nature water

Review article

https://doi.org/10.1038/s44221-026-00598-w

The paradoxes holding back progress on water security

Received: 20 August 2025

Accepted: 29 January 2026

Published online: 03 March 2026

Check for updates

Edoardo Borgomeo

Effective water management and policy play a critical role in shaping society's evolving relationship with water. Yet, the growing impacts of water-related risks worldwide show that many responses remain ineffective, often leading to unintended consequences that undermine stated policy objectives. These contradictions—referred to in the literature as water paradoxes—occur when well-intentioned efforts to manage water backfire. This Review argues that researchers should better characterize these paradoxes, and practitioners must integrate them in decision-making processes and economic evaluations of water policy. Four key paradoxes are examined: value, supply, efficiency and data. For each, relevant examples are highlighted, policy implications are explored and potential approaches for addressing them are suggested. Water management and policy should focus on addressing these paradoxes, rather than pursuing grand visions and missions detached from context.

Why are some of the world's most sacred rivers also among the most polluted? Why does global consensus on the value of water coexist with low levels of investment and policy action? Why do governments spend billions in subsidies that encourage pollution and wasteful water withdrawals? And why does growing interest in applying artificial intelligence (AI) to water management coexist with limited data access and severe gaps in hydrometeorological monitoring infrastructure?

These seemingly naive questions capture the contradictions that define local and global responses to the world's growing and multifaceted water crisis. These—and many other—contradictions give rise to 'water paradoxes'. Water paradoxes occur when well-intentioned actions to manage water resources (for example, building a flood embankment) lead to unintended consequences (for example, increased flood exposure) or when statements about water (for example, 'the river is sacred') contradict actual practices (for example, dumping untreated wastewater into the river).

Water paradoxes have been discussed extensively in the economics[1,2] and water resources literature[3]. However, scholars have not yet reviewed and synthesized them. This Review addresses this gap by proposing a conceptualization of water management and policy that is grounded in the notion of paradoxes. To do so, it explores two questions: (1) what are key water paradoxes, and how do they shed light on the contradictions and trade-offs that characterize water policy? and (2) how may researchers and practitioners actively address these paradoxes to develop more contextual and appropriate interventions that reflect the complexity of water management? The purpose of this Review is to address these questions and encourage scholars and practitioners to place paradox dynamics at the centre of water management and policy.

The motivation for promoting paradox thinking in water science, policy and management is threefold. First, paradoxes are a useful tool for advancing science because they reveal apparent contradictions in our understanding of the world, prompting the development of new theories and practices for resolving them[4]. Water science, policy and management need such innovations to confront challenges such as hydrological nonstationarity[5], the rapid emergence of new water contaminants[6] and inadequate pricing of water[7].

Second, scholars of organizational studies have long used paradox thinking to help individuals and organizations deal with 'wicked problems' characterized by conflictive objectives, large uncertainties and the need for transformative action and fundamental shifts in perception[8]. Water management is one such wicked problem[9,10], indicating that paradox thinking may offer valuable insights.

In the organizational studies and management theory literature, paradox thinking is seen as a driver of organizational development and success under conditions of uncertainty[11]. It is also used to design business models that leverage contradictions to help organizations be more competitive[12]. In psychology and conflict resolution studies,

Department of Engineering, University of Cambridge, Cambridge, UK. e-mail: eb973@cam.ac.uk

Table 1 | Overview of water paradoxes, policy implications and opportunities to address them

Paradox	Description	Policy implications	Opportunities to address the paradox
Value	Water has a high value in use but a low market price	• Water overuse and pollution • Insufficient cost recovery • Lower ability to expand access to unserved communities	• Integration of pricing and markets with complementary measures to address equity trade-offs, endogenous responses, institutional and governance requirements
Supply	Providing more infrastructure without accompanying economic incentives and regulations enables greater demand	• Greater exposure to water-related hazards • Ever-growing need to invest in new infrastructure • Risk of maladaptation	• Complementary demand, regulatory and communication interventions • Strategic planning to incorporate human–natural system interactions and adaptive responses
Efficiency	Higher water-use efficiency at the local level does not lead to expected basin-wide water savings	• Overall increase in water consumption (rebound effect) • Acceleration in water depletion • Lower return flows	• Water accounting • Caps on withdrawals and irrigated area • Behavioural interventions • Scale-based frameworks to understand efficiency
Data	Despite growing interest in AI, water-related data remain undervalued, poorly managed and not widely shared	• Full potential of AI in water not exploited • Weaker decision-making	• Open-access remote-sensing products • Large-sample publicly available datasets • Place-based observatories

paradox thinking has been applied to foster fundamental changes in attitude toward complex issues[13], including efforts to promote peace in conflicts that are traditionally viewed as intractable[14]. This point is particularly relevant in the context of water: the ubiquitous calls for fundamental changes in attitudes and practices around 'valuing water' have proved particularly difficult to implement. Paradox thinking may offer a promising approach for conceptualizing and designing interventions that are aimed at transforming how individuals and societies perceive and act upon the value of water.

