WATER

Valuing water for sustainable development

Measurement and governance must advance together

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Achieving universal, safely managed water and sanitation services by 2030, as envisioned by the United Nations (UN) Sustainable Development Goal (SDG) 6, is projected to require capital expenditures of USD 114 billion per year (*1*). Investment on that scale, along with accompanying policy reforms, can be motivated by a growing appreciation of the value of water. Yet our ability to value water, and incorporate these values into water governance, is inadequate. Newly recognized cascading negative impacts of water scarcity, pollution, and flooding underscore the need to change the way we value water (*2*). With the UN/World Bank High Level Panel on Water having launched the Valuing Water Initiative in 2017 to chart principles and pathways for valuing water, we see a global opportunity to rethink the value of water. We outline four steps toward better valuation and management (see the box), examine recent advances in each of these areas, and argue that these four steps must be integrated to overcome the barriers that have stymied past efforts.

MEASUREMENT UNDERPINS VALUATION

Robust water measurement, modeling, and accounting are the foundation for water valuation (step 1). The limitations in our knowledge about the volume, flux, and quality of water in lakes, rivers, soils, aquifers, and human-constructed storage and distribution facilities are remarkable given the importance of water. Persistent gaps in water usage data (*3*) hide evidence of waste, inefficiency, misallocation, and theft, substantially handicapping water management institutions. As a result, urban water systems lose approximately 32 billion cubic meters from leaky pipes per year (*2*), and unmetered water theft is prevalent from Bangalore to Tijuana (*4*).

Four steps toward sustainable development of water resources

1. **Measurement.** Information on watershed status, water use, and scenarios. Understand and measure components of the global water cycle, local water budgets, and water usage.
2. **Valuation.** Multiple values, and multiple ways of valuing them. Identify and value benefits associated with water at multiple temporal and spatial scales, including environmental, sociocultural, and economic values.
3. **Decision-making.** Reconciling values, resolving trade-offs. Incorporate different values of water and the trade-offs between them into systematic and inclusive decision-making processes.
4. **Governance.** Building institutional capacity at multiple scales. Strengthen water governance to ensure that policies and management decisions are actually delivered through an adaptive set of institutions, incentives, and instruments.

Despite widespread data deficits and uneven coverage of hydrological monitoring networks (*5*), the information and communications technology revolution has started to close some gaps—improving knowledge through remote sensing, machine learning, and low-cost monitoring devices (*6*). For example, "smart handpumps" transmit vibration data from handles being pumped in the field to estimate groundwater levels in data-sparse Africa (*7*).

Yet technological progress in water accounting is not sufficient on its own. The political economy of metering water has triggered resistance from India to Ireland because of concerns about equitable access and affordability of water services (*8*). Water users often perceive measurement as a step toward creating new tariffs or constraining use, rather than as a means to improve efficiency and sustainability. Measurement must thus be supported by robust institutions to effectively engage vested interests, monitor and control water use, and resolve valuation disputes.

The Joint Monitoring Program (JMP) offers one promising example that can inform efforts to monitor the widening range of targets established by SDG 6, including water resources. The JMP has enabled nationally comparable data on drinking water and sanitation services globally, building on interagency collaboration led by the UN Children's Fund and the World Health Organization with engagement across 190 countries. It has gained legitimacy as the global standard to guide policy and practice, providing insights into the societal and economic importance of water supply and sanitation sufficient to spur policy reform and investment (*9*). However, the SDGs establish a wider range of targets, including those associated with water scarcity and water-use efficiency, which have proven difficult to measure. Rather than valuing only what can be easily measured, the data architecture and monitoring frameworks for the SDGs must provide a broad and reliable basis for the valuation of water.

DIFFICULT, BUT NECESSARY, TO VALUE

Valuing water is difficult and contentious owing to water's physical, political, and economic characteristics, but it is necessary (*10*). Efforts to value water have advanced over the past 30 years, ranging from willingness to pay for drinking water and ecosystem services, to participatory processes that capture water's diverse cultural benefits (*11*). Yet existing approaches still struggle to recognize, measure, and reconcile the full range of economic, so-

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ciocultural, and environmental benefits in water management decisions (step 2). Water can be a private good, a public good, and a common pool resource, in economic terms. Hunger, urbanization, and other complex global challenges touch on these economic attributes of water, complicating valuation and management.

Water also has special cultural value, with a central role in many customs and rituals. For example, in 2013, over 100 million people came to the Ganges River and surrounding sites for the sacred Hindu Kumbh Mela pilgrimage. Cultural values may greatly exceed the value estimated using frameworks that sum individual parts of, or economic benefits from, the watershed, discount the future, and disregard the past (*11*). Yet, cultural values and economic values for water need not be mutually exclusive (*12*). The cultural and social imperative to meet basic water needs has motivated recognition of the UN Human Right to Water and Sanitation. This does not preclude pricing water as a legitimate approach to protect and sustain these rights subject to ensuring affordability of services for the poor.

