Hydrological Sciences Journal

ISSN: 0262-6667 (Print) 2150-3435 (Online) Journal homepage: www.tandfonline.com/journals/thsj20

On the value of a history of hydrology and the establishment of a History of Hydrology Working Group

Keith Beven, Stacey Archfield, Okke Batelaan, Changchun Chen, Fabrizio Fenicia, Chantal Gascuel-Odoux, Lucy Marshall, Jeffrey McDonnell, E. Mario Mendiondo, Cristina Prieto & Solomon Vimal

To cite this article: Keith Beven, Stacey Archfield, Okke Batelaan, Changchun Chen, Fabrizio Fenicia, Chantal Gascuel-Odoux, Lucy Marshall, Jeffrey McDonnell, E. Mario Mendiondo, Cristina Prieto & Solomon Vimal (2025) On the value of a history of hydrology and the establishment of a History of Hydrology Working Group, Hydrological Sciences Journal, 70:5, 717-729, DOI: 10.1080/02626667.2025.2452357

To link to this article: https://doi.org/10.1080/02626667.2025.2452357

Published online: 24 Feb 2025.

HYDROLOGICAL SCIENCES JOURNAL
2025, VOL. 70, NO. 5, 717–729
https://doi.org/10.1080/02626667.2025.2452357

OPINION
SPECIAL ISSUE: HISTORY OF HYDROLOGY

OPEN ACCESS Check for updates

On the value of a history of hydrology and the establishment of a History of Hydrology Working Group

Keith Beven[a], Stacey Archfield[b], Okke Batelaan[c], Changchun Chen[d], Fabrizio Fenicia[e], Chantal Gascuel-Odoux[f], Lucy Marshall[g], Jeffrey McDonnell[h,i,j], E. Mario Mendiondo[k], Cristina Prieto[l] and Solomon Vimal[m,n]

[a]Lancaster Environment Centre, Lancaster University, Lancaster, UK; [b]US Geological Survey, Water Resources Mission Area, Reston, Virgina, USA; [c]College of Science and Engineering, Flinders University, Adelaide, Australia; [d]School of Geographical Sciences, Nanjing University of Information Science and Technology, Nanjing, China; [e]EAWAG, Dübendorf, Switzerland; [f]INRAE, Inst Agro, UMR SAS, Rennes, France; [g]Faculty of Science and Engineering, Macquarie University, Sydney, Australia; [h]Global Institute for Water Security, University of Saskatchewan, Saskatoon, Saskatchewan, Canada; [i]School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham, UK; [j]North China University of Water Resources and Electric Power, Zhengzhou, China; [k]CRHEA, EESC-USP, University Sao Paulo, Sao CarlosSP, Brazil; [l]Instituto de Hidráulica Ambiental de la Universidad de Cantabria, Santander, Spain; [m]Geothara, New York City, New York, USA; [n]Cornell Tech, New York City, New York, USA

ABSTRACT
This paper presents some of the reasons for studying the history of hydrology and for the formation of the International Association of Hydrological Sciences (IAHS) History of Hydrology Working Group. In particular, we consider the importance of recording the histories of hydrological data, catchments, diversity in hydrology (of both people and topics), and what can be gained from the historical literature in hydrology. We also consider why the classical concepts of catchment response to rainfall have evolved slowly in hydrology, despite identified limitations, and how the major impetus for change in the 1970s, in the form of techniques for measuring environmental tracers, effectively came from developments outside the discipline. We conclude by speculating whether the questions posed by recent machine learning studies might lead to further change and understanding.

ARTICLE HISTORY
Received 10 August 2024
Accepted 11 November 2024

EDITOR
A. Fiori

GUEST EDITOR
(not assigned)

KEYWORDS
history of watersheds; diversity and recognition; hydrological paradigms; hydrological perceptual models; sociohydrology

Why study the history of hydrology?

> *"Everything of importance has been said before by somebody who did not discover it."*
> Alfred North Whitehead (18611947) in *Science*, 1906, p. 417

Hydrology is largely a historical geoscience; it depends on qualitative and quantitative observations recorded in the past and the experimental testing of hypotheses formed from these observations. In this way, it is also an inductive science, in that it relies on inferences made from those observations in different ways to make statements about places where there are no observations available. Hydrology aims to predict responses into the future where observations are not yet available, albeit while also making use of deductive principles in the conservation of mass, energy and momentum. Past observations have also shaped our perceptions about how hydrological systems work, such that scientists gain some perspective of the historical development of hydrological concepts about the catchment water balance. These observations have been recorded in the books on the history of hydrology by YiFu Tuan (1968) and Asit K. Biswas (1970), in a number of more recent articles (e.g. Dooge 1976, 2001, Koutsoyiannis and Mamassis 2021, Duffy 2017, Abbott *et al.* 2019), in papers in a special issue of *Hydrology and Earth System Science* on the History of Hydrology in 2020 (Barontini *et al.* 2020), and in the current Special Collection of *Hydrological Sciences Journal* (Barontini *et al.* 2024, Beven 2024a, Levia *et al.* 2024, McDonnell *et al.* 2024).

Perhaps one of the most fundamental developments in the history of hydrology is the catchment water cycle and the understanding that the flow of springs and streams could be supported by rainfall alone. Although this concept took time to be substantiated with data and scientific evidence, and to gain acceptance, it has existed as a perceptual model since the age of Greek philosophers (refer to Koutsoyiannis and Mamassis 2021). From non-European traditions, the development of descriptions of the water cycle from multiple sources can be cited, including the Indian Vedic period (Singh *et al.* 2020), the Sumerian and Akkadian eras (Perbidon 2024), the *Zhou Yi Book of Changes* (Zhou *et al.* 2011) and the water cosmogony of the Incas (Mazadiego *et al.* 2009). Pierre Perrault[1] and Edme Mariotte[2] in the 17th

CONTACT Keith Beven k.beven@lancaster.ac.uk Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK
[1]http://www.history-of-hydrology.net/mediawiki/index.php?title=Perrault,_Pierre (last accessed 11.f02.2025).
[2]http://www.history-of-hydrology.net/mediawiki/index.php?title=Mariotte,_Edme (last accessed 11.02.2025).

century are generally credited with being the first persons to quantify the catchment water balance and show that rainfall volumes exceeded those of river streamflows. But even they had some difficulties explaining how springs in the mountains could continue to flow in dry periods.

Since then, there has been a huge expansion of quantitative observations of catchment systems, and a great leap forward in process understanding is associated with the First International Hydrological Decade (IHD, 1965–1974) (Nace 1980). Another advancement started in the 1970s with the use of environmental tracers, followed by a further impetus in the 1990s with the increased use of remote sensing to reveal some of the spatial variability in catchment processes, and, more recently, there has been an increase of spatial and temporal data collection (e.g. Tauro *et al.* 2018). Yet we are still unsure that we have the correct perceptual understanding of how catchments respond to rainfall (Beven 2012, Beven and Chappell 2021, Wagener *et al.* 2021). In this respect, hydrologists and their perceptual models are the product of their own history as students and research scientists, as conditioned by their teachers, their reading and their field experience (Beven 1987). Indeed, there may be different competing perceptual models, especially in those parts of the system that lie below the ground surface and where recording observations is difficult (though refer, for example, to Binley *et al.* 2015). After all, we still cannot be sure of closing the water balance for any catchment, or any control volume outside the laboratory, by measurement (e.g. Beven 2006, 2019, Beven *et al.* 2020, Condon *et al.* 2020), so some uncertainty in interpretation is inevitable. In such circumstances, there is a temptation to fill any gaps with speculative reasoning. This was true in the days of François and Perrault in the 17th century (Barontini and Settura 2024, Beven 2024a, and McDonnell *et al.* 2024, in this Special Collection). It remains the case today given how leaky our headwater catchments might be (Tischendorf 1969, Fan 2019, Oda *et al.* 2024), how they can contribute directly to flow in larger watersheds (Ameli *et al.* 2018), and how old some of the water contributing to stream discharge can be (e.g. McDonnell *et al.* 2024). The one lesson we can learn from the history of science, in general, is that we can be sure our current concepts will be replaced in the future and that new observations or new types of observations might lead to reinterpretations of our perceptual models.

In this commentary, we address the issue of why the study of the history of hydrology is important, as illustrated by papers from this *Hydrological Sciences Journal* Special Collection. We consider what we can learn from the histories of hydrological data, catchments, past scientists, and past papers, and how they are relevant in what appears to be a period of significant change. With knowledge of the past, we can avoid making similar mistakes and shed light on how past concepts, ancestral knowledge and paradigms in hydrology have developed and changed. Recording these histories is part of the aims of the International Association of Hydrological Sciences (IAHS) Working Group on the History of Hydrology[3] that was constituted in 2023 following a session at the IAHS Congress in Montpellier, France, in June of that year. The working group particularly aims to record the contributions of female hydrologists (refer also to the recent paper of Ali *et al.* 2023) and the history of hydrology in countries and regions that historically have not been so widely acknowledged and reported.

The importance of the history of hydrological data

> "*History is merely a list of surprises. It can only prepare us to be surprised yet again.*"
>
> Kurt Vonnegut (19222007) in *Slapstick*, 1976

Hydrology is an observation-dependent field of study. Thus, the history of hydrological data is of particular importance, but standards of curation of data from past routine monitoring and research studies vary widely. In some countries, data are open source and readily available online (though often without the metadata of quality controls and uncertainty estimates). In some research studies, however, obtaining data from past field experiments is often difficult, with the only resort sometimes being digitizing figures in published papers. Older data, even when saved as charts, punched cards or magnetic tapes, may not have been converted to a form where it can easily be accessed, and access to information about issues with the data might be even more difficult. This challenge is currently particularly pertinent since a substantial part of recent hydrological research now aims to apply machine learning methods, which require large volumes of data to effectively model catchment behaviour. Although machine learning has shown promise in improving predictions (though not necessarily in enhancing our understanding, as noted by Beven 2020b), this approach is heavily dependent on the large databases such as Catchment Attributes and MEteorology for Largesample Studies (CAMELS) (e.g. Addor *et al.* 2017) that have been put together nationally and internationally. However, these databases are frequently limited to daily streamflow observations, restricting the applicability of machine learning techniques to other modelling scenarios such as higher frequency or water chemistry data.