Finally, paradox thinking can help to identify recurring patterns of policy failure, thereby supporting the study and understanding of disparate water-related challenges worldwide. In public policy, examining failures—situations where well-intentioned policies produce unintended or paradoxical outcomes—is particularly instructive, as it enables the development of generalizable lessons[15,16]. For instance, the study of policy failures has been promoted as a key instrument to inform groundwater policy in South Asia[17]. Paradox thinking, therefore, supports the development of an overarching framework for understanding water-related issues across time and space. This approach enables researchers and practitioners to identify options for action and explore how to address these paradoxes and achieve better outcomes.

This Review examines the theory and evidence related to four water paradoxes: value, supply, efficiency and data (Table 1). In presenting these paradoxes, I acknowledge that the list may not be exhaustive and that definitions and categorizations may require further refinement. For instance, additional paradoxes may arise in transboundary water management, where cooperation and conflict over shared waters often paradoxically coexist[18]. Similarly, in virtual water trade, hyper-arid countries or regions may paradoxically use scarce water resources to grow crops for export, jeopardizing long-term sustainability[19,20]. Moreover, positive social impacts of virtual water trade can mask paradoxical realities, such as increased local conflicts and scarcity[21].

Paradox of value

The paradox of value is a well-known concept in economics and philosophy. The economist Adam Smith is typically credited for having formalized this paradox in a well-known passage of *The Wealth of Nations*, where he noted that "Nothing is more useful than water: but it will purchase scarce any thing; scarce any thing can be had in exchange for it. A diamond, on the contrary, has scarce any value in use; but a very great quantity of other goods may frequently be had in exchange for it"[22]. Smith used the water–diamond paradox to explain marginal utility and the difference between market price and economic value, building on a long tradition in philosophy around the discussion of value and its meaning[23].

Building on this well-known framing, scholars have explored various corollaries of the paradox of value in water-related contexts. Examples include water pricing ("the price of water almost never equals its value and rarely covers its cost"[2]), water service delivery ("implementation of full cost recovery principles may exacerbate uneven access in heterogenous water supply systems"[24]), failure to act on the global water crisis ("a scarce and valuable resource is poorly managed"[1]) and virtual water trade ("water scarce countries export virtual water to water rich countries"[20]), among others.

It is no coincidence that the influential report published by the Global Commission on the Economics of Water in 2024 emphasizes the notion of value in its title *The Economics of Water: Valuing the Hydrological Cycle as a Global Common Good*[25]. This report builds on decades of international efforts to highlight the 'value of water', such as the business case for water valuation provided by the World Business Council for Sustainable Development[26], the Valuing Water Initiative launched in 2017 by the United Nations/World Bank High Level Panel on Water[27] and the United Nations World Water Development Report of 2021[28]. The emphasis on value stressed by the Global Commission on the Economics of Water also draws on influential work in the history of economic thought and the call to rethink the theory of value for the twenty-first century[29].

Despite these efforts, this emphasis on value has not, on its own, contributed to resolving the paradox. A new economics of water requires moving beyond conventional policy prescriptions that are founded on market-based solutions or generic recommendations based on global valuation studies towards locally grounded agendas that are informed by at least two elements. First, advances in the science and practice of water valuation and cost–benefit analysis, which have already demonstrated effectiveness in addressing the paradox of value and the unique characteristics of water[30]. For example, in the case of water quality, expanding cost–benefit analysis frameworks to account for both local and global benefits[31] and applying stated preference techniques[32] enable more precise assessments of the costs and benefits of water quality improvements.

The second element in resolving the paradox of value requires a deeper integration of economic policy tools (for example, pricing, markets) with complementary measures that address contradictions inherent in human behaviour, trade-offs and political priorities in its management. Achieving this integration demands a fundamental rethink of the economic approach to water[33]. Narrow applications of economic methods often perpetuate the paradox of value, for example, when economists design randomized controlled trials to assess sanitation interventions but fail to account for the role of other critical factors, such as housing policy, that influence sanitation outcomes[34]. Conversely, when tailored to local social and political contexts, economic research can improve policy design and evaluation.

 https://doi.org/10.1038/s44221-026-00598-w

For instance, economic research can: (1) shed light on the interactions between specific economic instruments and user behaviours, such as the relationship between subsidies for smallholder irrigation and farmers' perceptions[35]; (2) identify institutional and governance requirements for water allocation reforms, such as creating water markets (for example, the Water Markets Readiness Assessment framework[36]); and (3) quantify trade-offs between equity, economic efficiency and cost recovery when designing tariffs[37] or considering water allocation reforms[36]. This emphasis on incorporating equity also aligns with recent advances in systems modelling used for water policy evaluation[38] and the exploration of new property rights systems, such as 'Rights of Nature' approaches[39].

