Received: 17 April 2023 | Accepted: 18 April 2023

DOI: 10.1002/hyp.14889

COMMENTARY

WILEY

Watershed science: Coupling hydrological science and water resources management

Chansheng He[1,2] | Carol P. Harden[3] | Joseph Holden[4] | Anna Mdee[5]

[1]Department of Geography, Environment and Tourism, Western Michigan University, Kalamazoo, Michigan, USA

[2]Center for Dryland Water Resources Research and Watershed Science, Key Laboratory of West China's Environmental System (Ministry of Education), College of Earth and Environmental Sciences, Lanzhou University, Lanzhou, China

[3]Department of Geography, University of Tennessee, Knoxville, Tennessee, USA

[4]water@leeds, School of Geography, University of Leeds, Leeds, UK

[5]water@leeds, School of Politics and International Studies, University of Leeds, Leeds, UK

Correspondence
Chansheng He, Department of Geography, Environment and Tourism, Western Michigan University, Kalamazoo, Michigan, USA.
Email: he@wmich.edu

Funding information
National Natural Science Foundation of China, Grant/Award Numbers: 41530752, 42030501; Scherer Endowment Fund of Department of Geography, Western Michigan University; UK Natural Environment Research Council funding for iCASP, Grant/Award Number: NE/P011160/1

Abstract

While there have been advancements in hydrological science and water resources management, the world continues to face a water-supply crisis. In light of studies that report the missing links to be (i) effective collaborations between researchers and practitioners and (ii) interdisciplinary working, we promote the benefits of Watershed Science to address these gaps. Watershed Science incorporates basin hydrology, determines water resource thresholds, promotes water governance that forms partnerships between institutions, and enacts participatory decision making in water resources management. However, such partnerships must recognize the differential power and interests of different actors to ensure that outcomes are not skewed in favour of particular interests. It adds value to existing water management programs and has great potential for bringing disciplines and decision making together to address the global water crisis.

KEYWORDS

global water crisis, hydrology, integrations, river basin sustainability, water governance, water planetary boundary framework, watershed organizations, watershed science

Water is a key feature of the United Nations' Sustainable Development Goals (UN SDGs) (He & James, 2021; WWAP, 2020), and major water management actions are required to deliver them. Hydrological science and numerous water management programs, including ecohydrology (Eagleson, 2002), global hydrology (Bierkens, 2015), sociohydrology (Di Baldassarre et al., 2019), and integrated water resources management (IWRM) (Hering & Ingold, 2012), have evolved and expanded over the past decades to address pressing water issues (NRC, 2012). Despite science and management advancements, the world continues to face a water-supply crisis. More than 2 billion people lack access to safe drinking water, while more than 4 billion lack safely managed sanitation services (Gleick, 2016; He & James, 2021; Hering & Ingold, 2012; Howell, 2013; WWAP, 2020). Water quality challenges, which now include those posed by emerging contaminants (e.g., per- and polyfluoroalkyl substances, or PFASs, and endocrine disrupting chemicals, and micro plastics), diffuse pollution, or the spread of non-native species, are faced globally, even in the highest elevation watersheds (Quincey et al., 2022). Floods and droughts are causing increased impacts globally, affecting hundreds of millions of people each year, and leading to global annual financial losses exceeding US $65 billion and loss of human lives (Best et al., 2022; He & James, 2021; Hering & Ingold, 2012; Howell, 2013; Kreibich et al., 2022; WWAP, 2020). Why

