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HESS Opinions: Operationalizing sociohydrology from systems thinking to systems doing for sustainable and resilient water management

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Abstract. Sociohydrology has advanced explanations of coupled human-water systems, but its translation into decision support remains uneven. We argue that a practical bridge from systems thinking to systems doing can be built around two complementary abstractions: (i) canonical feedback structures that make cases comparable without erasing context, and (ii) critical pathways that trace how interventions propagate through behavior, exposure, and outcomes. Canonical forms help organize recurring emergent phenomena such as the levee effect and reservoir effect, while critical pathways turn these insights into a repeatable workflow for intervention design, monitoring, and adaptive learning. We propose a minimal "systems doing loop" that links feedback mapping, pathway tracing, indicator selection, and iteration, with equity and legitimacy treated as explicit constraints on what counts as useful knowledge and acceptable action. This framing complements integrated water resources management by making unintended consequences operational and by clarifying what to monitor and revisit when system behavior changes.

1 Introduction: making sociohydrology actionable

Sociohydrology was established to understand coupled human-water systems (CHWS) as co-evolving systems shaped by feedbacks between hydrology and society (Sivapalan et al., 2012; Di Baldassarre et al., 2019). Yet many studies still stop at explanation: models reproduce observed dynamics, but remain loosely connected to the concrete work of practice, including

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intervention design, monitoring choices, and iterative learning cycles. A useful opinion-level contribution is therefore not another call for "holistic" approaches, but a compact and defensible bridge that helps move from insight to action.

We suggest two requirements for this bridge. First, case representations should be comparable across places without erasing local context. Second, sociohydrological insights should connect explicitly to decisions: what to do next, what to monitor, and how to adapt when systems surprise us. These moves align with IAHS Panta Rhei and subsequent science-for-solutions efforts (Montanari et al., 2013; Kreibich et al., 2025; Arheimer et al., 2024). They also complement other integrative framings: water security and nexus approaches are valuable for defining risks, trade-offs, and cross-sector interdependence, whereas sociohydrology contributes most when endogenous social feedbacks, path dependence, and unintended consequences must be made explicit within human-water systems.

2 Canonical feedbacks and critical pathways for systems doing

Comparability does not require uniformity. A practical starting point is to describe CHWS with a minimal anatomy of interacting components (hydrology, infrastructure, institutions, society, economy, and environment, see Fig. 1) and then represent key feedbacks among them (Tian et al., 2025). Causal loop diagrams and related system dynamics tools provide a compact language for this purpose (Hjorth and Bagheri, 2006). They support the identification of canonical feedback structures that can reproduce a given emergent phenomenon even when local variables differ.

Two well-studied examples illustrate the value of canonical forms. The levee effect shows how structural protection can reduce perceived flood risk, stimulate development in exposed areas, and thereby increase future losses through reinforcing feedbacks (Di Baldassarre et al., 2013). The reservoir effect similarly shows how supply augmentation can reduce drought impacts at first, but later induce demand growth and increase vulnerability (Di Baldassarre et al., 2018). These cases differ in hazard, infrastructure, and institutions, but they share a recognizable structure: an intervention dampens risk in the short term while shifting behavior and exposure in ways that can undermine long-term goals. Organizing such phenomena in shared meta-models and libraries of canonical forms can support cumulative learning while keeping case-specific detail visible (Mijic et al., 2024; Tian et al., 2025).

