flow alterations that are as much a re-writing of a calendar as they are a change to a hydrograph (Dang and Pokhrel, 2024; Grumbine et al., 2012; Xue et al., 2011). Since the 1990s, dam construction in the river has been enabled and normalised by a basin governance architecture centred around the Mekong River Commission (Mekong River Commission, 2024). A political ecology reading of hydropower development highlights that beyond changing flow regimes (Räsänen et al., 2012), these developments embody a style of river management that prioritises control, predictability, and engineered optimisation (Middleton, 2022; Middleton and Allouche, 2016). The MRC has helped to codify and institutionalise the river's present material form, as much an outcome of diplomatic processes and investment priorities, as of hydrology (Sneddon and Fox, 2006; Sopera, 2022). In this way, physical and social realities are mutually constitutive. Understanding the multiple drivers of change and layered social-ecological effects on river ecosystems and dependent communities requires perspectives across hydrology, political ecology, and political economy.

These changes emerge through interactions within and across scales, where financing, governance, hydropower development, and its consequences unfold at fundamentally different scales, and interact with land use change, agricultural commodification, and dietary shifts (Burbano et al., 2020; Liu et al., 2020; Pittock et al., 2017; Ziv et al., 2012). These dynamics are further shaped by global market forces and climate change (Räsänen and Kumm, 2013), compounding pressures on and reconfiguring both the physical rhythms of the river and the livelihoods that depend on them.

4.4 Indigenous livelihoods and hydropower expansion in the Amazon Basin

The Amazon River basin is a grand social-ecological system. Home to unparalleled biodiversity and species richness, the Amazon is also the home of various Indigenous and ribeirinho (river people) communities. Along tributaries such as the Xingu River, they have organised their livelihoods around the river's seasonal flood pulse, which sustains fisheries critical to their food security and cultural identity (Ioris, 2020; Juruna et al., 2025). The Amazon's water cycle is strongly coupled to

regional vegetation: evapotranspiration from forest cover drives substantial moisture recycling, contributing roughly 30% of precipitation within the basin, while the remainder is primarily supplied by moisture advected from the Atlantic Ocean, making forest loss a critical threat to both ecological and human systems (Lima et al., 2014; Marengo, 2006; Dominquez et al. 2022).

No single disciplinary lens can capture the full complexity of Amazonian freshwater systems. Hydrological modelling, economic cost-benefit analysis, and ecological assessment each illuminate different dimensions of the same reality (Cabral de Sousa Junior and Reid, 2010; Caravaggio et al., 2017). Community-based monitoring programmes, such as the Independent Territorial Environmental Monitoring Program (MATI-VGX), contribute granular, place-specific observations that formal monitoring often misses (Juruna et al., 2025). As Fearnside (2005) argues, robust decision-making requires integrating this full range of perspectives before committing to irreversible infrastructure; a condition that, in practice, is rarely met.

The Belo Monte dam illustrates how a single infrastructure decision propagates across scales and sectors in ways that no single perspective could have anticipated alone. Hydrologically, diverting over 80% of the Xingu's flow has reshaped the river's flood pulse, inundating over 400 km² of land with downstream consequences for biodiversity and water quality (Diamond and Poirier, 2010; Marengo, 2006). Economically, the dam's performance has proven weaker than projected, with Ioris (2020) noting the resulting pressure to expand hydropower capacity elsewhere in the basin, contributing to proposals for additional dams that compound environmental and social impacts. Socially, the disruption of seasonal hydrology has undermined communities whose livelihoods and cultural practices are inseparable from river dynamics, while the forced relocation of between 20,000 and 40,000 people has severed the territorial relationships on which those practices depend (Fearnside, 2016; Jaichand and Sampaio, 2013; Juruna et al., 2025). These impacts are shaped by cross-scale dynamics, where decisions made at national and international levels interact with local ecological processes and are experienced most directly by affected communities.

Table 1: Envisioned implications and case study examples of holding the presented social-ecological orientations.