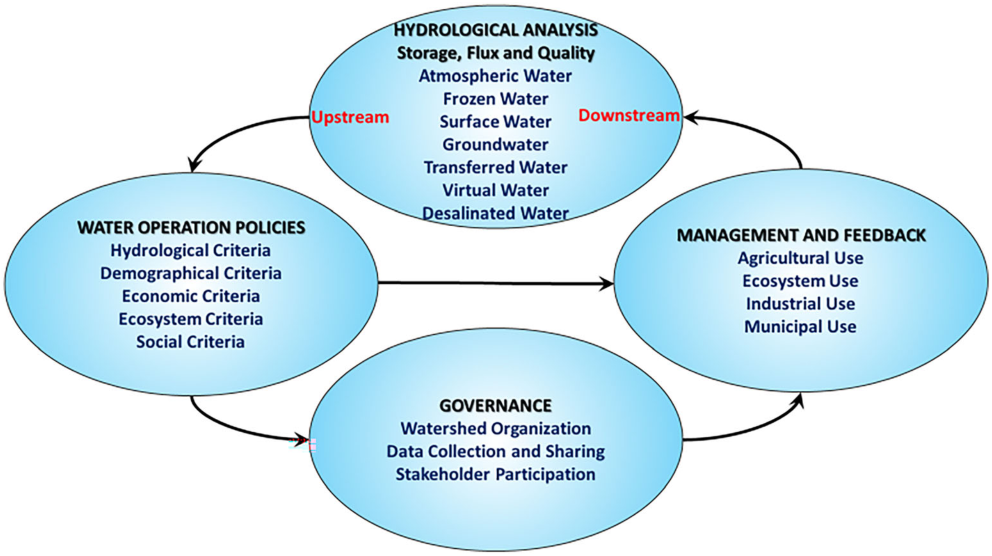

FIGURE 1 Framework of watershed science.

have water problems not yet been resolved? In light of studies that report the missing links to be (i) effective interactions between researchers and political and civil decision makers (Di Baldassarre et al., 2019; Garrick et al., 2017; Johnson et al., 2001; Matondo, 2002; Zipper et al., 2020) and (ii) interdisciplinary collaborations tackling complex systems (Martin-Ortega, 2023; Mdee et al., 2022), we promote the benefits of Watershed Science to address these gaps.

The watershed (often also termed river basin or catchment) is widely used as a fundamental unit for hydrological research and water resources management due to its propensity to derive water budget data (NRC, 1999) even though, ironically, watersheds are often absent from water management programs (Hering & Ingold, 2012; Johnson et al., 2001). Watersheds can be considered, and nested, across a large range of spatial scales, from small tributaries to continental river basins (e.g., the Nile River Basin, and the Mississippi River Basin) (He & James, 2021). Defining appropriate geographical areas is critical for water resources management (Garrick et al., 2017; Hering and Ingold), but working at multiple watershed and political scales and systematically integrating hydrological science and decision-/policy-making for watersheds remain complex challenges (He & James, 2021; Mdee, 2017; NRC, 1999).

The emerging field of Watershed Science (WS) integrates studies of the interactions among human, ecological, and hydrological systems impacting the water cycle in a river basin with studies and practices of management and governance. The goal is to develop research and management processes, and collaborative water solutions, to support sustainable activity within the watershed (He & James, 2021). WS programs appear in some university curricula but may lack consideration of watershed governance and interactions among stakeholders (He & James, 2021). We summarize the four main components of WS here and in Figure 1.

1 | HYDROLOGICAL ANALYSIS

The stores, fluxes and pathways of water, including external supplies of water (transferred, desalinated water, and virtual water), are measured, monitored, modelled, and analysed with current tracking, remote sensing, transmitting, analysing, computing, and visualizing technology to provide quantifications of states, transfer rates and quality of the water in the study watershed (He & James, 2021; Zipper et al., 2020). These data provide a baseline for the study watershed and support an evolving perceptual model of the watershed system (Wagener et al., 2021; Zipper et al., 2020). Critical questions also have to be asked about how this analysis is conducted, who owns the data and who has the capacity to use it.

2 | WATER-OPERATION POLICIES

Locally safe operating boundaries can be defined using a water planetary boundary framework (Zipper et al., 2020). This approach combines watersheds and political areas, and integrates climatic, demographical, economic and sociocultural values of water to develop local water-operation policies (Garrick et al., 2017; Zipper et al., 2020). Comparing the current state of a watershed system to defined thresholds helps identify the actions needed to modify human actions (e.g., irrigation use or nutrient loading from point and diffuse sources) and constrain patterns of water use and water quality to remain within locally and globally safe thresholds (Garrick et al., 2017; Zipper et al., 2020). However, it is essential to create policy that relates realistically to the implementation capability of the actors involved, rather than creating fantasy policy wish lists (Mdee & Harrison, 2019).