Moreover, the reliability of model predictions and the inferences about catchment processes are fundamentally shaped by the quality of the underlying data, including precipitation, streamflow, and landscape maps. This is seldom reported in detail, even in databases like CAMELS, which do not include any information on the quality control or reliability of those data. Although there are International Organization for Standardization (ISO) standards and World Meteorological Organization (WMO) recommendations for particular types of point measurements (WMO 2008, ISO 2020), it is still the case that there is a lack of common standards for hydrological observations, even within single countries, making comparisons difficult, and the source of uncertainties associated with the data are rarely reported. Other types of data, such as vegetation and land management, including some remote sensing data, are often recorded only as classes, with a consequent need for an (uncertain) interpretation of their hydrological significance.

[3]See https://iahs.info/Initiatives/Working-Groups/History-of-Hydrology/. (last accessed 11.02.2025)

There are important issues of reliability and accuracy for spatially and temporally variable patterns of rain and snow inputs at catchment scale, for actual evapotranspiration estimates in space and time, for streamflow estimates, and for characterizing the flow response of catchments, especially smaller and flashier catchments. Additionally, data collected during projects of limited duration, even during the digital age, can be lost even when most grant awarding agencies now insist on having an explicit data archiving plan for a project to be funded. In other cases, data are treated as commercial, in confidence, and are not readily available to researchers or other practitioners.

The value of historical data is enhanced in times of change, and we are living through a time of change (Milly *et al.* 2008). Although many experimental catchment studies in the past have been concerned with the characterization of the response of catchments, at particular periods of time such data are invaluable when trying to assess the nature and magnitude of changes. Such changes might be in terms of changing land use, including deforestation, reforestation or urban development, or as a result of crossboundary water transfers for irrigation or other purposes, or because of changing climate forcings. Revisiting past catchment experiments or maintaining sites with long records can be a valuable source of information.

An important question, then, is how we, as scientists, can ensure that the historical information about our data and how it is derived is not lost to time – and surely much of the information from the time when both rainfalls and water levels were recorded on paper charts is almost certainly lost (refer to Westerberg and Karlsen 2024). For for some iconic research catchments, there have been some recent efforts to save and digitize old charts (e.g. the Maimai catchment in New Zealand, McDonnell *et al.* 2021b). As more and more journals insist on explicit data statements and more datasets are made open source with DOI references, this situation will gradually improve. We note, however, the need for such datasets to be provided along with the associated metadata and some indication of uncertainty estimates.

The importance of the history of catchments in hydrology

> "It has been said that history repeats itself.
> This is perhaps not quite correct; it merely rhymes."
> Theodor Reik, (18881969) in *The Unreachables*, 1965.

Another theme on the historyofhydrology.net site is the history of "experimental and representative catchments." This wording was introduced in the first IHD organized by WMO and the United Nations Educational, Scientific and Cultural Organization (UNESCO) starting in 1965 (UNESCO 2015), which will celebrate its 50th anniversary in 2025. Many experimental and representative catchments were started in that decade. Some have survived with (more or less) continuous data to the present day, including within the UNESCO Flow Regimes from International Experimental and Network Data (FRIEND) initiative (UNESCO 2023)[4] and the EuroMediterranean Network of Experimental and Representative Basins (ERB).[5] But the histories of most of those catchments (and earlier experimental catchments) are not that well known. By histories, here, we mean the way in which the characteristics of the catchments studied have changed, the records and metadata of the observations made in those catchments, and the results of analyses made for different purposes, which may only appear in grey literature in the local language, resulting in less accessibility than journal publications or books published in the English language. This has led to some excellent catchment science research being neglected.

Some histories of experimental catchments have been written, for example for the Maimai catchment in New Zealand (McDonnell *et al.* 2021a) and the Panola catchment in the USA (Aulenbach *et al.* 2021). Books or special issues of journals have been published on some research catchments (such as Hubbard Brook, Coweeta, Walnut Gulch, Plynlimon, KervidyNaizin, etc.), but much of the history is missing. There have also been collective initiatives in the form of long-term hydrological observatories (e.g. Bogena *et al.* 2018a, 2018b, Fovet *et al.* 2018, Gaillardet *et al.* 2018), but again the history of those observatories is not very well recorded. More generally, away from research catchments, there has been a tendency for centralization and privatization of regional and national water management and the hydrological observations that they collect. This potentially results in the loss of local knowledge about the idiosyncrasies of catchments (and their datasets) associated with local observers with "boots on the ground."

This can be an even greater problem where catchments have been hydrologically modified for water resource engineering or other applications involving, for example, the construction of reservoirs, water transfers across divides, agricultural irrigation and underdrainage, urban drainage networks and major land use and land management changes. This is particularly the case for agricultural and urban catchments, due to their high heterogeneity. Such modifications are often not well recorded (or may be treated as commercial in confidence) and, therefore, cannot be easily included in modelling studies for decision making. Similarly, significant natural events such as fires, insect infestations, past catastrophic floods and droughts, and past climates and glaciations can have a residual impact on the current hydrology. The history and its effects on the apparent catchment water balance and response processes can be important but may not be recorded (but refer, for example, to Woodsmith *et al.* 2004). What we observe today is the result of that history, and much of that history is lost to time (Beven 2015).

Another aspect of the history of catchments is the application of hydrological models to the data from those catchments. This inevitably involves some simplifying assumptions, even

[4]See also https://en.unesco-montpellier.org/friend-water-program#:~:text=FRIEND%2DWater%20(Flow%20Regimes%20From,and%20temporal%20distribution%20of%20%20water. (last accessed 11.02.2025)
[5]https://erb-network.simdif.com/. (last accessed 11.02.2025)

when the purpose of a model application is to test hypotheses about the hydrological response processes for that catchment, including the possibility of multiple hypotheses (e.g. Clark *et al.* 2011, Prieto *et al.* 2021). More generally, models are often applied for purely pragmatic or legacy reasons or as institutionalized recipes to give working solutions for practical problems (e.g. Addor and Melsen 2019, Melsen 2022). More rarely, some models are used for post-audit analyses of the type conducted, such as those by Konikow and Bredehoeft (1992) and Anderson and Woessner (1992) for groundwater modelling applications. Emphasizing and expanding these types of analyses could be valuable for understanding what methods and models might work or be improved.

Changing paradigms in hydrology (or not)?

> *"A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it."*
> Max Planck (1858–1947)

It is often suggested that science progresses through the evolution of paradigms (Kuhn 1962) or research programmes (Lakatos 1970), which have a degree of historical inertia. In practice, and certainly in hydrology, progress is somewhat messier than a transition from one paradigm to another. In the mythologies of the philosophies of science, the Popperian concept of inducing paradigm change by the experimental falsification of hypotheses is far too simplistic (Popper 1959). Historical studies in the sociology of science have suggested that the evolution of concepts is more constructed amongst groups of researchers (e.g. Latour 1987). The extreme post-positivist view that all science is a social construct is likely not valid, but understanding the development of hydrological thought, and the limitations of hydrological theory, can empower the development of any scientist and facilitate the generation of new ideas.

Catchments are unique (e.g. Beven 2000), and although catchment theories strive for generalization, they are often developed under specific conditions that limit their broader applicability. The same challenge applies to models. Although there is a growing push for the development of community hydrological models, these models reflect the conditions in which they were created and are not easily generalizable. Like all sciences, hydrology seeks to create universal theories and models that can be applied across diverse contexts. However, this pursuit carries the risk of misapplication, such as using models outside the conditions for which they were originally designed and tested (Beven 1989, Grayson *et al.* 1992). To avoid such pitfalls, a deep understanding of the history of hydrological theory and model development is crucial. Only by recognizing the contexts in which these tools were created can we ensure they are applied appropriately.

In hydrology, hypothesis testing by experiment is very difficult at any scale of interest (Beven 2001, 2010, Davies *et al.* 2011, 2019). That is, in part, because of the necessarily approximative nature of the science and the multiple sources of epistemic uncertainties that provide the context for interpretation of understanding of catchment systems (Beven 2019, Beven and Lane 2022). It is often difficult to close the water balance by observation without allowing for substantial uncertainty in any of the terms of the water balance equation; it is even more difficult to gain some appreciation of the complex spatially and temporally variable processes that control the hydrograph response to an event input. Even in the early days of the IHD, there were arguments about the value of experimental catchments (refer, for example, to Hewlett *et al.* 1969), but such field studies provide valuable means of generating hypotheses and support abductive reasoning (Baker 2017, McKnight 2017).

Despite good field evidence to question many classical hydrological concepts, these concepts continue to be used to the present day. The classical concepts that have constituted the dominant paradigm in hydrological thinking include the widespread occurrence of Hortonian infiltration excess runoff generation (even though Horton himself had a more sophisticated perceptual model of infiltration; Beven 2004b, 2021); the use of the Richards equation (or Richardson-Richards equation; refer to Raats and Knight 2018 or Nimmo 2024) to represent water flow in soils (even though in the case of Richards 1931, it was based on the wrong experiment, excluding the possibility of bypass flow; refer to Beven 2014, 2018); the advection–dispersion equation for transport in stream, soils and groundwater (with spatial dependence induced by heterogeneities, bypassing and dead zones); or the misuse of velocities in the time of concentration response and geomorphological unit hydrograph concepts (e.g. Beven 2020a). It would seem that in these hydrological cases, contrary to the Planck quote above, the classical concepts are outlasting their opponents, such that the dominant paradigm survives despite the identified limitations.