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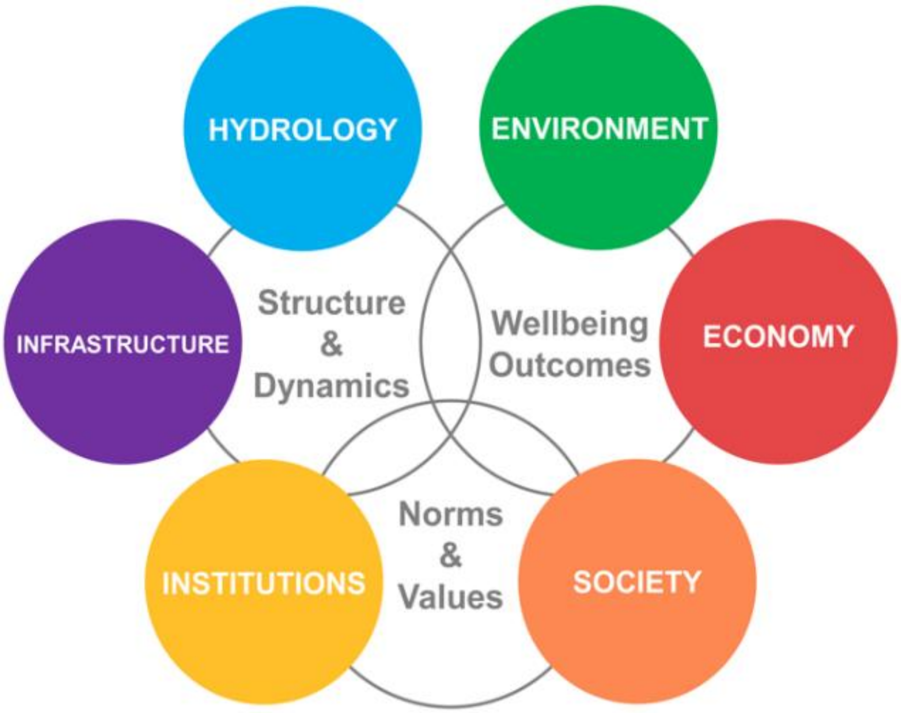

Figure 1. A minimal CHWS anatomy for systems doing. Six interacting components (hydrology, infrastructure, institutions, society, economy, and environment) provide a scaffold for mapping feedbacks, identifying emergent phenomena, and tracing critical pathways from interventions to outcomes.

Canonical feedbacks help explain why unintended consequences recur. To make them actionable, sociohydrology needs a transparent way to connect specific actions to outcomes through the most influential chains of effects. We call these chains critical pathways: simplified causal sequences linking an intervention to changes in behavior, exposure, and outcomes, including where feedbacks amplify or dampen impacts (Tian et al., 2025).

Critical pathways complement established intervention heuristics such as leverage points (Meadows, 2012). Leverage points ask where to intervene in a system; critical pathways make those opportunities explicit by tracing how an intervention actually propagates. For the levee effect, a critical pathway can run from levee height to perceived safety to land-use change to exposure and losses (Di Baldassarre et al., 2013). This framing clarifies why purely structural solutions can be self-defeating and highlights non-structural leverage points along the pathway, such as zoning, insurance design, risk communication, or managed retreat. For the reservoir effect, the pathway from added capacity to reduced perceived scarcity to expanded use and rising vulnerability points to leverage points in demand management and institutional allocation rules (Di Baldassarre et al., 2018). Methodologically, critical pathways are not tied to a single approach. They can be elicited from case narratives and qualitative evidence, from participatory mapping with stakeholders, or from simulation experiments that

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compare candidate interventions under uncertainty. The goal is not a single best pathway, but a small set of plausible pathways that can guide decisions and monitoring.

3 Comparative learning, data, and participation

Comparative synthesis and place-based investigation serve different inference goals and should be coupled deliberately. Comparative work can identify recurring mechanisms, pathway motifs, and boundary conditions across cases. Place-based work provides causal detail, contextual interpretation, and legitimacy for applying insights to a specific decision setting. The connection between the two should be explicit: synthesis suggests hypotheses about pathways and leverage points; local inquiry tests whether those mechanisms operate and how institutions, culture, and biophysical constraints reshape them.

This coupling requires reporting that is comparable but not constraining. Rather than a single rigid framework, sociohydrology would benefit from minimum reporting elements with modular extensions. A short core could include: (i) system boundary and time horizon; (ii) key interventions and decision actors; (iii) outcomes of concern and how they are measured; (iv) the main feedbacks and candidate critical pathways; and (v) contextual descriptors of governance and infrastructure that condition behavior. Optional modules can then support different comparative designs, from qualitative typologies to quantitative meta-analysis.