3 | GOVERNANCE

Structures that facilitate more inclusive, participatory and trusted governance, such as cooperative watershed organizations (e.g., the Yellow River Conservancy Commission), can help provide policies and management decisions that have a greater chance of successful implementation across the watershed (Garrick et al., 2017; He et al., 2020; He & James, 2021). An effective watershed organization promotes close interactions among stakeholders, such as national, regional, and local government agencies, businesses, public or non-profit groups, and the research community (Garrick et al., 2017; He & James, 2021). The latter ought to include explicit recognition of social and political sciences, each considered on an equal basis to hydrological science, as a necessary requirement for deriving sustainable river basin solutions (Martin-Ortega, 2023). Discussion and acceptance of the water management plan through decision-making that is informed via a participatory approach, taking account of local knowledge and cultural requirements, facilitates successful implementation of the plan and understanding of its socio-economic and environmental costs and trade-offs among stakeholders (Garrick et al., 2017; He et al., 2020; Zipper et al., 2020). However, it is essential to recognize that so called participatory processes can be captured by vested interests and can produce highly unequal outcomes.

4 | MANAGEMENT AND FEEDBACK

The watershed organization, with users from many sectors, develops a management mechanism for delivering, monitoring, and evaluating the water-management plan, with flexible and ongoing approaches to modifying the plan (Bierkens, 2015; Garrick et al., 2017; He & James, 2021; Hering & Ingold, 2012). If a pre- and post-implementation comparison of hydrological, demographical, ecological, and socio-economic variables indicates improvements have occurred and the system meets defined safe water-operating policies, the management plan is seen as viable to meet competing demands from different sectors and stay within safe operating thresholds. If not, water management decisions should be modified to respond to the changing environment, and new or additional management strategies developed to alleviate conflicts (Garrick et al., 2017; He & James, 2021; Hering & Ingold, 2012; Zipper et al., 2020). Where possible, the management system should encourage confidence in decision-making, provide societal resilience to water stressors and hazards and thereby enhance investment and returns through the basin becoming a more attractive place to live, work and enjoy. Recognizing that this is essentially a political distribution challenge in any management system, there will inevitably be conflicting priorities and claims for water, and fair and equitable processes for adjudicating competing claims are required.

Key challenges of WS are: (1) establishing systems for systematically collecting high-resolution and consistent datasets over time on water fluxes and water quality (Bierkens, 2015; Wagener et al., 2021); (2) bringing together researchers from physical, ecological, engineering, humanities, and social science disciplines and sectors with practitioners and policy makers to develop water policies for the watershed; and (3) forming structures to enable meaningful stakeholder participation and deliberation that ensures engaged interactions between government agencies, businesses, community groups, and researchers for dynamic implementation and monitoring of water solutions, which recognizes water as a political and contested resource. (He et al., 2020; He & James, 2021; Martin-Ortega, 2023; Mdee et al., 2022).

Despite these challenges, recent advancements offer good potential for WS to be taken forward. While there is still room for technological development, observations of climate, hydrology, carbon, nutrient and energy fluxes, land use/cover, water quality, and socio-economic metrics, are often systematically collected, interrogated and disseminated, with ever increasing amounts of open data and associated analysis tools (Bierkens, 2015; He & James, 2021; Richardson et al., 2021). Examples of watershed-based management are available globally, and while the structure and authority of river basin governance varies a lot, there are increasing numbers of platforms for participatory decision making among stakeholders that allow for shared future foresight and adaptive management.