The world urgently needs increased application of economic instruments—such as water pricing and markets—to address the paradox of value and adapt to climate change. However, these applications will only succeed if combined with a deep understanding of the governance structures implementing interventions (for example, water utilities, river basin agencies, water user associations) and the behavioural responses of the users that they affect.

Paradox of supply

Water resources management and planning traditionally focus on ensuring reliable and cost-effective access to water services, such as flood protection or water supplies, to a range of users. The conventional approach to delivering these services relies on expanding the supply capacity, through investments in reservoirs, inter-basin transfers and, more recently, desalination infrastructure, all of which are aimed at meeting the demands of cities, industries and farms[40]. This supply-led approach is also widely applied in flood risk management, where the demand consists of the need to protect assets, and the supply largely takes the form of flood control infrastructure, such as embankments, to protect people and property from the destructive force of water[41].

The supply-led approach has served society well, enabling urban expansion and economic growth in arid regions and floodplains; however, it has produced two paradoxical outcomes. First, rather than reaching an equilibrium with demand, it has enabled even greater demands for water supply or flood protection[3]. Second, it has heightened society's vulnerability and exposure to water-related hazards, by incentivising risk-taking behaviours—for example, irrigating cotton in drought-prone areas or settling in floodplains exposed to high-impact floods—in a classic case of what economists call a moral hazard problem[42].

This is the paradox of supply: providing more infrastructure without accompanying economic incentives and regulations enables greater demand and increases vulnerability and exposure to water-related hazards. This paradox has been extensively documented in the water engineering and economics literature, with examples reported for cities, irrigated areas and floodplains, among others.

In cities around the world, expanding the water supply capacity through reservoirs or transfers has typically resulted in higher levels of water consumption. Historical analyses of water resources development in Athens[43] and Isfahan[44] illustrate a positive feedback loop between the construction of reservoirs and transfers and the subsequent increase in water demand. Similarly, the 'reservoir effect' shows that global water demand has grown faster than reservoir storage capacity in recent decades, offsetting the initial benefits of additional water supply provided by reservoirs built during the 1970s and 1980s[3]. In a historical assessment, it has been hypothesized that over-reliance on reservoirs may have contributed, alongside socio-political factors, to the collapse of the Mayan civilization in the ninth century[45]. Reservoirs allowed continued urban and population growth; however, when they ran dry during prolonged droughts, the impacts were more severe. These impacts probably contributed to destabilizing Mayan societies already under pressure from warfare, economic challenges and socio-political crises[46].

Similar patterns are observed in irrigated areas around the world. Providing cheap, abundant water for agriculture through reservoirs, canals and groundwater pumping—without corresponding incentives to farmers to limit water use or plant crops that are adequate to local climates—typically leads to increased water demand. Groundwater irrigation in the Great Plains of the United States encouraged the production of water-intensive crops, heightening vulnerability to drought[47]. Similarly, while irrigation boosts crop productivity in the face of hydrological variability, it also paradoxically increases vulnerability to drought globally[42]. Abundant, cheap irrigation water in dry areas incentivizes the cultivation of crops that are unsuited to these climates, so when droughts occur and crop water demands cannot be met, farmers suffer greater losses[42].

In the context of flood risk management, the paradox of supply takes the form of the 'levee effect'. This well-known paradox arises from the provision of flood control and protection: constructing flood protection infrastructure reduces risk perception and encourages development in highly exposed floodplains[48]. Despite awareness of this phenomenon in the hydrological and engineering literature[49–51], empirical estimates of its magnitude and policy insights on ways to reverse it are only beginning to emerge and inform flood risk management. For example, studies have shown that areas protected by levees along the Jamuna River in Bangladesh experienced higher mortality rates during extreme floods[52]. In Florida, newly constructed levees increased the rate of residential development by 50% (ref. 53). Similarly, historical analysis of floodplain expansion in the United States reveals that levee construction accelerated urban growth by 62%, compared with a national average of 29% between 1940 and 1970[54]. The same analysis also identified the role of land-use planning in reversing this effect. This research underscores a clear shift in risk perception after levees are built, and emphasizes the importance of combining infrastructure provisions with economic incentives and regulations—such as floodplain zoning—that signal residual risks and the cost of protection.

The limitations of a supply-led approach to water management have long been recognized[55]; however, current water resources management and planning frameworks do not take into account the paradox of supply. This is concerning given the growing uptake of technologies that create additional water supplies, such as desalination[56], and the continued expansion of urban areas in floodplains[57].

Paradox of efficiency

With rising water scarcity and human impacts on freshwater ecosystems, sustaining economic development—particularly food production—while limiting water use has become an urgent challenge[58]. A key response to this challenge is improving water-use efficiency. In agriculture, this involves deploying irrigation technologies such as drip irrigation systems, which maintain or increase agricultural output for the same or reduced water input at the field level, thereby improving the 'crop per drop' ratio (that is, the proportion of water that actually supports crop growth, rather than being lost through conveyance, weed irrigation or evaporation)[59]. Drip irrigation typically ensures that around 85–95% of the water taken from a source reaches the crop, compared with much lower volumes for surface water systems[60].