The one area where there has been some fundamental change in thought and understanding in hydrology is in the perceptual models of runoff generation in catchments. Even if the Hortonian infiltration excess concept persists, its applicability is now recognized as being far more limited than originally believed, mainly confined to dry catchments or during exceptionally intense rainfall events. Its dominance of the "era of infiltration" (Beven 2021) could not survive the evidence of environmental tracers, starting in the 1970s, suggesting that much of the storm response hydrograph in many wet catchments could be made up of water stored prior to the event. Indeed, explaining this was deemed a double paradox by Kirchner (2003), albeit that a (perhaps overly simplistic) explanation in terms of celerities being faster than velocities had been expressed long before (e.g. Beven 1989). As more detailed studies were made of the spatial and temporal variability of tracer concentrations in rainfall and throughfall, and various possibilities of fractionation due to evaporation and vegetation uptake, the perceptual model became necessarily more complex.

The history of how the hydrological community has responded to the tracer evidence for pre-event water in the hydrograph has yet to be properly explored. Early attempts to model the combined flow and tracer responses were based on modifications to conceptual storage models (such as the Birkenes model of Christophersen and Wright 1981). A more comprehensive theory of storage-age-selection functions has been developed more recently but has normally been applied with flow as a specified input (e.g. Rinaldo *et al.* 2015, Harman 2019, Benettin *et al.* 2022). There are still several models of catchment flow and tracer responses that do not explicitly recognize the difference between flow velocities and celerities. Alternative conceptual frameworks exist to integrate flow and tracer transport, such as percolation theory or random particle tracking for flow through soils (Davies *et al.* 2013, Hunt *et al.* 2014), but have not been widely explored. Other water quality characteristics might also yield insights where such data are made available (see e.g. Lehmann *et al.* 2007, Janzen and McDonnell 2015, at the hillslope scale). There remains a lack of datasets with high-frequency observations of water quality variables or environmental tracers (e.g. Bieroza *et al.* 2023, Kirchner *et al.* 2023).

There is another important aspect of the difference in water velocities and pressure wave celerities in catchment response, in addition to the implications for water residence and transit times (McDonnell and Beven 2014). That is in the treatment of storage-flow hysteresis at the catchment scale, since the difference suggests that the hysteresis should be state and scale dependent (as shown, for example in McGlynn and McDonnell 2003, Davies and Beven 2015). At the pore scale in soil physics there have been explicit treatments of hysteresis. However, at the catchment scale, hysteresis has been left implicit in the representation of catchment storages and their parameters in hydrological models. There is information in the changing hysteresis in flow, tracers and water quality that can yet be exploited. That is another area where a change of paradigm might be needed.

One aspect of paradigm change is that it is often associated with critical inputs from outside a discipline. An example in hydrological thinking is the use of isotope tracers in demonstrating the sources of water used by plants in transpiration (Dawson and Ehleringer 1991, Brooks *et al.* 2010, McCormick *et al.* 2021). In fact, hydrology overlaps with many other disciplines, with water acting as a driver and transport agent, as well as hydrological processes being affected by the evolution of soils, vegetation and landforms, anthropogenic interventions and climate change. This implies that an interdisciplinary approach to hydrology is necessary (refer, for example, to Gascuel-Odoux *et al.* 2018). Indeed, perhaps there is much more to learn from a study of the history of such disciplinary overlaps in different contexts.

These are just some examples where the tracing of history might more objectively uncover fundamental changes and evolution of ideas in the development of hydrological thinking. It is not as if changes in paradigm have not been suggested (refer, for example, to Beven 1987, Falkenmark 2004, 2006, McDonnell *et al.* 2007, Wagener *et al.* 2008, Zehe *et al.* 2013, Sivapalan 2015, Peters-Lidard *et al.* 2017, Savenije and Hrachowitz 2017, 2018, Hunt *et al.* 2021). We suggest that there is indeed value in such studies and more research themes that might be worthy of better understanding such histories.

The importance of the history of people in hydrology

> "*History will be kind to me for I intend to write it.*"
> Winston S. Churchill (1874–1965)

In addition to understanding the history of hydrology as a discipline, the history of the individuals who shaped its development can be equally important. The personal journeys of researchers provide valuable insights into the evolution of scientific ideas and the human elements behind major breakthroughs. However, preserving the records of past scientists presents a notable challenge. Historically, when records were kept on paper they were often thrown away upon retirement from a post or after death. Now, most of those records are in digital form, some of which will remain traceable for some time (journal articles as portable document formats (PDFs), prize nomination speeches, etc.) but correspondence in the form of emails, and records of the development of projects, might not be so readily accessible. Even curricula vitae (CVs), which will normally have a complete compilation of publications over a career, can disappear on retirement from an institution.[6] Even for Robert Horton, a 20th century hydrologist, new research is still adding to his list of publications (Vimal *et al.* 2024).

It is, therefore, rather important to create biographies, archives and interviews, either personally or for groups and institutions, while this is still relatively easy to do (e.g. refer to Rosbjerg 2020, Houben and Batelaan 2022; together with Black and Werrity 2024 and Houben *et al.* 2024 in this Special Collection). That is another aim of the IAHS working group, with initiatives to increase the number of biographies on the history-of-hydrology.net wiki site (managed by Keith Beven, Lancaster Environment Centre),[7] to increase the number of interviews with eminent hydrologists on the History of Hydrology YouTube site (managed by Okke Batelaan, Flinders University),[8] and to create a digital archive of the 94 boxes of papers from Robert Horton[9] in the US National Archives (see Beven 2004a, Smith *et al.* 2024, Vimal *et al.* 2024; 2025 marks the 150th anniversary of Horton's birth). Discussions are also underway with the Dooge Center of Water Resources Research, University College Dublin, about creating an archive of the papers and notes left by Professor James C. I. Dooge.[10] Other contributions and initiatives would be welcomed by the Working Group, particularly from the less

[6]When Keith Beven cleared his office on retiring from Lancaster University in 2015, many boxes of papers associated with particular projects were thrown away, as well as many boxes of reprints from the days before digital copies were readily available, collections of card bibliographies, and 5.25″ floppy disks for which readers have all but disappeared. He still has some boxes of 3.5″ floppy disks, but earlier boxes of punched cards of computer programs and data, outputs in the form of line-printer paper and backups in the form of magnetic tapes had already been lost in previous moves.
[7]www.history-of-hydrology.net. (last accessed 11.02.2025)
[8]https://www.youtube.com/@historyofhydrologyintervie846. (last accessed 11.02.2025)
[9]http://www.history-of-hydrology.net/mediawiki/index.php?title=Horton,_Robert_Elmer. (last accessed 11.02.2025)
[10]http://www.history-of-hydrology.net/mediawiki/index.php?title=Dooge,_JCI_(Jim). (last accessed 11.02.2025)

represented countries, many of which have long histories of hydrological studies and water resource engineering. It is important that our history reflects the diversity of those scientists and countries who have contributed to it.

The importance of documenting the work of historically neglected groups

> *"Certain people discouraged me, saying [science] was not a good career for women. That pushed me even more to persevere."*
> Francoise Barre-Sinoussi, 2008 Nobel Laureate

Doumenting history and work is a particular problem for those scientists and countries that are not so well represented in the literature because of gender and/or language issues. There is a documented bias going back millennia (Ali *et al.* 2023) that has consciously and unconsciously excluded the acknowledgement of women's contributions to and participation in hydrology and the geosciences. Women were banned outright from many universities around the world, and from scientific conferences until around 1939 (Gewin 2019); however, they were sometimes allowed to be present because women were believed to provide social cohesion for the men in attendance – a form of benevolent sexism that conveys a set of attitudes which seemed positive at the surface but served to minimize and undermine women. Women's participation also boosted the financial success of a conference because male members bought extra tickets for them (Gewin 2019). Yet we know that women provided substantial, unseen contributions to the geosciences (e.g. Foote 1856, Livingston 1910) that failed to be recognized, and their contributions and discoveries were often credited to men. It was common for male scientists to have women assistants, and the well-known male geologists of the time encouraged women to do some of the most time-consuming work of writing and illustrating (Burek and Higgs 2021). When these men died, several biographies of them were written after their death by women to whom they were related. These biographies show the depth of understanding the women authors had of the geological material and the importance of publishing the work posthumously (Burek and Higgs 2021). Prior to personal computers, administrative assistants – overwhelmingly women – had the responsibility to typeset manuscripts for publication over time. We can infer that to become efficient in their role, they would have also had to deeply understand the material they were transcribing.

Recent attempts to categorize the history of women in ecology (Langenheim 1996), limnology (Catalán *et al.* 2023), geology (Vincent 2020), and hydrology (Ali *et al.* 2023) review the presence of women throughout these disciplines, their significant – yet unrewarded or unacknowledged – contributions, and the exclusionary practices that they endured. Mattheis *et al.* (2022) show that many of these barriers are still in existence today due to strongly hierarchical environments with severe power imbalances. These barriers lead to the continued denial of opportunities for women's career advancement, such as honours and awards (Holmes *et al.* 2020, Meho 2021, Krause and Gehmlich 2022), first authorship (Pico *et al.* 2020) and peer review outcomes (Fox and Paine 2019); speaking opportunities at technical meetings (Ford *et al.* 2018); leadership of editorial boards (Henriques and Garcia 2022); recommendation letters (Dutt *et al.* 2016); and other exclusionary behaviour for historically excluded groups (Marin-Spiotta *et al.* 2023).