Across watersheds worldwide, we observe unsustainable water extraction and changes in land use and land management, which degrade water quality and leave insufficient water for aquatic ecosystems. These trends reflect that freshwater's environmental services are undervalued relative to other values. Yet these services sustain human well-being. Unsustainable water use can reduce economic welfare by depreciating natural capital. For instance, Kansas lost approximately $110 million per year of capital value from depletion of its groundwater supply from 1996 to 2005 (*13*).

Although efforts to account for and measure the value of natural capital are not new, emerging approaches highlight the challenge and need to combine social, biophysical, and economic modeling and data to guide trade-offs about competing uses (*13*). However, nonmarket values may be ignored even when economic estimates exist. For example, the regulatory impact analysis to determine whether wetlands are covered by the U.S. Clean Water Act hinges on whether to include up to USD 500 million in estimated annual benefits from wetlands (*14*). Disputes may arise regardless of the validity and precision of valuation methods, reflecting the inevitable trade-offs underlying water governance.

NAVIGATING TRADE-OFFS

Exploring water's diverse values usually exposes the need for hard choices, including potential trade-offs between efficiency and equity. Measurement and valuation must be embedded in decision-making processes to ensure more systematic, explicit, and inclusive trade-offs (step 3). Despite decades of nonmarket valuation studies, cost-benefit assessments of irrigation, hydropower, or flood protection projects often have a narrowly bounded view of the value of water, and inadequate attention has been paid to multiple perspectives and distributional issues. Recent advances in decision science have produced approaches to incorporate a richer set of values and perspectives in project appraisal and policy design (*15*). For example, participatory mapping captured the flood resilience and bird biodiversity benefits generated by the Inner Forth estuary of coastal Scotland, which were under-recognized by monetary valuation alone (*11*). Deliberative processes that combine participatory mapping with monetary valuation may produce management priorities that are more consistent with local and regional perceptions of fairness (*11*). Greater understanding of catchments, water accounting, and water productivity has underpinned more systematic approaches to water management in some locations. For example, current efforts by Mexican water authorities to maintain the integrity and resilience of the aquifers under Mexico City and in the catchments of the broader region draw upon increasingly sophisticated technologies. These include ways to monitor, model, and dynamically manage water use through a portfolio of regulatory approaches and incentive-based conservation measures (*16*). These efforts require participatory approaches that include consultation with river basin councils to identify the values and metrics relevant to local stakeholders. Combining stakeholder knowledge with monitoring and modeling has established incentives to measure, value, and pay for ecosystem services and other benefits and costs typically excluded from decision-making. As a consequence of these partnerships, new policies and investment priorities have included both gray and green infrastructure, ranging from catchment management to traditional water supply infrastructure.

VALUING INSTITUTIONS

Valuing and managing water requires capable institutions. Even when equitable decisions are made, they will not yield the desired outcomes without implementation and enforcement. There is no single blueprint for effective water management institutions, and relatively few examples exist of large-scale, successful, and sustained collective action (*17*). Efforts to promote integrated water resource management—coordinating allocation and investment decisions at the basin scale—have met with limited success. In Australia's Murray-Darling Basin, for example, intensifying scarcity spurred development of one of the most active formal water trading systems in the world. Yet disputes persist between upstream and downstream states, and also between irrigation and environmental water uses (*17*). These conflicts impede innovations and approaches that could increase benefits for both the economy and ecosystems within the basin.

PHOTO: AMY MCCOY

Interstate and binational cooperation in the Colorado River since 2001 illustrates one potential pathway for institutional development. On 27 September 2017, the United States and Mexico adopted Minute 323, an update to the 1944 U.S.-Mexico Water Treaty, to coordinate management of shortages, water efficiency projects, and restoration of the Colorado Delta. This progress has relied on modeling, valuation, and planning in response to sustained drought and the associated shortage risks (*18*). Proactive engagement of key water user groups (e.g., irrigation districts and states) in modeling studies and planning processes has allowed diverse stakeholders to seize the window of opportunity created by droughts and an earthquake in Northern Mexico. These processes have created new alignments among historically competing economic and environmental values (*17*). Although engagement has been lengthy, fragile, and incomplete (with limited engagement of Tribal Nations until recently), it creates knowledge, trust, and buy-in to reconcile diverse values and assist parties to come together on common goals when crises arise. Such partnerships

The Colorado River at Morelos Dam. Mexico and the USA are cooperating to address shortage, water use efficiency and restoration of the Lower Colorado and Delta ecosystems.

also avoid the pitfalls of reactive decisions or capture by vested interests that can breed resentment, resistance, and lock-in.