Moving from systems thinking to systems doing requires integrated data that captures not only hydrology and infrastructure, but also social variables that sit on critical pathways, such as risk perception, trust, compliance, and institutional change. Data plans should be designed around the pathway variables that decisions can plausibly influence and around leading indicators that can warn when a system is drifting toward lock-in or failure.

Citizen science, community monitoring, and participatory data collection can strengthen CHWS understanding by expanding spatiotemporal coverage and improving the salience of indicators, but they do not automatically democratize knowledge or represent marginalized groups (Buytaert et al., 2016). Their value is greatest when they are tied to concrete pathway variables, for example by co-defining drought indicators, documenting infrastructure failures, or improving datasets on flood memory and warning response. Participation should therefore be treated as a design choice with clear objectives, roles, and safeguards. FAIR principles can improve findability and reuse of datasets (Wilkinson et al., 2016), while CARE principles clarify expectations around Indigenous data governance, benefit, and authority (Carroll et al., 2020).

4 Equity, legitimacy, and mainstreaming into water management

Sociohydrological models can shape decisions, so the standards for useful knowledge extend beyond predictive skill. Equity, legitimacy, and governance should therefore be treated as related but distinct dimensions of systems doing, not as interchangeable labels. A minimal equity-aware stance asks three questions at the outset of a study: who is represented in the model and data, who benefits or bears harm under candidate interventions, and what decision processes are considered

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legitimate (Arnstein, 1969; Schlosberg, 2007). This does not imply that participation replaces formal accountability, nor that all projects must use the same co-production model. It implies that distributional effects, procedural legitimacy, and recognition of affected communities are treated as first-class variables and constraints, not as afterthoughts.

Participatory modelling can support shared problem framing and learning, but it does not guarantee interdisciplinarity or transdisciplinarity. In practice, legitimacy depends on transparent choices about whose knowledge is included, how disagreement is handled, and how outputs feed into decisions.

The science-society interface does not require a transition from theory to practice; it requires fit-for-purpose tools that can travel across that interface. Sociohydrology can complement integrated water resources management by adding explicit feedback thinking and by operationalizing unintended consequences through canonical forms and critical pathways. For water managers, the practical value lies in a repeatable doing loop: map feedbacks, identify critical pathways, choose interventions and indicators along those pathways, and iterate as new evidence arrives (Table 1). This loop should cover multiple hazards and compound extremes, not only emerging climate risks.

Table 1. A minimal systems-doing loop for sociohydrology in science and practice.

Step	Shared object	Science output	Practice output
1 Define the decision setting	CHWS boundary and objective	System boundary, time horizon, outcomes, candidate drivers	Decision question, constraints, accountable actors, stakeholder map
2 Map feedbacks	Canonical feedback structure	Causal loop diagram, hypothesized emergent phenomena	Shared mental model, list of plausible unintended consequences
3 Trace critical pathways	Intervention-to-outcome pathways	Candidate pathways, pathway variables, testable hypotheses	Candidate leverage points, intervention options, trade-offs
4 Design data and indicators	Monitoring plan	Measurement strategy for pathway variables, FAIR and CARE choices	Leading indicators, roles for agencies and communities, triggers for review
5 Iterate and learn	Adaptive cycle	Model updates, cross-case comparison of pathways and boundary conditions	Policy adjustment, evaluation of distributional impacts and legitimacy

5 Conclusions

If sociohydrology is to matter for sustainable and resilient water management, it should be judged by whether it improves intervention choice, monitoring, and learning in real decision settings, while making equity and legitimacy constraints explicit rather than implicit. Canonical feedbacks and critical pathways offer a compact way to make that bridge practical.

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Code and data availability

No code or datasets were used in this opinion article

Author contributions

FT led the conceptualization and drafting. All authors contributed to discussion, writing, and revisions.

Competing interests

At least one of the (co-)authors is a member of the editorial board of Hydrology and Earth System Sciences.

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