	Freshwater as a physical and a social reality	Many valid knowledge systems exist and multiple perspectives are necessary	Freshwater as an open social-ecological system
Envisioned implications for freshwater resilience science	Freshwater resilience in social-ecological systems cannot be reduced to biophysical indicators alone. Approaches must reflect both social and ecological conditions. These conditions are co-constituted and not linearly additive.	No single discipline, dataset, framework, research community, or knowledge system can offer a complete and authoritative picture of freshwater resilience. Understanding freshwater resilience rests on holding together multiple perspectives that are not necessarily reducible to common terms or metrics.	Freshwater resilience emerges from multiple processes that cross and shape system boundaries. These processes operate across a wide range of spatial and temporal scales.
	Examples from case studies		
The almond debate in California's Central Valley (Section 4.1)	Water scarcity arises from a combination of physical trends (increasing droughts, reduced snowpack), economic incentives (crop markets), and regulatory regimes (water laws).	Hydrological models, virtual water assessments, economic analysis, and political ecology each contribute a unique analysis on the almond debate.	Global market demands and trade networks drive local groundwater depletion. Control of local water resources drives large land system transformations.
The Sahelian paradox (Section 4.2)	Increasing runoff despite prolonged drought demonstrates that hydrological signals cannot be explained without accounting for land-use change, social organisation, and governance.	Satellite indicators suggest landscape re-greening, yet farmers consistently report that "wetter is not better". This contradiction reveals that remote sensing and local knowledge capture fundamentally different dimensions of the same system.	Colonial-era (technocratic) governance legacies shape local flood and drought exposure and define who bears the burden.
The flood pulse in the Mekong (Section 4.3)	The flood pulse structures both hydrological functioning and social organisation. Flow alterations disrupt both biophysical and sociocultural systems.	Flow gauges can quantify the magnitude change in flow regimes. Craftsmanship, seasonal calendars, and oral histories constitute a distinct, practice-based epistemology of the river. Full characterisation of Mekong resilience requires interaction across hydrology, political ecology, and political economy.	Hydropower financing, governance, and downstream consequences operate at fundamentally different scales, and propagate through basin hydrology to reshape livelihoods and ecological functions. Erosion of traditional ecological knowledge reflects the cumulative interaction of transboundary infrastructure, global market forces, and shifting local practice.
Indigenous livelihoods and hydropower expansion in the Amazon Basin (Section 4.4)	Flow alteration disrupts fisheries, seasonal mobility, and livelihoods of Indigenous and ribeirinho communities, while dam infrastructure inundates land and drives displacement.	Hydrological modelling and economic analysis prioritise infrastructure performance, while community-based monitoring captures place-based ecological change, livelihood impacts, and culturally embedded knowledge.	National energy policy and international investment drive dam construction, while impacts are experienced locally, highlighting cross-scale dynamics and limited influence of affected communities in decision-making.

5 Contextualised freshwater resilience in the Anthropocene

Freshwater resilience is a useful concept to seek increasingly comprehensive knowledge about freshwater systems, their dynamics, possible system regimes and configurations, and their stability. However, the wide variety in how freshwater resilience insights are generated (Fig. 1) hinders their synthesis. Building on our proposed social-ecological orientations (Fig. 2), we argue that applications of freshwater resilience could benefit from providing increasingly context-rich descriptions of how freshwater resilience is represented and critically reflecting on potential biases that relate to this. In this way, we envision that freshwater resilience science may be more practically applicable in decision-relevant contexts, such as in supporting decision-makers in understanding cost-benefit trade-offs in managing complex systems for normatively determined outcomes, identifying potential intervention points for desired system transformation (Anderies et al., 2006), and exploring mechanisms through which multiple desired system states can co-occur.

Holding the social-ecological orientations comes, however, with major challenges that can be illustrated through two metaphors. Studying freshwater resilience from multiple perspectives maps analogously onto the classic parable of the blind scientists studying an elephant (Fig. 3a), in which each scientist is interacting with parts of the elephant and arriving at contrasting conclusions when being blind to the whole animal: for instance, the tail is thought to be a rope and the tusk is thought to be a spear. Only by connecting these fragmented insights is the elephant properly identified. In freshwater systems that are our elephants; social and physical dimensions, the variety of disciplines and knowledge systems, and the cross-scalar dynamics represent the anatomy we need to consider as being a part of a greater whole.