There is also a great deal of variability in how well the recent history of hydrology in different countries is recorded, particularly when the original papers are not published in the English language. Papers in this Special Collection of *Hydrological Science Journal* are concerned with the countries of Slovakia, Croatia, Lebanon, Ukraine, Russia, Japan, Brazil France, Germany, the Czech Republic, Turkey and Austria (Faybishenko *et al.* 2024, Holko *et al.* 2024, Houben *et al.* 2024, Hrončeková *et al.* 2024, Kutchment and Gelfan 2024, Levia *et al.* 2024, Merheb *et al.* 2024, Nakamura *et al.* 2024, Pavlić *et al.* 2024, Pereira *et al.* 2024), and the history of the organization of water management on the Mekong River (Orieschnig and Venot 2024). In France, efforts by Charles Obled to highlight the work of Eduard Imbeaux in the late 19th century (Beven 2020a), by Bruno Ambroise to recognize the work on variable contributing areas by Pierre Cappus in 1960,[11] and by Vazken Andréassian on the legacy of Evald Oldekop (Andréassian *et al.* 2016) are notable, and in the German-speaking area by Georg Houben to highlight the founding groundwater hydrology contributions of father and son Thiem (Houben and Batelaan 2022) and Philipp Forchheimer (Houben *et al.* 2024). Recent papers by McDonnell (2023) and Nan *et al.* (2024) have started to look at the history of experimental hydrology in China, which was greatly influenced by the changing political situation in the 20th century. The contributions of Russian hydrologists are gradually becoming more widely known, with more publications in English (e.g. Smakhtin 2002), and an archive of hundreds of biographies that has been created from an independent initiative in Russia.[12] There have also been some histories of hydrological institutions, including the history of IAHS (Rosbjerg and Rodda 2019) and the International Commission on Water Resource Systems (Uysal *et al.* 2024 in this Special Collection).

People from underrepresented groups are often unfairly and unequally burdened with the unseen labour of advocacy, representation, and (or) mentoring (refer to McKinsey & Company and LeanIn.org 2021, Bangham *et al.* 2022). These activities siphon time away from traditional research and academic activities that tend to be rewarded in the sciences. The underrepresentation of women on the History of Hydrology working group wiki site and YouTube channel are evidence of this phenomenon; that is, the difficult task of uncovering the erased or

[11] http://www.history-of-hydrology.net/mediawiki/index.php?title=Cappus,_Pierre. (last accessed 11.02.2025)
[12] at https://hydrohistory.ru/ (in Russian). (last accessed 11.02.2025)

overlooked contributions of underrepresented groups or regions tends to fall to those peoples or regions already marginalized. This is a complex but important issue that remains persistent in the sciences. Effort such as the History of Hydrology can provide a framework to overcome these barriers, but ultimately it will likely fall to our community to commit to acknowledge, equally value, and even reward this labour.

The history of hydrological literature

> "*There is nothing new, except what has been forgotten.*" Attributed to Marie Antoinette

> "*Indeed, history is nothing more than a tableau of crimes and misfortunes.*"
> Voltaire, in *L'Ingénu*, 1767, ch. 10

As noted earlier, having an accurate understanding of the current paradigm and its limitations is an important part of instigating change. That means trying to encourage early career scientists to read and understand original papers that were seminal in the development of different frameworks in hydrological thought. The IAHS has played an important role towards this aim by publishing the series of *Benchmark Papers in Hydrology* for nine different areas of hydrology, with Jeff McDonnell as the series editor.[13] Each of these volumes is accompanied by an introductory summary and commentary on each of the selected papers written by the editors for each volume. These outline some of the reasons why those particular papers were chosen as Benchmarks.

Nearly every early career researcher in hydrology will produce a literature review. This is generally considered an important part of the learning process in demonstrating background knowledge of a subject area. However, a lot of that knowledge is received knowledge that is repeated (including in hydrological textbooks) without going back to the original sources. The original papers are not always consistent with the perceptions of those studies in the collective memory. Examples are the rejection of the Manning equation (which he did not originate) in Manning's original paper (see Williams 1970), and Horton's thinking about infiltration (see Beven 2004b). Too often, now, sources are cited without being properly studied, and there are complaints that many reviews and meta-analyses are of poor quality (Baveye 2024). With the widespread use of search engines such as Google Scholar, this problem is exacerbated by the ease of finding paper titles and copying citations, often without the need to look further than the abstract. Proper and serious treatment of the literature is important to understand how hydrology has developed and to contextualize current research, and can lead to important insights about how concepts have been misused in the past (e.g. Beven 2020a, 2021). Some of the most important original papers continue to offer critical information as to how hydrology has evolved and the gaps that remain (refer to Vimal and Singh 2022 for Horton's original work on evaporation and his extensive reliance on original sources and large bodies of work dating back to the 1700s and late 1800s).

Many seminal papers are now available online (including the entire series of IAHS Red Books, and all the Transactions series of the American Geophysical Union (AGU)), but some are not, either for copyright reasons or because the hard copy has not been scanned. For the pre-internet age, it has been reported that for every article that is accessible, there may be two others that are not indexed in search engines (Google Scholar, Web of Science, among others; Vimal *et al.* 2024).[14] A critical question is how best to harness modern technology to provide an informative guide to that past literature and the overwhelming production of papers today (e.g. Brandt and Tague 2023). Large language models (LLMs) are indeed advancing the way historical analysis can be done with advanced language processing capabilities. For example, in a recent work (Miao *et al.* 2024), 310 000 studies published globally between 1980 and 2023 were analysed to trace the evolution of hydrological research. This analysis revealed the changing global patterns of production of scientific papers and collaborations between institutions in hydrology over time, but also how there has been insufficient attention paid in the literature to some major basins prone to heavy rainfall and frequent flooding, such as the Mekong, Brahmaputra, Irrawaddy, Huaihe, and Haihe River basins. It is currently an open question as to how far artificial intelligence will help or hinder a correct appreciation of the literature, in summarizing what is available, where what is available might include misinterpretations.

What more can we learn from the history of hydrology?

> "*The past is a foreign country; they do things differently there.*" L. P. Hartley (1895–1972), in *The Go-Between*, 1953

> "*In this context, we can learn a lot from the human–water interactions of ancient civilisations [. . .], provided the difference in the socio-political and economic systems can be accounted for (Question 23). The importance of the historical perspective comes from the inability to perform experiments on the interaction of people and water, which is reminiscent of the general difficulty of experimentation in hydrology . . ..*"
> Blöschl *et al.* (2019, p. 1151)

The hydrological past was considered "a foreign country," especially before the widespread availability of digital computers, and there has been undoubted progress in hydrology in the last 100 years. That progress includes a better understanding of how catchments work (particularly from the use of tracers), better measurement techniques (including remote sensing), better computational tools (including improved visualization tools) and greater appreciation for uncertainties in hydrological data. Yet the discussion above suggests that progress has perhaps been limited by a certain historical inertia in the slow evolution of dominant paradigms in hydrology, despite the limitations of those paradigms in dealing with

[13]see https://iahs.info/Publications-News/?category=6. (last accessed 11.02.2025)
[14]Keith Beven's most cited paper, published in 1979, does not appear on Web of Science (nor do any of the papers in the Hydrological Sciences Bulletin precursor of this journal) but has 9838 citations on Google Scholar!

spatial heterogeneities, surface and subsurface preferential flows, explicit treatment of state- and scale dependent storage-flow hysteresis, defining the control volume of a catchment, and ... [add your own favourite epistemic challenge here]. And all this against a backdrop of declining field work in favour of the development and application of models (Burt and McDonnell 2015).

A major reason for this slow evolution is that, given the uncertainties in hydrological data and the subsequent approximations needed in the analysis of even the water balance equation, the theory and models have been largely accepted as sufficient, with parameter fitting taking up the slack of those uncertainties (Beven 2024a). Such acceptance is conditioned by the requirements of practical applications of hydrology, as reflected in the nature of hydrological education and textbooks. It owes more to sociology of science and engineering applications as activities with a history than the classical positivist model of hypothesis generation and testing in how a science *should* work (refer to Addor and Melsen 2019 and Melsen 2022, in relation to models in this respect).

This then raises the question as to just *how* the various aspects of the history of hydrology might address current hydrological issues and inform future studies. One example is the way in which various post-positivist viewpoints are now being developed, particularly in the realm of sociohydrology in dealing with the impacts of change in (nonstationary) hydrological systems, for example within the current IAHS Hydrology Engaged Local People IN a Global world (HELPING) programme.[15] This wider interdisciplinary framework includes works on intergenerational visions (i.e. van Hateren *et al.* 2023), composite risks in codependent scales (Pörtner 2022), human-centred early warning systems (WMO 2022), panarchy theory of convergence (Sundström *et al.* 2023), climate justice (Bustamante *et al.* 2023), planetary boundaries (Richardson *et al.* 2023), ancestral co-creation of water knowledge with inclusiveness (Doubleday 2019, Roca-Servat *et al.* 2021, Krenak 2024), and the recent open hydrology initiative (UNESCO 2024). In a changing global history, where decarbonization, digitalization and decolonization of science are rapidly emerging, these wider views, many taken from history, can expand our vision, models and dialogue.

A further example is provided by how the history might inform an evaluation of hydrological models. Another objective of the History of Hydrology working group is to clarify and reconstruct the reasoning behind model development, track the origin of model assumptions, and distinguish concepts such as perceptual models from their implementation in equations and computer codes, including solution methods, model diagnosis, and probabilistic formulations and uncertainty estimation. Increasing transparency in model development would help assess the realism of model assumptions and identify gaps in knowledge. The dominant positivist paradigm has, until recently, been associated with a great many (but only relatively few classes of) hydrological models (refer, for example, to Beven 2012 and the discussion of Fenicia *et al.* 2024). There have been articles published on the histories of various models, but mostly written from the viewpoint of their developers (e.g. the Stanford Watershed Model in Crawford and Burges 2004; SWAT in Gassman *et al.* 2007; PDM in Moore 2007, SHE in Refsgaard *et al.* 2010; Topmodel in Beven *et al.* 2021, HBV in Seibert and Bergström 2022). These accounts are, perhaps, filtered through a perspective of model success. But, as noted earlier, these models have not generally been subjected to any form of post-audit analyses based on comparing historical simulations with actual data on outcomes. Such analyses might help in learning how to identify, select and improve model structures, how to make predictions in data-scarce environments and ungauged catchments, and how to use model diagnostics or limits of acceptability in hypothesis testing to select models that can be accepted as fit-for-purpose (Fenicia *et al.* 2014, Beven and Lane 2022, Prieto *et al.* 2022, Beven 2024b). To do so, however, requires that the histories of those applications and the past simulations be stored and be accessible.