Considering this potential, governments around the world heavily subsidize the roll-out of drip irrigation technologies, assuming that they will save water in agriculture and release it for other uses, notably ecosystems. However, decades of research have shown that these expected water savings rarely materialize. Evidence from interventions across multiple regions—Southwestern USA[61], India[62], Chile, the Western USA and southern Spain[63] and Australia[64]—reveals that farmers equipped with advanced irrigation systems use more, not less, water, and that overall water availability across river basins tends to decline[65]. This is the paradox of efficiency: greater water-use efficiency at the field level does not deliver expected water savings at the basin level[60].

https://doi.org/10.1038/s44221-026-00598-w

The paradox of efficiency is not only relevant for water conservation in agriculture. Subsidies for water-efficient devices in households can sometimes lead to increased water consumption[66]. Communities that experience plentiful water supplies after drought often see consumption rebound despite the implementation of efficiency improvements, as observed in Australia[67] and California[68]. The paradox of efficiency can also affect the feasibility of wastewater reuse. Efficiency improvements at the household level can have unintended consequences on downstream wastewater availability and quality. In Southern California, urban water conservation measures reduced wastewater effluent flows and increased effluent salinity, limiting the amount and quality of wastewater available for recycling or for discharge into ecosystems[69].

While intuitive and consistent with broader economic concepts such as the Jevons paradox and the rebound effect[70], resolving the paradox of efficiency requires careful policy design because of the multi-scale, complex nature of hydrological systems. This paradox serves as a warning against simplistic calls to improve water-use efficiency as a solution to water scarcity, but nor is it a panacea to guide water management[71], or worse, a justification for reducing or limiting water conservation efforts[72]. Addressing this paradox calls for water monitoring and accounting, along with limits on water abstractions or irrigated areas. These measures should be complemented and informed by policy analysis frameworks that map how perceptions of efficiency vary across spatial scales and stakeholder viewpoints[73].

Paradox of data

The advent of AI is providing new opportunities in hydrological sciences and water management more broadly[74]. Scientists and water managers have used AI methods for decades to support specific functions in water management, such as artificial neural networks for predicting water quality parameters[75]. However, recent advances in machine learning that do not require human supervision and domain expertise, combined with computational improvements, have led to an exponential growth in their application to water over the past decade. Recent examples of AI applications in water management include flood prediction in ungauged catchments[76] and spatial and temporal infilling of water quality data[77].

The robustness of AI approaches depends on the quality and quantity of available data. Despite this well-known link between AI and data quality and availability, and despite the increasing emphasis that practitioners, funding agencies and researchers place on AI, the capacity to access and generate high-quality data on water resources is not improving globally. The number of river gauging stations reporting to global and publicly available databases, such as the Global Runoff Data Centre operated by the World Meteorological Organization, is declining[78]. Water quality data are notoriously sparse and inconsistent, meaning that AI applications in water quality lag well behind other fields of environmental science[77]. Furthermore, existing global databases still provide only a very partial understanding of the location, status and operation of key water infrastructure assets, such as reservoirs, wastewater treatment plants, water transfers and irrigation canals, and offer limited insights on water-use dynamics. This lack of data on infrastructure and water use is concerning, given that at least two-thirds of the world's rivers are human-impacted[79]. Information on infrastructure location and operation, as well as water-use dynamics, could help to improve the predictive ability of AI-based models[80,81].

This is the paradox of data: despite being the foundation for AI development and applications, global capacity for water monitoring is declining, and water-related data remain undervalued, poorly managed and not widely shared. Long-term efforts aimed at data collection, harmonization and consolidation are typically not supported or funded[82] and water-related data are not valued[83]. AI researchers are aware of this paradox. The largest bottleneck to deep learning applications in water quality is data availability[77], and the development of publicly available global water datasets is crucial to fully leverage the potential of AI for water security[76].

Continued development and application of open-access remote-sensing products broaden opportunities to monitor, assess and forecast water-related variables. When coupled with systematic ground-truthing and field measurements, remote sensing can help to resolve the paradox of data. For example, water accounting procedures based on remote sensing are foundational tools for managing water scarcity and promoting sustainable water management[84]. These approaches are crucial for advancing demand–management solutions, such as water markets, in a cost-effective and transparent way[36]. Reviews of one of the most developed water markets in the world—the Murray–Darling Basin of Australia—demonstrate the importance of water accounting in enabling fully transparent auditing of water availability and use, and in increasing market participation[85].

Additional opportunities to resolve the paradox of data include the creation of large-sample, publicly available AI-ready datasets[86–88], place-based research observatories[89] and new developments in data collection, such as unmanned aerial vehicles and citizen science. However, these opportunities have not yet been fully realized: research and funding attention remain focused on testing AI approaches and model performance, rather than promoting a fundamental rethinking of how water data are collected, managed and interpreted in the age of AI. Data infrastructure facilities, such as the UK's national Floods and Droughts Research Infrastructure, offer a promising means of addressing this paradox and should be prioritized over generic efforts to test and apply AI models.