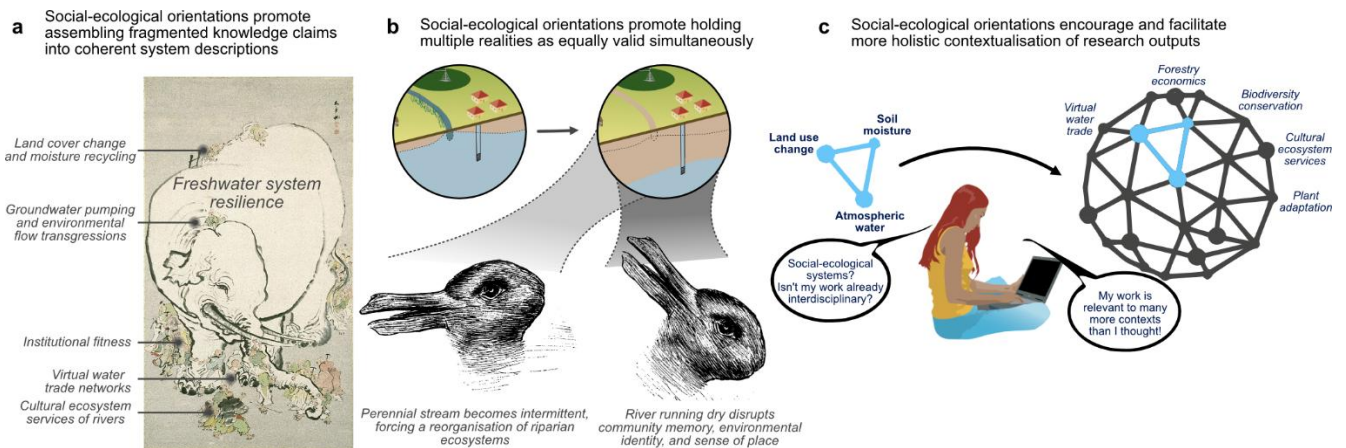


Figure 3: Envisioned benefits and implications of holding the presented social-ecological orientations for freshwater resilience studies. (a) Fostering the capacity to work across and integrate fragmented insights. (b) Fostering the capacity to hold multiple perspectives at once. (c) Fostering the capacity to situate one's work within a network of broader disciplines working to study different aspects of the same system.

Nevertheless, connecting fragmented insights should not mean forcibly integrating them into a single understanding as a rule. In our second metaphor of the rabbit-duck illusion (Fig. 3b), the same ambiguous drawing can be perceived as either a duck or a rabbit depending on the orientation and perception of the viewer. While neither understanding is wrong,

the two cannot be reconciled into a single coherent account. The challenge here is not in how completely a system can be observed, but rather in how disciplinary orientations reveal different aspects of the same reality. Unlike the blind scientists' parable where integration of fragmented and partial insights leads to a collective clarity, the rabbit-duck illusion demonstrates the dangers of forcing integration across incompatible knowledge systems. Forced integration can come with risking both usability and representativeness of the resulting resilience insights, and we see that resolving this structural tension is one of the grand challenges for future freshwater resilience science to address.

Working with multiple partial perspectives and resolving tensions between them has recently been discussed across other Earth system science domains, as well. For instance, it is increasingly accepted that reproducing high fidelity “digital twins” of the human-Earth system is untenable (Saltelli et al., 2024), and the endless pursuit of representing all physical features at a level of detail matching reality is allegorized as the “map maker’s dilemma” (Reinecke et al., 2024). Rather, approaches to address a complex problem may become “fit-for-purpose”, meaning they are developed to reflect specific dynamics or system interactions, at a given spatial and temporal scale of analysis, and with explicitly or implicitly defined boundary conditions and limitations for a given problem statement. The development of a sustained commitment to explicitly clarify which resilience aspects are considered in generating freshwater resilience insights would be wise, while further considering how the representations of social positions, values, and power shape study outcomes (Fallon et al., 2022).

In addition to promoting integration across fragmented insights (Fig. 3a) and holding multiple perspectives at once (Fig. 3b), adopting our proposed core orientations may unlock cognitive and perceptual barriers that have hindered more collaborative forms of freshwater resilience science. The orientations can equip individual researchers and communities with the conceptual scaffolding to situate their work relative to other disciplines (Fig. 3c), which corresponds directly with social-ecological research guides generally calling for a richer diversity of methods, knowledge systems, and collaboration across disciplines and communities (Levin et al., 2013; Preiser et al., 2018; Reyers and Selomane, 2018; Tengö et al., 2014). While the orientations are grounded on established social-ecological systems literature, we here articulate them explicitly in the context of freshwater resilience. With this, we may anticipate wider uptake of social-ecological perspectives in freshwater science, even independent of whether a study is explicitly focused on resilience.

Finally, the orientations we have proposed are squarely suited to support freshwater resilience in the Anthropocene. Following Ellis’ (2023) description of the “Anthropocene condition” as a reference point (“[the] coupling of socially produced environmental challenges with disruptive social changes”), we argue that the orientations presented can support freshwater science in the Anthropocene. By incorporating the integrative nature of social-ecological systems in our proposed orientations, we promote moving beyond studying predominantly the physical dimensions of Earth system change and with that, favouring the representation of those social dimensions that can conveniently be integrated with quantitative approaches. Although the orientations presented here offer no template solutions for freshwater science and resilience, they advocate for reflection about perspective, bias, and limitations. Thus, a wider adoption of social-ecological perspectives can

345 encourage greater reflexivity in freshwater resilience, and in doing so, equip the field to better navigate the tensions between
rigour and pluralism that freshwater resilience challenges in the Anthropocene demand.

Code and data availability

No code or original data were used in preparing this Perspective.

Author contributions

350 This manuscript was produced collaboratively through iterative working sessions of the Global Freshwater Systems Science
Workshop (<https://freshwatersystemsworkshop.org/>). XH and VV led facilitation of group brainstorming activities, but all
authors contributed to these activities and thus the formulation of this Perspective. XH and VV led manuscript drafting with
support from EK and CK. HD, PV, RL, BV, SF, and EP led case study writing. All authors contributed to manuscript
conceptualisation, writing, editing, and revising.

355 Competing interests

Authors have no competing interests to disclose.

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