An example is the Yorkshire Integrated Catchment Solutions Program (iCASP) in the United Kingdom (Richardson et al., 2021). iCASP was initiated in 2017 with funding of US $7 million from the UK Natural Environment Research Council to provide environmental, societal and economic impacts through embedding existing science into co-developed projects between academic and non-academic partners, creating new tools and a greater shared understanding of potential solutions to water issues (Richardson et al., 2021). iCASP focusses on the Ouse River Basin, located in Yorkshire in northern England which has a drainage area of 10 770 km^2 before it merges with the River Trent and drains to the Humber Estuary on the North Sea coast. The headwaters of the Ouse tributaries such as the Rivers Aire, Calder, Nidd, Ure, Swale, Don and Rother have wet plateau uplands which quickly drop into steep, formerly glaciated valleys, then flow through multiple urban areas, many of which were at the heart of the Industrial Revolution. Major environmental challenges in the basin include flooding and drought, exacerbated by the terrain and the hydrology of the local soils which leads to flashy river regimes. There are also key challenges around freshwater quality, degradation of peatlands, depletion of organic carbon from arable soils, and aquatic invasive species. iCASP brings together over 190 institutions including universities, national and local governmental agencies, businesses, nonprofit organizations, water companies, trade associations, community groups and other local stakeholders to form a partnership to determine solutions for the basin. Working with the partners, through co-design, co-production, and co-dissemination, iCASP also aims to produce transferable and scalable outputs for use elsewhere. As the program has progressed we have seen enhanced science-user engagement, policy formation and implementation, and practical benefits (Richardson et al., 2021). In turn, this work has led to new business cases for investment in on-the-ground river basin solutions (e.g., for invasive species, natural flood management schemes, green and blue infrastructure to enhance human wellbeing, soil health and drought resilience) being developed for funding by national or regional governments, or from consortia of other organizations (Richardson et al., 2021). As it is user-driven, iCASP serves as a model of bringing academia, civic society and industry together to generate transformative change (https://icasp.org.uk/about/).

In summary, WS offers an inherent appreciation that watershed processes form complex socio-technological, environmental and cultural systems. It can significantly enhance existing water management programs while offering curated routes for bringing disciplines and decision making together to address the current global water crisis and move to the next level looking beyond the UN's SDGs. However, a concerted effort is still needed to further experiment, refine, apply, and promote WS among researchers (and their funding agencies), government bodies, practitioners, water use communities, and the general public to ensure the human prosperity, ecosystem security, and environmental sustainability of a river basin.

ACKNOWLEDGEMENTS

This work is partially funded by the National Natural Science Foundation of China (Grants: 42030501 and 41530752) and Scherer Endowment Fund of Department of Geography, Western Michigan University. Chansheng He also acknowledges the support of Fulbright UK Commission scholar program, and the assistance from water@leeds and School of Geography during his visit to the University of Leeds. Joseph Holden acknowledges UK Natural Environment Research Council funding for iCASP (grant NE/P011160/1).

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

ORCID

Chansheng He https://orcid.org/0000-0001-7748-0485
Joseph Holden https://orcid.org/0000-0002-1108-4831

REFERENCES

Best, J., Ashmore, P., & Darby, S. E. (2022). Beyond just floodwater. *Nature Sustainability*, *5*, 811–813. https://doi.org/10.1038/s41893-022-00929-1

Bierkens, M. F. P. (2015). Global hydrology 2015: State, trends, and directions. *Water Resources Research*, *51*, 4923–4947. https://doi.org/10.1002/2015WR017173

Di Baldassarre, G., Sivapalan, M., Rusca, M., Cudennec, C., Garcia, M., Kreibich, H., Konar, M., Mondino, E., Mård, J., Pande, S., & Sanderson, M. R. (2019). Sociohydrology: Scientific challenges in addressing the sustainable development goals. *Water Resources Research*, *55*, 6327–6355. https://doi.org/10.1029/2018WR023901

Eagleson, P. S. (2002). *Ecohydrology: Darwinian expression of vegetation form and function*. Cambridge University Press.