Muddling through

Addressing paradoxes requires exploring unintended consequences and tensions in water management and policy. It also shifts the focus from 'fixing' to 'coping': water solutions are always partial, as society's expectations change and human modifications of the environment, including climate change, exceed the capacity of infrastructure and institutions to cope. Contradictions between supply and demand, and water's destructive and constructive forces, define a dynamic relationship. Consequently, water management and policy move away from a conventional emphasis on control and fixing problems towards a dynamic process of 'coping with'[90] or 'muddling through'[91] these paradoxes. This shift aligns with current trends in water research, which include defining place-specific water security pathways[92], understanding and modelling multi-sector dynamics[93], and empirically studying the co-evolution of human–water systems[94,95].

The concluding message is not that these paradoxes represent universal truths. Rather, they offer a useful lens for water policy researchers and practitioners to engage non-water experts and the public on the unintended consequences of seemingly intuitive policy responses to complex water challenges. Far from being overly critical or pessimistic, this framing shifts the focus towards reducing the risk of paradoxical and unintended outcomes, rather than pursuing grand visions and missions that are detached from context.

References

1. Barbier, E. B. *The Water Paradox: Overcoming the Global Crisis in Water Management* (Yale Univ. Press, 2019).
2. Grafton, R. Q., Chu, L. & Wyrwoll, P. The paradox of water pricing: dichotomies, dilemmas, and decisions. *Oxf. Rev. Econ. Policy* **36**, 86–107 (2020).
3. Di Baldassarre, G. et al. Water shortages worsened by reservoir effects. *Nat. Sustain.* **1**, 617–622 (2018).
4. Wilczek, F. Nobel Lecture: Asymptotic freedom: from paradox to paradigm. *Rev. Mod. Phys.* **77**, 857–870 (2005).
5. Borgomeo, E. et al. Risk-based water resources planning: incorporating probabilistic nonstationary climate uncertainties. *Water Resour. Res.* **50**, 6850–6873 (2014).