Other regions may benefit from new methodologies to diagnose governance deficits and strengthen institutions to be fit for purpose, particularly where capacity is limited. Elinor Ostrom and colleagues advanced frameworks for understanding factors and institutions contributing to sustainable resource management (*19*). Many of the lessons from smaller-scale common-pool resources have proved difficult to scale up. Nonetheless, guidance for large-scale collective action exists: (i) Share costs and benefits to spur investments and guide water allocation decisions (e.g., allocating water based on shares rather than fixed volumes); (ii) ensure conflict-resolution mechanisms, both informal and formal (e.g., ranging from weekly phone calls to courts); (iii) foster nested governance arrangements with linkages across sectors and scales (e.g., vesting authority and building capacity in users' associations, water utilities, and districts, supported by wider planning); and (iv) establish effective venues for participation and decision-making (e.g., river basin organizations or regional authorities) (*19*). Specific application of these principles will depend on context.

Applying such principles to strengthen water governance will require complementary actions at multiple scales and across public, private, and civil society actors (*20*). This also requires giving "voice" to communities that are historically underrepresented or ignored in decision-making processes, such as indigenous peoples. Efforts to scale up institutional capacity should avoid sidelining informal institutions and diverse perspectives. For example, New Zealand has placed the Māori worldview at the center of management for the Whanganui River, and created a comanagement framework that actively engages with diverse stakeholders. More testing is needed to identify the pathways for strengthening institutions to better value water in this complex context.

RESEARCH AND POLICY

Sustainable development of water resources will require progress on all four steps, including (i) investment in measurement and modeling that captures the opportunity of low-cost sensing and communication, while avoiding backsliding on essential long-term monitoring networks; (ii) innovation in valuing water, to address concerns about incomplete, approximate, and conflicting estimates. Expertise in existing approaches such as willingness to pay, natural capital accounting, and participatory mapping needs to be enhanced, and more attention must be directed to the interface of economic and cultural valuation techniques; (iii) advances in water planning to account for diverse values. Decision-making methodologies that take account of multiple values, uncertainty, and sequencing are now maturing (*15*). Further innovation and experience are needed to ensure that these methods are inclusive and applicable to a wide range of contexts. This is particularly challenging in capacity-constrained, data-sparse, and disaster-prone settings; and, finally: (iv) identifying and addressing governance deficits by developing pathways of investment in institutions, information, and infrastructure. Institutional reforms will be needed to create rules and incentives for fair and efficient allocation across multiple sectors and scales. The balance and sequence of reforms in this iterative process will vary by context. Above all, a more inclusive, transparent, and flexible governance architecture is needed to spur collective action commensurate with the challenge of sustainably managing water resources and ensuring a better water future for all. ■

REFERENCES AND NOTES

1. G. Hutton, M. Varughese, The Costs of Meeting the 2030 Sustainable Development Goal Targets on Drinking Water, Sanitation, and Hygiene (World Bank Group, Water and Sanitation Program, Washington, DC, 2016).
2. R. Damania *et al.*, *Uncharted Waters: The New Economics of Water Scarcity and Variability* (World Bank, Washington, DC, 2017).
3. P. H. Gleick, M. Palaniappan, *Proc. Natl. Acad. Sci. U.S.A.* **107**, 11155 (2010).
4. K. Meehan, *Environ. Plann. D Soc. Space* **31**, 319 (2013).
5. C. Lorenz, H. Kunstmann, *J. Hydrometeorol.* **13**, 1397 (2012).
6. P. Karimi, W. G. M. Bastiaanssen, D. Molden, *Hydrol. Earth Syst. Sci.* **17**, 2459 (2013).
7. F. E. Colchester, H. G. Marais, P. Thomson, R. Hope, D. A. Clifton, *Environ. Model. Softw.* **91**, 241 (2017).
8. A. Mukherji, A. Das, *Water Int.* **39**, 671 (2014).
9. J. Bartram *et al.*, *Int. J. Environ. Res. Public Health* **11**, 8137 (2014).
10. W. M. Hanemann, in *Water Crisis: Myth or Reality*, P. P. Rogers, M. R. Llamas, L. M. Cortina, Eds. (CRC Press, London, 2006), pp. 61–76.
11. J. O. Kenter, *Ecosyst. Serv.* **21**, 291 (2016).
12. J. J. Schmidt, C. Z. Peppard, *Wiley Interdiscip. Rev. Water* **1**, 533 (2014).
13. E. P. Fenichel *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **113**, 2382 (2016).
14. K. J. Boyle, M. J. Kotchen, V. K. Smith, *Science* **358**, 49 (2017).
15. N. L. Poff *et al.*, *Nat. Clim. Chang.* **6**, 25 (2016).
16. P. Romero Lankao, *Environ. Urban.* **22**, 157 (2010).
17. R. Q. Grafton *et al.*, *Nat. Clim. Chang.* **3**, 315 (2013).
18. A. K. Gerlak, *Rev. Policy Res.* **32**, 100 (2015).
19. M. Cox, G. Arnold, S. Villamayor Tomás, *Ecol. Soc.* **15**, art38 (2010).
20. E. Ostrom, *Am. Econ. Rev.* **100**, 641 (2010).

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