Machine learning models have shown improved streamflow predictions compared to traditional models by leveraging data from multiple catchments, rather than relying solely on data from a single catchment (e.g. Kratzert *et al.* 2024). This is noteworthy both for practical applications and because it highlights potential gaps in our understanding as captured by traditional models in treating catchments as unique (Beven 2000, 2020b). However, machine-learning models challenge several established paradigms that have long guided model development, such as physical laws like mass balance, which they do not explicitly enforce; the principle of parsimony, as they involve vastly more parameters; and consistency with physical expectations (e.g. more rainfall should lead to more flow, and higher temperatures to less), which they often fail to meet (Reichert *et al.* 2024).

Although the results of machine learning models are promising, there is still no compelling reason to abandon traditional modelling principles entirely. Additionally, these models are heavily dependent on historical data, which carry their own uncertainties and inconsistencies. This highlights the importance of critically examining the limitations of historical data in order to maximize what we might learn from the machine learning research programme (as with all models in hydrology; Beven 2019). If machine learning is to inform future hydrological understanding, then it is possible that it might lead to another paradigm shift. Perhaps history will just again find another form of compensation for the limitations of the observations in taking advantage of the spatial history across multiple catchments as well as the more traditional temporal history for a single catchment. History will, in time, tell us.

In fact, there is more to be done on all of the historical topics outlined above, particularly in terms of how the developments of hydrological thinking and concepts have evolved within the sociological contexts of research groups and funding priorities over time. We hope that the IAHS History of Hydrology Working Group will be able to make some progress in enhancing the histories, especially the contributions of women and minority groups that have been less recognized in the past, and the co-evolutionary human–water feedbacks of interconnected

[15]https://iahs.info/Initiatives/Scientific-Decades/helping-working-groups/. (last accessed 11.02.2025)

water resource systems. We encourage more active participation in the working group to achieve these ends.

"Difficulty is the excuse history never accepts."
Edward R. Murrow (1908–1965)

Acknowledgements

We thank Stefano Barontini and John Nimmo, and a referee, Markus Hrachowitz, for their comments that helped improve the presentation. EMM appreciates the support from FAPESP 22/07521-5 OUR EYES (Global changes & sustainable development with water-energy viability and economic solvency) and FAPESP 22/08468-0 DREAMS (Flash drought event evolution characteristics and the response mechanism to climate change).

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Keith Beven http://orcid.org/0000-0001-7465-3934
Stacey Archfield http://orcid.org/0000-0002-9011-3871
Okke Batelaan http://orcid.org/0000-0003-1443-6385

Papers cited in the HSJ special issue collection on the history of hydrology

Barontini, S. and Settura, M., 2024. The debate on the origin of springs in Italy at the age of the scientific revolution. *Hydrological Sciences Journal*, 70 (2), xxxx. doi:10.1080/02626667.2024.2424916

Beven, K.J., 2024a. On "The Science of Waters" by Père Jean François from 1653. *Hydrological Sciences Journal*, 69 (12), 1561–1570. doi:10.1080/02626667.2024.2377352

Black, A. and Werrity, A., 2024. W N McClean – pioneer of Scottish hydrometry. *Hydrological Sciences Journal*, 70 (3). doi:10.1080/02626667.2024.2435537

Faybishenko, B., *et al.* 2024. Hydrogeological research in Ukraine: a historical review. *Hydrological Sciences Journal*, accepted.

Fenicia, F., *et al.* 2024. A historical perspective on modelling the relationship between catchment wetness and streamflow response. *Hydrological Sciences Journal*, in press.

Holko, L., *et al.* 2024. History of hydrology in small catchments in Slovakia and its links to water management. *Hydrological Sciences Journal*, 70 (1), 10–26. doi:10.1080/02626667.2024.2422532

Houben, G.J., *et al.* 2024. The force of Forchheimer – the contributions of Philipp Forchheimer to groundwater hydrology. *Hydrological Sciences Journal*, 70 (3). doi:10.1080/02626667.2024.2438337

Hrončeková, B., *et al.* 2024. Reconstruction of the Historic Flood of 1813 on Rivers in the Mountains of the Western Carpathians (Slovakia). *Hydrological Sciences Journal*, 69 (16), 2356–2371. doi:10.1080/02626667.2024.2411422

Kuchment, L. and Gelfan, A., 2024. Development of runoff generation models in the former USSR and Russia: a historical overview. *Hydrological Sciences Journal*, 69 (16), 2323–2336. doi:10.1080/02626667.2024.2413013

Levia, D.F., *et al.* 2024. Forest-water interactions: a multilingual perspective through six historical vignettes. *Hydrological Sciences Journal*, accepted.

McDonnell, J., *et al.* 2024. The first catchment water balance: new insights into Pierre Perrault, his perceptual model and his peculiar catchment. *Hydrological Sciences Journal*, 70 (1), 27–36. doi:10.1080/02626667.2024.2427890

Merheb, M., *et al.* 2024. Hydro-history of Lebanon from Antiquity to modern times. *Hydrological Sciences Journal*, accepted.

Nakamura, S., *et al.* 2024. Emergence and developments in hydrology -suimongaku- in Japan from the late 19th century to 1970. *Hydrological Sciences Journal*, accepted.

Nimmo, J.R., 2024. New insights on the origin of the Richardson-Richards equation. *Hydrological Sciences Journal*, 69 (15), 2153–2158. doi:10.1080/02626667.2024.2404714

Orieschnig, C. and Venot, J.-P., 2024. The history of hydrological studies on the mekong floodplains - from colonial experiments to computational models. *Hydrological Sciences Journal*, 69 (16), 2391–2404. doi:10.1080/02626667.2024.2420866

Pavlić K., *et al.* 2024. The history of hydrology in Croatia. *Hydrological Sciences Journal*, submitted.

Pereira, B., *et al.* 2024. Hydrological heritage: a historical exploration of human-water dynamics in Northeast Brazil. *Hydrological Sciences Journal*, submitted.

Smith, J.A., *et al.* 2024. Cloudbursts and the upper tail of short-duration, rainfall: hortonian perspectives. *Hydrological Sciences Journal*, 69 (16), 2337–2355. doi:10.1080/02626667.2024.2404712

Uysal, G., *et al.* 2024. Historical synthesis of the international commission on water resources systems. *Hydrological Sciences Journal*, 69 (16), 2372–2390. doi:10.1080/02626667.2024.2412726

Vimal, S., *et al.* 2024. Curating Robert Elmer Horton's bibliography. *Hydrological Sciences Journal*, accepted.

References

Abbott, B.W., *et al.* 2019. A water cycle for the anthropocene. *Hydrological Processes*, 33 (23), 3046–3052. doi:10.1002/hyp.13544

Addor, N., *et al.* 2017. The CAMELS data set: catchment attributes and meteorology for large-sample studies. *Hydrology and Earth System Sciences*, 21 (10), 5293–5313. doi:10.5194/hess-21-5293-2017

Addor, N. and Melsen, L., 2019. Legacy, rather than adequacy, drives the selection of hydrological models. *Water Resources Research*, 55 (1), 378–390. doi:10.1029/2018WR022958

Ali, G., *et al.* 2023. A Commentary on women's contributions in hydrology. *Journal of Hydrology*, 624, 129884. doi:10.1016/j.jhydrol.2023.129884

Ameli, A.A., *et al.* 2018. Groundwater subsidy from headwaters to their parent water watershed: a combined field-modeling approach. *Water Resources Research*, 54 (7), 5110–5125. doi:10.1029/2017WR022356

Anderson, M.P. and Woessner, W.W., 1992. The role of the post audit in model validation. *Advances in Water Resources*, 15 (3), 167–173. doi:10.1016/0309-1708(92)90021-S

Andréassian, V., Mander, Ü., and Pae, T., 2016. The Budyko hypothesis before Budyko: the hydrological legacy of Evald Oldekop. *Journal of Hydrology*, 535, 386–391. doi:10.1016/j.jhydrol.2016.02.002

Aulenbach, B.T., *et al.* 2021. The evolving perceptual model of streamflow generation at the Panola Mountain research watershed. *Hydrological Processes*, 35 (4). doi:10.1002/hyp.14127

Baker, V.R., 2017. Debates—hypothesis testing in hydrology: pursuing certainty versus pursuing uberty. *Water Resources Research*, 53 (3), 1770–1778. doi:10.1002/2016WR020078

Bangham, J., Chacko, X., and Kaplan, J., eds. 2022. *Invisible labour in modern science*. Lanham: Rowman and Littlefield Publishers.

Barontini, S. and Settura, M., 2020. Beyond Perrault's experiments: repeatability, didactics and complexity. *Hydrology and Earth System Sciences*, 24 (4), 1907–1926. doi:10.5194/hess-24-1907-2020

Baveye, P.C., 2024. Possible editorial responses to the proliferation of problematic meta-analyses and research syntheses. *European Science Editing*, 50, e131528. doi:10.3897/ese.2024.e131528

Benettin, P., *et al.* 2022. Transit time estimation in catchments: recent developments and future directions. *Water Resources Research*, 58 (11), e2022WR033096. doi:10.1029/2022WR033096

Beven, K.J., 1987. Towards a new paradigm in hydrology. *In*: *Water for the future: hydrology in perspective*. Wallingford, UK: IAHS Publ. No. 164, 393–403.