https://doi.org/10.1038/s44221-026-00598-w

6. Li, L. et al. Assessing antimicrobial resistance connectivity across One Health sectors. *Nat. Water* **3**, 1100–1113 (2025).
7. Wheeler, S. A., Nauges, C. & Grafton, R. Q. Water pricing and markets: principles, practices and proposals. *Appl. Econ. Perspect. Policy* **47**, 487–514 (2025).
8. Schad, J. & Bansal, P. Seeing the forest and the trees: how a systems perspective informs paradox research. *J. Manage. Stud.* **55**, 1490–1506 (2018).
9. Reed, P. M. & Kasprzyk, J. Water resources management: the myth, the wicked, and the future. *J. Water Resour. Plan. Manage.* **135**, 411–413 (2009).
10. Grafton, Q. R. Responding to the 'wicked problem' of water insecurity. *Water Resour. Manage.* **31**, 3023–3041 (2017).
11. Lewis, M. W. Exploring paradox: toward a more comprehensive guide. *Acad. Manage. Rev.* **25**, 760–776 (2000).
12. Smith, W. K. & Lewis, M. W. Toward a theory of paradox: a dynamic equilibrium model of organizing. *Acad. Manage. Rev.* **36**, 381–403 (2011).
13. Hameiri, B., Bar-Tal, D. & Halperin, E. Paradoxical thinking interventions: a paradigm for societal change. *Soc. Issues Policy Rev.* **13**, 36–62 (2019).
14. Hameiri, B., Porat, R., Bar-Tal, D., Bieler, A. & Halperin, E. Paradoxical thinking as a new avenue of intervention to promote peace. *Proc. Natl Acad. Sci. USA* **111**, 10996–11001 (2014).
15. Dörner, D. *The Logic of Failure: Recognizing and Avoiding Error in Complex Situations* (Perseus Books, 1996).
16. Bovens, M., & 't Hart, P. in *Fiascos in Public Policy and Foreign Policy* (eds Oppermann, K. & Spencer, A.) 23–36 (Routledge, 2018).
17. Balasubramanya, S. Groundwater pricing in agriculture in South Asia: research for practical policy-making. *Rev. Environ. Econ. Policy* **19**, 175–194 (2025).
18. Zeitoun, M. The conflict vs. cooperation paradox: fighting over or sharing of Palestinian-Israeli groundwater? *Water Int.* **32**, 105–120 (2007).
19. Ma, J., Hoekstra, A. Y., Wang, H., Chapagain, A. K. & Wang, D. Virtual versus real water transfers within China. *Trans. R. Soc. B* **361**, 835–842 (2006).
20. Greco, F. Introducing an historical perspective to virtual water flows: how hydrometabolism explains the "bad" virtual water flows from non renewable/overexploited groundwater. In *4th EGU Leonardo Conference: Hydrology and Society – Connections between Hydrology and Population Dynamics, Policy Making and Power Generation* (European Geosciences Union, 2012).
21. Dell'Angelo, J., D'Odorico, P. & Rulli, M. C. The neglected costs of water peace. *WIREs Water* **5**, e1316 (2018).
22. Smith, A. *An Inquiry into the Nature and Causes of the Wealth of Nations* (Oxford Univ. Press, 2008).
23. Hanemann, W. in *Water Crisis: Myth or Reality?* (eds Rogers, P. et al.) 61–91 (CRC Press, 2005).
24. Rusca, M. & Schwartz, K. The paradox of cost recovery in heterogeneous municipal water supply systems: ensuring inclusiveness or exacerbating inequalities? *Habitat Int.* **73**, 101–108 (2018).
25. *The Economics of Water: Valuing the Hydrological Cycle as a Global Common Good* (Global Commission on the Economics of Water, 2024).
26. *Water Valuation: Building the Business Case* (World Business Council for Sustainable Development, 2012); http://english.cbcsd.org.cn/databases/database_water/policies/International/20130809/download/WaterValuation-BuildingBusinessCase.pdf
27. *Valuing Water Initiative: Final Report* (Global Water Partnership, 2017); https://www.gwp.org/contentassets/b16f990348a34ffcaf9ce6f444216b34/hlpw---vwi---final-report_nov-2017.pdf
28. *The United Nations World Water Development Report 2021: Valuing Water* (UNESCO, 2021); https://www.unwater.org/publications/un-world-water-development-report-2021
29. Mazzucato, M. *The Value of Everything: Making and Taking in the Global Economy* (Penguin Books, 2018).
30. Olmstead, S. M. The economics of managing scarce water resources. *Rev. Environ. Econ. Policy* **4**, 179–198 (2010).
31. Downing, J. A., Polasky, S., Olmstead, S. M. & Newbold, S. C. Protecting local water quality has global benefits. *Nat. Commun.* **12**, 2709 (2021).
32. Bateman, I. J., Keeler, B., Olmstead, S. M. & Whitehead, J. Perspectives on valuing water quality improvements using stated preference methods. *Proc. Natl Acad. Sci. USA* **120**, e2217456120 (2023).
33. Garrick, D. E., Hanemann, M. & Hepburn, C. Rethinking the economics of water: an assessment. *Oxf. Rev. Econ. Policy* **36**, 1–23 (2020).
34. Whittington, D., Radin, M. & Jeuland, M. Evidence-based policy analysis? The strange case of the randomized controlled trials of community-led total sanitation. *Oxf. Rev. Econ. Policy* **36**, 191–221 (2020).
35. Balasubramanya, S., Buisson, M.-C., Mitra, A. & Stifel, D. Price, credit or ambiguity? Increasing small-scale irrigation in Ethiopia. *World Dev.* **163**, 106149 (2023).
36. Wheeler, S. A. in *Water Markets: A Global Assessment* (ed. Wheeler, S. A.) 235–251 (Edward Elgar Publishing, 2021).
37. Nauges, C. & Whittington, D. Evaluating the performance of alternative municipal water tariff designs: quantifying the tradeoffs between equity, economic efficiency, and cost recovery. *World Dev.* **91**, 125–143 (2017).
38. Fletcher, S. et al. Equity in water resources planning: a path forward for decision support modelers. *J. Water Resour. Plan. Manage.* **148**, 02522005 (2022).
39. Talbot-Jones, J. & Bennett, J. Toward a property rights theory of legal rights for rivers. *Ecol. Econ.* **164**, 106352 (2019).
40. Loucks, D. P. & van Beek, E. *Water Resource Systems Planning and Management: An Introduction to Methods, Models, and Applications* (Springer, 2017).
41. Verschuur, J. Book review: Over the seawall: tsunamis, cyclones, drought, and the delusion of controlling nature. *Nat. Hazards Earth Syst. Sci.* **24**, 2705–2706 (2024).
42. Damania, R. et al. *Uncharted Waters: The New Economics of Water Scarcity and Variability* (The World Bank, 2017).
43. Kallis, G. Coevolution in water resource development: the vicious cycle of water supply and demand in Athens, Greece. *Ecol. Econ.* **69**, 796–809 (2010).
44. Gohari, A. et al. Water transfer as a solution to water shortage: a fix that can backfire. *J. Hydrol.* **491**, 23–39 (2013).
45. Kuil, L., Carr, G., Viglione, A., Prskawetz, A. & Blöschl, G. Conceptualizing socio-hydrological drought processes: the case of the Maya collapse. *Water Resour. Res.* **52**, 6222–6242 (2016).
46. Douglas, P. M. J., Demarest, A. A., Brenner, M. & Canuto, M. A. Impacts of climate change on the collapse of lowland Maya civilization. *Annu. Rev. Earth Planet. Sci.* **44**, 613–645 (2016).
47. Hornbeck, R. & Keskin, P. The historically evolving impact of the Ogallala aquifer: agricultural adaptation to groundwater and drought. *Am. Econ. J. Appl. Econ.* **6**, 190–219 (2014).
48. White, G. F. *Human Adjustment to Floods* Research Paper No. 29 (Univ. Chicago, 1945).
49. Tobin, G. A. The levee love affair: a stormy relationship? *J. Am. Water Resour. Assoc.* **31**, 359–367 (1995).
50. Montz, B. E. & Tobin, G. A. Livin' large with levees: lessons learned and lost. *Nat. Hazards Rev.* **9**, 150–157 (2008).