Garrick, D. E., Hall, J. W., & Dobson, A. (2017). Valuing water for sustainable development. *Science*, *358*, 1003–1005. https://doi.org/10.1126/science.aao4942

Gleick, P. H. (2016). Water strategies for the next administration. *Science*, *354*, 555–556. https://doi.org/10.1126/science.aaj2221

He, C., Harden, C. P., & Liu, Y. (2020). Comparison of water resources management between China and the United States. *Geography and Sustainability*, *1*, 98–108. https://doi.org/10.1016/j.geosus.2020.04.002

He, C., & James, L. A. (2021). Watershed science: Linking hydrological science with sustainable management of river basins. *Science China Earth Sciences*, *64*, 677–690. https://doi.org/10.1007/s11430-020-9723-4

Hering, J. G., & Ingold, K. M. (2012). Water resources management: What should be integrated? *Science*, *336*, 1234–1235. https://doi.org/10.1126/science.1218230

Howell, L. (Ed.). (2013). *Global risks 2013* (8h ed.). World Economic Forum, Cologny/Geneva.

Johnson, N., Revenga, C., & Echeverria, J. (2001). Managing water for people and nature. *Science*, *292*, 1071–1072. https://doi.org/10.1126/science.1058821

Kreibich, H., Van Loon, A. F., & Schröter, K. (2022). The challenge of unprecedented floods and droughts in risk management. *Nature*, *608*, 80–86. https://doi.org/10.1038/s41586-022-04917-5

Martin-Ortega, J. (2023). We cannot address global water challenges without social sciences. *Nature Water*, *1*, 2–3. https://doi.org/10.1038/s44221-022-00013-0

Matondo, J. I. (2002). A comparison between conventional and integrated water resources planning and management. *Physics and Chemistry of the Earth, Parts A/B/C*, *27*, 831–838. https://doi.org/10.1016/S1474-7065(02)00072-4

Mdee, A. (2017). Disaggregating orders of water scarcity - the politics of nexus in the Wami-Ruvu River basin, Tanzania. *Water Alternatives*, *10*(1), 100–115.

Mdee, A., & Harrison, E. (2019). Critical governance problems for farmer-led irrigation: Isomorphic mimicry and capability traps. *Water Alternatives*, *12*(1), 30–45.

Mdee, A., Ofori, A., & Lopez-Gonzalez, G. (2022). The top 100 global water questions: Results of a scoping exercise. *One Earth*, *5*, 563–573. https://doi.org/10.1016/j.oneear.2022.04.009

National Research Council (US). (1999). *New Strategies for America's Watersheds*. National Academies Press.

National Research Council (US) (Ed.). (2012). *Challenges and opportunities in the hydrologic sciences*. National Academies Press.

Quincey, D. J., Kay, P., & Wilkinson, J. (2022). High concentrations of pharmaceuticals emerging as a threat to Himalayan water sustainability. *Environmental Science and Pollution Research*, *29*, 16749–16757. https://doi.org/10.1007/s11356-021-18302-8

Richardson, J. C., Ferré, M., Rabb, B. L., Armstrong, J. C., Martin-Ortega, J., Hodgson, D. M., Willis, T. D. M., Grayson, R., Leeder, P., & Holden, J. (2021). Yorkshire Integrated Catchment Solutions Programme (iCASP): A new model for research-based catchment management. In R. Ferrier & A. Jenkins (Eds.), *Handbook of catchment management* (2nd ed.). Wiley-Blackwell.

Wagener, T., Dadson, S. J., & Hannah, D. M. (2021). Knowledge gaps in our perceptual model of Great Britain's hydrology. *Hydrological Processes*, *35*(7), e14288. https://doi.org/10.1002/hyp.14288

WWAP (United Nations World Water Assessment Programme). (2020). *The United Nations World Water Development Report 2020: Water and climate change*. UNESCO.

Zipper, S. C., Jaramillo, F., & Wang-Erlandsson, L. (2020). Integrating the water planetary boundary with water management from local to global scales. *Earth's Future*, *8*, e2019EF001377. https://doi.org/10.1029/2019EF001377

How to cite this article: He, C., Harden, C. P., Holden, J., & Mdee, A. (2023). Watershed science: Coupling hydrological science and water resources management. *Hydrological Processes*, *37*(5), e14889. https://doi.org/10.1002/hyp.14889