Beven, K.J., 1989. Interflow. *In*: H.J. Morel-Seytoux, ed. *Proceding NATO ARW on unsaturated flow in hydrological modelling*. Dordrecht: Kluwer, 191–219.

Beven, K.J., 2000. Uniqueness of place and process representations in hydrological modelling. *Hydrology and Earth System Sciences*, 4 (2), 203–213. doi:10.5194/hess-4-203-2000

Beven, K.J., 2001. On hypothesis testing in hydrology. *Hydrological Processes (Hptoday)*, 15 (9), 1655–1657. doi:10.1002/hyp.436

Beven, K.J., 2004a. Surface runoff at the horton hydrologic laboratory (or not?). *Journal of Hydrology*, 293 (1–4), 219–234. doi:10.1016/j.jhydrol.2004.02.001

Beven, K.J., 2004b. Robert Horton's perceptual model of infiltration. *Hydrological Processes*, 18 (17), 3447–3460. doi:10.1002/hyp.5740

Beven, K.J., 2006. The Holy Grail of scientific hydrology:Q_t=*H(SR)A* as closure. *Hydrology and Earth Systems Science*, 10 (5), 609–618. doi:10.5194/hess-10-609-2006

Beven, K.J., 2012. *Rainfall-runoff modelling – the primer*. 2nd ed. Chichester: Wiley-Blackwell.

Beven, K.J., 2014. BHS Penman lecture: "Here we have a system in which liquid water is moving; let's just get at the physics of it" (Penman 1965). *Hydrology Research*, 45 (6), 727–736. doi:10.2166/nh.2014.130

Beven, K.J., 2015. What we see now: event-persistence in predicting the responses of hydro-eco-geomorphological systems? *Ecological Modelling*, 298, 4–15. doi:10.1016/j.ecolmodel.2014.07.019

Beven, K.J., 2018. A century of denial: preferential and nonequilibrium water flow in soils, 1864–1984. *Vadose Zone Journal*, 17 (1), 180153. doi:10.2136/vzj2018.08.015

Beven, K.J., 2019. Towards a methodology for testing models as hypotheses in the inexact sciences. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 475 (2224), 20180862. doi:10.1098/rspa.2018.0862

Beven, K.J., *et al*. 2020. Developing observational methods to drive future hydrological science: can we make a start as a community? *Hydrological Processes*, 34 (3), 868–873. doi:10.1002/hyp.13622

Beven, K.J., 2020a. A history of the concept of time of concentration. *Hydrology and Earth System Sciences*, 24 (5), 2655–2670. doi:10.5194/hess-24-2655-2020

Beven, K.J., 2020b. Deep learning, hydrological processes and the uniqueness of place. *Hydrological Processes*, 34 (16), 3608–3613. doi:10.1002/hyp.13805

Beven, K.J., 2021. The era of infiltration. *Hydrology and Earth System Sciences*, 25 (2), 851–866. doi:10.5194/hess-2020-308

Beven, K.J., *et al*. 2021. A history of TOPMODEL. *Hydrology and Earth System Sciences*, 25 (2), 527–549. doi:10.5194/hess-25-527-2021

Beven, K.J., 2024b. A short history of philosophies of hydrological model evaluation and hypothesis testing. *Wiley Interdisciplinary Reviews: Water*, e1761. doi:10.1002/wat2.1761

Beven, K.J. and Chappell, N.A., 2021. Perceptual perplexity and parameter parsimony. *Wiley Interdisciplinary Reviews: Water*, 8 (4), e1530. doi:10.1002/wat2.1530

Beven, K.J. and Lane, S., 2022. On (in)validating environmental models. 1. Principles for formulating a Turing-like Test for determining when a model is fit-for purpose. *Hydrological Processes*, 36 (10), e14704. doi:10.1002/hyp.14704.

Bieroza, M., *et al*. 2023. Advances in catchment science, hydrochemistry, and aquatic ecology enabled by high-frequency water quality measurements. *Environmental Science and Technology*, 57 (12), 4701–4719. doi:10.1021/acs.est.2c07798

Binley, A., *et al*. 2015. The emergence of hydrogeophysics for improved understanding of subsurface processes over multiple scales. *Water Resources Research*, 51 (6), 3837–3866. doi:10.1002/2015WR017016

Biswas, A., 1970. *History of Hydrology*. Amsterdam and London: North-Holland Publishing Company, 336pp.

Blöschl, G., *et al*. 2019. Twenty-three unsolved problems in hydrology (UPH)–a community perspective. *Hydrological Sciences Journal*, 64 (10), 1141–1158. doi:10.1080/02626667.2019.1620507

Bogena, H.R., *et al*. 2018a. The TERENO-Rur hydrological observatory: a multiscale multi- compartment research platform for the advancement of hydrological science. *Vadose Zone Journal*, 17 (1), 180055. doi:10.2136/vzj2018.03.0055

Bogena, H.R., *et al*. 2018b. Toward better understanding of terrestrial processes through long-term hydrological observatories. *Vadose Zone Journal*, 17 (1), 1–10. doi:10.2136/vzj2018.10.0194

Brandt, W. and Tague, C., 2023. How to address publication overload in environmental science. *Eos Transactions American Geophysical Union*, 104. Published on 22 September 2023. doi:10.1029/2023EO230361

Brooks, R.J., *et al*. 2010. Ecohydrologic separation of water between trees and streams in a Mediterranean climate. *Nature Geoscience*, 3 (2), 100–104. doi:10.1038/ngeo722

Burek, C.V. and Higgs, B.M., eds. 2021. *Celebrating 100 years of female fellowship of the geological society: discovering forgotten histories*. London: Special Publication 506, Geological Society.

Burt, T.P. and McDonnell, J.J., 2015. Whither field hydrology? The need for discovery science and outrageous hydrological hypotheses. *Water Resources Research*, 51 (8), 5919–5928. doi:10.1002/2014WR016839

Bustamante, M., *et al*. 2023. Ten new insights in climate science 2023. *Global Sustainability*, 7, e19. doi:10.1017/sus.2023.25

Catalán, N., *et al*. 2023. Women in limnology: from a historical perspective to a present-day evaluation. *Wiley Interdisciplinary Reviews: Water*, 10 (1), e1616. doi:10.1002/wat2.1616

Christophersen, N. and Wright, R.F., 1981. Sulfate budget and a model for sulfate concentrations in stream water at Birkenes, a small forested catchment in southernmost Norway. *Water Resources Research*, 17 (2), 377–389. doi:10.1029/WR017i002p00377

Clark, M.P., Kavetski, D., and Fenicia, F., 2011. Pursuing the method of multiple working hypotheses for hydrological modeling. *Water Resources Research*, 47 (9), W09301. doi:10.1029/2010WR009827

Condon, L.E., *et al*. 2020. Where is the bottom of a watershed? *Water Resources Research*, 56 (3), e2019WR026010. doi:10.1029/2019WR026010

Crawford, N.H. and Burges, S.J., 2004. History of the Stanford Watershed model. *Water Resources Impact*, 6 (2), 3–6. Available from: https://www.jstor.org/stable/wateresoimpa.6.2.0003

Davies, J., *et al*. 2011. A discrete particle representation of hillslope hydrology: hypothesis testing in reproducing a tracer experiment at Gårdsjön, Sweden. *Hydrological Processes*, 25 (23), 3602–3612. doi:10.1002/hyp.8085

Davies, J., *et al*. 2013. Integrated modelling of flow and residence times at the catchment scale with multiple interacting pathways. *Water Resources Research*, 49 (8), 4738–4750. doi:10.1002/wrcr.20377

Davies, J. and Beven, K.J., 2015. Hysteresis and scale in catchment storage, flow and transport. *Hydrological Processes*, 29 (16), 3604–3615. doi:10.1002/hyp.10511

Dawson, T.E. and Ehleringer, J.R., 1991. Streamside trees that do not use stream water. *Nature*, 350 (6316), 335–337. doi:10.1038/350335a0

Dooge, J.C.I., 1976. The concept of the hydrological cycle in Britain (1687-1802). *Water International*, 1 (4), 18–23. doi:10.1080/02508067608685733

Dooge, J.C.I. 2001, Concepts of the hydrological cycle, ancient and modern. *In*: *International Symposium: Origins and History of Hydrology*, 9–11 May 2001 Dijon, France, 1–10.

Doubleday, N.C., 2019. Culture as vector: agency for social-ecological systems change. *In*: R. Boschman and M. Trono, eds. *On active grounds: agency and time in the environmental humanities*. Waterloo: Wilfrid Laurier University Press, 327–347.

Duffy, C.J., 2017. The terrestrial hydrologic cycle: an historical sense of balance. *Wiley Interdisciplinary Reviews: Water*, 4 (4), e1216. doi:10.1002/wat2.1216

Dutt, K., *et al*. 2016. Gender differences in recommendation letters for postdoctoral fellowships in geoscience. *Nature Geoscience*, 9 (11), 805–808. doi:10.1038/ngeo2819

Falkenmark, M., 2004. Towards integrated catchment management: opening the paradigm locks between hydrology, ecology and policy-making. *International Journal of Water Resources Development*, 20 (3), 275–281. doi:10.1080/0790062042000248637

Fan, Y., 2019. Are catchments leaky? *Wiley Interdisciplinary Reviews: Water*, 6 (6), e1386. doi:10.1002/wat2.1386

Fenicia, F., *et al*. 2014. Catchment properties, function, and conceptual model representation: is there a correspondence? *Hydrological Processes*, 28 (4), 2451–2467. doi:10.1002/hyp.9726

Foote, E., 1856. Circumstances affecting the heat of the sun's rays. *The American Journal of Science and Arts*, 22 (66), 382–383.