51. Di Baldassarre, G., Castellarin, A. & Brath, A. Analysis on the effects of levee heightening on flood propagation: some thoughts on the River Po. *Hydrol. Sci. J.* **54**, 1007–1017 (2009).
52. Ferdous, M. R., Di Baldassarre, G., Brandimarte, L. & Wesselink, A. The interplay between structural flood protection, population density, and flood mortality along the Jamuna River, Bangladesh. *Reg. Environ. Change* **20**, 5 (2020).
53. Georgic, W. & Klaiber, H. A. A flood of construction: the role of levees in urban floodplain development. *Land Econ.* **98**, 78–97 (2022).
54. Ding, M. et al. Reversal of the levee effect towards sustainable floodplain management. *Nat. Sustain.* **6**, 1578–1586 (2023).
55. Gleick, P. H. Water management: soft water paths. *Nature* **418**, 373–373 (2002).
56. Borgomeo, E. A desalination research agenda fit for the 21st century. *Desalination* **586**, 117910 (2024).
57. Rentschler, J. et al. Global evidence of rapid urban growth in flood zones since 1985. *Nature* **622**, 87–92 (2023).
58. Uhlenbrook, S., Yu, W., Schmitter, P. & Smith, D. M. Optimising the water we eat—rethinking policy to enhance productive and sustainable use of water in agri-food systems across scales. *Lancet Planet. Health* **6**, e59–e65 (2022).
59. Perry, C., Steduto, P. & Karajeh, F. *Does Improved Irrigation Technology Save Water? A Review of the Evidence* (FAO, 2017).
60. Grafton, R. Q. et al. The paradox of irrigation efficiency. *Science* **361**, 748–750 (2018).
61. Ward, F. A. & Pulido-Velazquez, M. Water conservation in irrigation can increase water use. *Proc. Natl Acad. Sci. USA* **105**, 18215–18220 (2008).
62. Birkenholtz, T. in *Groundwater and Climate Change: Multi-Level Law and Policy Perspectives* (eds Cullet, P. & Stephan, R. M.) 23–37 (Routledge, 2018).
63. Scott, C. A., Vicuña, S., Blanco-Gutiérrez, I., Meza, F. & Varela-Ortega, C. Irrigation efficiency and water-policy implications for river basin resilience. *Hydrol. Earth Syst. Sci.* **18**, 1339–1348 (2014).
64. Grafton, R. Q. & Wheeler, S. A. Economics of water recovery in the Murray-Darling Basin, Australia. *Annu. Rev. Resour. Econ.* **10**, 487–510 (2018).
65. Pérez-Blanco, C. D., Hrast-Essenfelder, A. & Perry, C. Irrigation technology and water conservation: a review of the theory and evidence. *Rev. Environ. Econ. Policy* **14**, 216–239 (2020).
66. Campbell, H. E., Johnson, R. M. & Larson, E. H. Prices, devices, people, or rules: the relative effectiveness of policy instruments in water conservation. *Rev. Policy Res.* **21**, 637–662 (2004).
67. Beal, C. D., Makki, A. & Stewart, R. A. What does rebounding water use look like? An examination of post-drought and post-flood water end-use demand in Queensland, Australia. *Water Sci. Technol. Water Supply* **14**, 561–568 (2014).
68. Gonzales, P. & Ajami, N. Social and structural patterns of drought-related water conservation and rebound. *Water Resour. Res.* **53**, 10619–10634 (2017).
69. Schwabe, K., Nemati, M., Amin, R., Tran, Q. & Jassby, D. Unintended consequences of water conservation on the use of treated municipal wastewater. *Nat. Sustain.* **3**, 628–635 (2020).
70. Wheeler, S. A., Carmody, E., Grafton, R. Q., Kingsford, R. T. & Zuo, A. The rebound effect on water extraction from subsidising irrigation infrastructure in Australia. *Resour. Conserv. Recycl.* **159**, 104755 (2020).
71. Lankford, B. A. Resolving the paradoxes of irrigation efficiency: irrigated systems accounting analyses depletion-based water conservation for reallocation. *Agric. Water Manage.* **287**, 108437 (2023).
72. Gleick, P. H., Christian-Smith, J. & Cooley, H. Water-use efficiency and productivity: rethinking the basin approach. *Water Int.* **36**, 784–798 (2011).
73. Lankford, B. et al. A scale-based framework to understand the promises, pitfalls and paradoxes of irrigation efficiency to meet major water challenges. *Glob. Environ. Change* **65**, 102182 (2020).
74. Richards, C. E., Tzachor, A., Avin, S. & Fenner, R. Rewards, risks and responsible deployment of artificial intelligence in water systems. *Nat. Water* **1**, 422–432 (2023).