Ford, H.L., *et al.* 2018. Gender inequity in speaking opportunities at the American geophysical union fall meeting. *Nature Communications*, 9 (1), 1358. doi:10.1038/s41467-018-03809-5

Fovet, O., *et al.* 2018. AgrHyS: an observatory of response times in agro-hydro systems. *Vadose Zone Journal*, 17 (1), 1–16. doi:10.2136/vzj2018.04.0066

Fox, C.W. and Paine, C.E.T., 2019. Gender differences in peer review outcomes and manuscript impact at six journals of ecology and evolution. *Ecology and Evolution*, 9 (6), 3599–3619. doi:10.1002/ece3.4993

Gaillardet, J., *et al.* 2018. OZCAR: the French network of critical zone observatories. *Vadose Zone Journal*, 17 (1), 1–24. doi:10.2136/vzj2018.04.0067

Gascuel-Odoux, C., *et al.* 2018. Evolution of scientific questions over 50 years in the Kervidy-Naizin catchment: from catchment hydrology to integrated studies of biogeochemical cycles and agroecosystems in a rural landscape. *Cuadernos de investigación geográfica: Geographical Research Letters*, 44 (2), 535–555. doi:10.18172/cig.3383

Gassman, P.W., *et al.* 2007. The soil and water assessment tool: historical development, applications, and future research directions. *Transactions of the ASABE*, 50 (4), 1211–1250. doi:10.13031/2013.23637

Gewin, V., 2019. How the scientific meeting has changed since Nature's founding 150 years ago. *Nature*, 576 (7787), S70–S72. doi:10.1038/d41586-019-03851-3

Grayson, R.B., Moore, I.D., and McMahon, T.A., 1992. Physically-based hydrologic modelling: 2. Is the concept realistic. *Water Resources Research*, 28 (10), 2659–2666. doi:10.1029/92WR01259

Harman, C.J., 2019. Age-ranked storage-discharge relations: a unified description of spatially lumped flow and water age in hydrologic systems. *Water Resources Research*, 55 (8), 7143–7165. doi:10.1029/2017WR022304

Henriques, M.H. and Garcia, L.F., 2022. Women underrepresentation in editorial boards of geology journals and the utopia of gender equality. *Frontiers in Earth Science*, 10, 803900. doi:10.3389/feart.2022.803900

Hewlett, J.D., Lull, H.W., and Reinhart, K.G., 1969. In defense of experimental watersheds. *Water resources research*, 5 (1), 306–316.

Holmes, M.A., Myles, L., and Schneider, B., 2020. Diversity and equality in honours and awards programs – steps towards a fair representation of membership. *Advances in Geosciences*, 53, 41–51. doi:10.5194/adgeo-53-41-2020

Houben, G.J. and Batelaan, O., 2022. The Thiem team – Adolf and Günther Thiem, two forefathers of hydrogeology. *Hydrology and Earth System Sciences*, 26 (15), 4055–4091. doi:10.5194/hess-26-4055-2022

Hunt, A., Ewing, R., and Ghanbarian, B., 2014. *Percolation theory for flow in porous media* 3rd ed. Dordrecht: Springer-Verlag. http://dx.doi.org/10.1007/978-3-319-03771-4

Hunt, A.G., Faybishenko, B., and Ghanbarian, B., 2021. Predicting characteristics of the water cycle from scaling relationships. *Water Resources Research*, 57 (9), e2021WR030808. doi:10.1029/2021WR030808

ISO, 2020. *Hydrometric Uncertainty Guidance (HUG)*. ISO 25377, International Standards Organisation. Available from: https://www.iso.org/obp/ui/#iso:std:iso:25377:ed-1:v1:en

Janzen, D. and McDonnell, J.J., 2015. A stochastic approach to modelling and understanding hillslope runoff connectivity dynamics. *Ecological Modeling*, 298, 64–74. doi:10.1016/j.ecolmodel.2014.06.024

Kirchner, J.W., 2003. A double paradox in catchment hydrology and geochemistry. *Hydrological Processes*, 17 (4), 871–874. doi:10.1002/hyp.5108

Kirchner, J.W., Benettin, P., and van Meerveld, I., 2023. Instructive surprises in the hydrological functioning of landscapes. *Annual Review of Earth and Planetary Sciences*, 51 (1), 277–299. doi:10.1146/annurev-earth-071822-100356

Konikow, L.F. and Bredehoeft, J.D., 1992. Groundwater models cannot be validated? *Advances in Water Resources*, 15 (1), 75–83. doi:10.1016/0309-1708(92)90033-X

Koutsoyiannis, D. and Mamassis, N., 2021. From mythology to science: the development of scientific hydrological concepts in Greek antiquity and its relevance to modern hydrology. *Hydrology and Earth System Sciences*, 25 (5), 2419–2444. doi:10.5194/hess-25-2419-2021

Kratzert, F., *et al.* 2024. HESS Opinions: never train a Long Short-Term Memory (LSTM) network on a single basin. *Hydrology and Earth System Sciences*, 28 (17), 4187–4201. doi:10.5194/hess-28-4187-2024

Krause, S. and Gehmlich, K., 2022 Does the persistent lack of female recipients of academic awards have to Surprise us if few scientific prizes and medals are named after women? *In*: *EGU General Assembly 2022*, 23–27 May 2022 Vienna, Austria, EGU22–2562. doi:10.5194/egusphere-egu22-2562

Krenak, A., 2024. *Ancestral future*. Cambridge: Polity Press. EAN/UPC 9781509560738.

Kuhn, T., 1962. *The structure of scientific revolutions*. Chicago: University of Chicago Press.

Lakatos, I., 1970. Falsification and the methodology of scientific research programmes. *In*: I. Lakatos and A. Musgrave, eds. *Philosophy, science, and history*. London: Routledge, 89–94,91–195.

Langenheim, J.H., 1996. Early history and progress of women ecologists: emphasis upon research contributions. *Annual Review of Ecology and Systematics*, 27 (1), 1–53. Available from: http://www.jstor.org/stable/2097228

Latour, B., 1987. *Science in action: how to follow scientists and engineers through society*. Cambridge, Massachusetts: Harvard University Press.

Lehmann, P., *et al.* 2007. Rainfall Threshold for hillslope outflow: an emergent property of flow pathway connectivity. *Hydrology and Earth System Science*, 11 (2), 1047–1063. doi:10.5194/hess-11-1047-2007

Livingston, G.J., 1910. *An annotated bibliography of evaporation*. Washington, DC: United States Weather Bureau.

Marin-Spiotta, E., *et al.* 2023. Exclusionary behaviors reinforce historical biases and contribute to loss of talent in the Earth sciences. *Earth's Future*, 11 (3), e2022EF002912. doi:10.1029/2022EF002912

Mattheis, A., *et al.* 2022. "Maybe this is just not the place for me:" Gender harassment and discrimination in the geosciences. *PLoS ONE*, 17 (5), e0268562. doi:10.1371/journal.pone.0268562

Mazadiego, L.F., Puche, O., and Hervás, A.M., 2009. Water and Inca cosmogony: myths, geology and engineering in the Peruvian Andes. *In*: M. Kólbl-Ebert, ed. *Geology and religion: a history of harmony and hostility*. The Geological Society. London: Special Publications Vol. 310, 17–24. doi:10.1144/SP310.3

McCormick, E.L., *et al.* 2021. Widespread woody plant use of water stored in bedrock. *Nature*, 597 (7875), 225–229. doi:10.1038/s41586-021-03761-3

McDonnell, J.J., *et al.* 2007. Moving beyond heterogeneity and process complexity: a new vision for watershed hydrology. *Water Resources Research*, 43 (7), W07301. doi:10.1029/2006WR005467

McDonnell, J.J., *et al.* 2021a. The Maimai M8 experimental catchment database: forty years of process-based research on steep, wet hillslopes. *Hydrological Processes*, 35 (5). doi:10.1002/hyp.14112

McDonnell, J.J., *et al.* 2021b. Fill-and-spill: a process description of runoff generation at the scale of the beholder. *Water Resources Research*, 57 (5). doi:10.1029/2020WR027514

McDonnell, J.J., 2023. Wei-Zu Gu and the remarkable rise of hydrological process research in China. *Hydrological Processes*, 37 (5). doi:10.1002/hyp.14896

McDonnell, J.J. and Beven, K.J., 2014. Debates—The future of hydrological sciences: a (common) path forward? A call to action aimed at understanding velocities, celerities and residence time distributions of the headwater hydrograph. *Water Resources Research*, 50 (6), 5342–5350. doi:10.1002/2013WR015141

McGlynn, B. and McDonnell, J.J., 2003. Quantifying the relative contributions of riparian and hillslope zones to catchment runoff. *Water Resources Research*, 39 (11), 1310. doi:10.1029/2003WR002091

McKinsey & Company and LeanIn.org, 2021. *Women in the workplace report*. Available from: https://wiw-report.s3.amazonaws.com/Women_in_the_Workplace_2020.pdf

McKnight, D.M., 2017. Debates—Hypothesis testing in hydrology: a view from the field: the value of hydrologic hypotheses in designing field studies and interpreting the results to advance hydrology. *Water Resources Research*, 53 (3), 1779–1783. doi:10.1002/2016WR020050

Meho, L.I., 2021. The gender gap in highly prestigious international research awards, 2001–2020. *Quantitative Science Studies*, 2 (3), 976–989. doi:10.1162/qss_a_00148

Melsen, L.A., 2022. It takes a village to run a model—the social practices of hydrological modeling. *Water Resources Research*, 58 (2), e2021WR030600. doi:10.1029/2021WR030600

Miao, C., *et al.* 2024. Hydrological research evolution: a large language model-based analysis of 310,000 studies published globally between 1980 and 2023. *Water Resources Research*, 60 (6), e2024WR038077. doi:10.1029/2024WR038077

Milly, P.C.D., *et al.* 2008. Stationarity is dead: whither water management? *Science*, 319 (5863), 573–574. doi:10.1126/science.1151915

Moore, R.J., 2007. The PDM rainfall-runoff model. *Hydrology and Earth System Sciences*, 11 (1), 483–499. doi:10.5194/hess-11-483-2007

Nace, R.L., 1980. Hydrology comes of age: impact of the International Hydrological Decade. *Eos, Transactions American Geophysical Union*, 61 (53), 1241. doi:10.1029/EO061i053p01241

Nan, Y., *et al.* 2024. A historical overview of experimental hydrology in China. *Hydrological Processes*, 38 (7). doi:10.1002/hyp.15233

Oda, T., *et al.* 2024. Scale-dependent inter-catchment groundwater flow in forested catchments: analysis of multi-catchment water balance observations in Japan. *Water Resources Research*, 60 (7), e2024WR037161. doi:10.1029/2024WR037161

Perbidon, A., 2024. Between the mouth of the two rivers. The agency of water, springs, rivers and trees in ancient mesopotamian cosmology and religion. *Journal of Croatian Ethnological Society*, 51 (44). doi:10.15378/1848-9540.2021.44.02

Peters-Lidard, C.D., *et al.* 2017. Scaling, similarity, and the fourth paradigm for hydrology. *Hydrology and Earth System Sciences*, 21 (7), 3701–3713. doi:10.5194/hess-21-3701-2017

Pico, T., *et al.* 2020. First authorship gender gap in the geosciences. *Earth and Space Science*, 7 (8), e2020EA001203. doi:10.1029/2020EA001203

Popper, K., 1959. *The logic of scientific discovery*. New York, NY: Basic Books.

Pörtner, H.-O., 2022. Technical summary. *In*: H.-O. Pörtner, ed. *Climate change 2022: impacts, adaptation and vulnerability*. Contribution of WG II to AR6 of the IPCC. Cambridge, UK: Cambridge University Press, 37–118. doi:10.1017/9781009325844.002

Prieto, C., *et al.* 2021. Identification of dominant hydrological mechanisms using Bayesian inference, multiple statistical hypothesis testing, and flexible models. *Water Resources Research*, 57 (8), e2020WR028338. doi:10.1029/2020WR028338

Prieto, C., *et al.* 2022. An exploration of Bayesian identification of dominant hydrological mechanisms in ungauged catchments. *Water Resources Research*, 58 (3), e2021WR030705. doi:10.1029/2021WR030705

Raats, P.A.C. and Knight, J.H., 2018. The contributions of Lewis Fry Richardson to drainage theory, soil physics, and the soil-plant-atmosphere continuum. *Frontiers in Environmental Science*, 6, 13. doi:10.3389/fenvs.2018.00013

Refsgaard, J.-C., Storm, B., and Clausen, T., 2010. Système Hydrologique Europeén (SHE): review and perspectives after 30 years development in distributed physically-based hydrological modelling. *Hydrology Research*, 41 (5), 355–377. doi:10.2166/nh.2010.009

Reichert, P., *et al.* 2024. Metamorphic testing of machine learning and conceptual hydrologic models. *Hydrology and Earth System Sciences*, 28 (11), 2505–2529. doi:10.5194/hess-28-2505-2024

Richards, L.A., 1931. Capillary conduction of liquids through porous mediums. *Physics*, 1 (5), 318–333. doi:10.1063/1.1745010

Richardson, K., *et al.* 2023. Earth beyond six of nine planetary boundaries. *Science Advances*, 9 (37), p.eadh2458. doi:10.1126/sciadv.adh2458

Rinaldo, A., *et al.* 2015. Storage selection functions: a coherent framework for quantifying how catchments store and release water and solutes. *Water Resources Research*, 51 (6), 4840–4847. doi:10.1002/2015WR017273

Roca-Servat, D., Arias-Henao, J.D., and Botero-Mesa, M., 2021. Decolonizing hegemonic approaches of water: exploring Latin American proposals for communality and community. *Ambiente & Sociedade*, 24, e00961. doi:10.1590/1809-4422asoc20200096r1vu2021L4TD

Rosbjerg, D., 2020. Hydrology and beyond: the scientific work of August Colding revisited. *Hydrology and Earth System Sciences*, 24 (9), 4575–4585. doi:10.5194/hess-24-4575-2020

Rosbjerg, D. and Rodda, J., 2019. IAHS: a brief history of hydrology. *History of Geo- and Space Sciences*, 10 (1), 109–118. doi:10.5194/hgss-10-109-2019

Savenije, H.H. and Hrachowitz, M., 2017. HESS opinions catchments as meta-organisms–a new blueprint for hydrological modelling. *Hydrology and Earth System Sciences*, 21 (2), 1107–1116. doi:10.5194/hess-21-1107-2017

Seibert, J. and Bergström, S., 2022. A retrospective on hydrological catchment modelling based on half a century with the HBV model. *Hydrology and Earth System Sciences*, 26 (5), 1371–1388. doi:10.5194/hess-26-1371-2022

Singh, P.K., *et al.* 2020. Hydrology and water resources management in ancient India. *Hydrology and Earth System Sciences*, 24 (10), 4691–4707. doi:10.5194/hess-24-4691-2020

Sivapalan, M., 2015. Debates—Perspectives on socio-hydrology: changing water systems and the "tyranny of small problems"—Socio-hydrology. *Water Resources Research*, 51 (6), 4795–4805. doi:10.1002/2015WR017080

Smakhtin, V.U., 2002. Some early Russian studies of subsurface stormflow processes. *Hydrological Processes*, 16 (13), 2613–2620. doi:10.1002/hyp.1016

Sundström, S.M., *et al.* 2023. Panarchy theory for convergence. *Sustainability Science*, 18 (4), 1667–1682. doi:10.1007/s11625-023-01299-z

Tauro, F., *et al.* 2018. Measurements and observations in the XXI century (MOXXI): innovation and multi-disciplinarity to sense the hydrological cycle. *Hydrological Sciences Journal*, 63 (2), 169–196. doi:10.1080/02626667.2017.1420191

Tischendorf, W.G., 1969. *Tracing storm flow to varying source area in small forested watershed in the Southeastern Piedmont*. Unpublished PhD dissertation. Athens, GA: University of Georgia.

Tuan, Y.-F., 1968. *The hydrologic cycle and Wisdom of God: a theme in geoteleology*. Toronto, Canada: University of Toronto Press, 160pp.

UNESCO, 2015. *Water, people and cooperation: 50 years of water programmes for sustainable development at UNESCO*. Paris: UNESCO.

UNESCO, 2023. FRIEND-Water: a global perspective 2014-2022; facts and figures. Report SC-2023/HYD/PI/4. Paris, UNESCO, 96.

UNESCO, 2024. Open Hydrology, Report SC-2024/HYD/PI/14. Paris, UNESCO, 99.

van Hateren, T.C., *et al.* 2023. Where should hydrology go? An early-career perspective on the next IAHS Scientific Decade: 2023–2032. *Hydrological Sciences Journal*, 68 (4), 529–541. doi:10.1080/02626667.2023.2170754

Vimal, S. and Singh, V.P., 2022. Rediscovering Robert E. Horton's lake evaporation formulae: new directions for evaporation physics. *Hydrology and Earth System Sciences*, 26 (2), 445–467. doi:10.5194/hess-26-445-2022

Vincent, A., 2020. Reclaiming the memory of pioneer female geologists 1800–1929. *Advances in Geosciences*, 53, 129–154. doi:10.5194/adgeo-53-129-2020

Wagener, T., *et al.* 2021. Knowledge gaps in our perceptual model of Great Britain's hydrology. *Hydrological Processes*, 35 (7), e14288. doi:10.1002/hyp.14288

Wagener, T., Sivapalan, M., and McGlynn, B., 2008. Catchment classification and services—toward a new paradigm for catchment hydrology driven by societal needs. *In*: M.G. Anderson (Editor-in-Chief), ed. *Encyclopedia Of hydrological sciences*. Chichester: Wiley, 1–12.

Westerberg, I.K. and Karlsen, R.H., 2024. Sharing perceptual models of uncertainty: on the use of soft information about discharge data. *Hydrological Processes*, 38 (5), e15145. doi:10.1002/hyp.15145

Williams, G.P., 1970. Manning formula—a misnomer? *Journal of the Hydraulics Division ASCE*, 96 (1), 193–200. doi:10.1061/JYCEAJ.0002260

WMO, 2008, *Guide to hydrological practices, volume I+II: hydrology – from measurement to hydrological information*. Geneva: World Meteorological Organisation. WMO Report No. 168. Available from: https://community.wmo.int/en/bookstore/guide-hydrological-practices-volume-iii-hydrology-measurement-hydrological-information

WMO, 2022. *Early warnings for all initiative, Geneva*. Available from: https://wmo.int/activities/early-warnings-all/wmo-and-early-warnings-all-initiative

Woodsmith, R., *et al*. 2004. The Entiat experimental forest: catchment-scale runoff data before and after a 1970 wildfire. *Water Resources Research*, 40 (11), W11701. doi:10.1029/2004WR003296

Zehe, E., *et al*. 2013. A thermodynamic approach to link self-organization, preferential flow and rainfall–runoff behaviour. *Hydrology and Earth System Sciences*, 17 (11), 4297–4322. doi:10.5194/hess-17-4297-2013

Zhou, Y., Zwahlen, F., and Wang, Y., 2011. The ancient Chinese notes on hydrogeology. *Hydrogeology Journal*, 19 (5), 1103–1114. doi:10.1007/s10040-010-0682-1