75. Maier, H. R. & Dandy, G. C. The use of artificial neural networks for the prediction of water quality parameters. *Water Resour. Res.* **32**, 1013–1022 (1996).
76. Nearing, G. et al. Global prediction of extreme floods in ungauged watersheds. *Nature* **627**, 559–563 (2024).
77. Zhi, W., Appling, A. P., Golden, H. E., Podgorski, J. & Li, L. Deep learning for water quality. *Nat. Water* **2**, 228–241 (2024).
78. Ruhi, A., Messager, M. L. & Olden, J. D. Tracking the pulse of the Earth's fresh waters. *Nat. Sustain.* **1**, 198–203 (2018).
79. Grill, G. et al. Mapping the world's free-flowing rivers. *Nature* **569**, 215–221 (2019).
80. Addor, N. et al. Large-sample hydrology: recent progress, guidelines for new datasets and grand challenges. *Hydrol. Sci. J.* **65**, 712–725 (2020).
81. Tran, V. N. et al. AI improves the accuracy, reliability, and economic value of continental-scale flood predictions. *AGU Adv.* **6**, e2025AV001678 (2025).
82. Tetzlaff, D., Carey, S. K., McNamara, J. P., Laudon, H. & Soulsby, C. The essential value of long-term experimental data for hydrology and water management. *Water Resour. Res.* **53**, 2598–2604 (2017).
83. Garrick, D. E. et al. Valuing water for sustainable development. *Science* **358**, 1003–1005 (2017).
84. Karimi, P., Bastiaanssen, W. G. M., Molden, D. & Cheema, M. J. M. Basin-wide water accounting based on remote sensing data: an application for the Indus Basin. *Hydrol. Earth Syst. Sci.* **17**, 2473–2486 (2013).
85. Wheeler, S. A. & Garrick, D. E. A tale of two water markets in Australia: lessons for understanding participation in formal water markets. *Oxf. Rev. Econ. Policy* **36**, 132–153 (2020).
86. Mulligan, M., van Soesbergen, A. & Sáenz, L. GOODD, a global dataset of more than 38,000 georeferenced dams. *Sci. Data* **7**, 31 (2020).
87. Jones, E. R., van Vliet, M. T. H., Qadir, M. & Bierkens, M. F. P. Country-level and gridded estimates of wastewater production, collection, treatment and reuse. *Earth Syst. Sci. Data* **13**, 237–254 (2021).
88. Kratzert, F. et al. Caravan—a global community dataset for large-sample hydrology. *Sci. Data* **10**, 61 (2023).
89. Hope, R. et al. Science–practitioner partnerships for sustainable development. *Nat. Water* **2**, 502–504 (2024).
90. Handy, C. *The Age of Paradox* (Harvard Business School Press, 1994).
91. Lindblom, C. E. The science of "muddling through". *Public Adm. Rev.* **19**, 79–88 (1959).
92. Garrick, D. & Hall, J. W. Water security and society: risks, metrics, and pathways. *Annu. Rev. Environ. Resour.* **39**, 611–639 (2014).
93. Reed, P. M. et al. Multisector dynamics: advancing the science of complex adaptive human–Earth systems. *Earths Future* **10**, e2021EF002621 (2022).
94. Galli, N., Dell'Angelo, J., Epifani, I., Chiarelli, D. D. & Rulli, M. C. Socio-hydrological features of armed conflicts in the Lake Chad Basin. *Nat. Sustain.* **5**, 843–852 (2022).
95. Rachunok, B. & Fletcher, S. Socio-hydrological drought impacts on urban water affordability. *Nat. Water* **1**, 83–94 (2023).

https://doi.org/10.1038/s44221-026-00598-w

Acknowledgements
E.B. was supported by 4000133905/21/I-EF (EO AFRICA R&D Facility), project G918315; RCUK | Engineering and Physical Sciences Research Council (EPSRC) – EP/X525686/1; and the INT/UCam Early Career Support Scheme (award no. G122390). Feedback on earlier versions of this work, from C. Rulli, D. D. Chiarelli, M. Giuliani, M. Muller and participants at the 2025 Tony Allan Workshop and 2025 PRIMA NEXUS-NESS Project Final Conference, is gratefully acknowledged. All views expressed in this paper belong to the author.

Competing interests
The author declares no competing interests.

Additional information
Correspondence and requests for materials should be addressed to Edoardo Borgomeo.

Peer review information *Nature Water* thanks David Gold, R. Quentin Grafton and the other, anonymous, reviewer for their contribution to the peer review of this work.