



Panta Rhei: a decade of progress in research on change in hydrology and society

Heidi Kreibich, Murugesu Sivapalan, Amir AghaKouchak, Nans Addor, Hafzullah Aksoy, Berit Arheimer, Karsten Arnbjerg-Nielsen, Cynthia Vail-Castro, Christophe Cudennec, Mariana Madruga de Brito, Giuliano Di Baldassarre, David C. Finger, Keirnan Fowler, Wouter Knoben, Tobias Krueger, Junguo Liu, Elena Macdonald, Hilary McMillan, E. Mario Mendiondo, Alberto Montanari, Marc F. Muller, Saket Pande, Fuqiang Tian, Alberto Viglione, Yongping Wei, Attilio Castellarin, Daniel Peter Loucks, Taikan Oki, María J. Polo, Huub Savenije, Anne F. Van Loon, Ankit Agarwal, Camila Alvarez-Garreton, Ana Andreu, Marlies H. Barendrecht, Manuela Brunner, Louise Cavalcante, Yonca Cavus, Serena Ceola, Pedro Chaffe, Xi Chen, Gemma Coxon, Zhao Dandan, Kamran Davary, Moctar Dembélé, Benjamin Dewals, Tatiana Frolova (Bibikova), Animesh K. Gain, Alexander Gelfan, Mohammad Ghoreishi, Thomas Grabs, Xiaoxiang Guan, David M. Hannah, Joerg Helmschrot, Britta Höllermann, Jean Hounkpè, Elizabeth Koebele, Megan Konar, Frederik Kratzert, Sara Lindersson, Maria Carmen Llasat, Alessia Matanó, Maurizio Mazzoleni, Alfonso Mejia, Pablo Mendoza, Bruno Merz, Jenia Mukherjee, Farzin Nasiri Saleh, Bertil Nlend, Rodric Merime Nonki, Christina Orieschnig, Katerina Papagiannaki, Gopal Penny, Olga Petrucci, Rafael Pimentel, Sandra Pool, Elena Ridolfi, Maria Rusca, Nivedita Sairam, Adarsh Sankaran Namboothiri, Ana Carolina Sarmiento Buarque, Elisa Savelli, Lukas Schoppa, Kai Schröter, Anna Scolobig, Mojtaba Shafiei, Anna E. Sikorska-Senoner, Magdalena Smigaj, Claudia Teutschbein, Thomas Thaler, Andrijana Todorovic, Faranak Tootoonchi, Roshanak Tootoonchi, Elena Toth, Ronald van Nooijen, Franciele Maria Vanelli, Nicolás Vásquez, David W. Walker, Marthe Wens, David J. Yu, Heidar Zarei, Changrang Zhou & Günter Blöschl

To cite this article: Heidi Kreibich, Murugesu Sivapalan, Amir AghaKouchak, Nans Addor, Hafzullah Aksoy, Berit Arheimer, Karsten Arnbjerg-Nielsen, Cynthia Vail-Castro, Christophe Cudennec, Mariana Madruga de Brito, Giuliano Di Baldassarre, David C. Finger, Keirnan Fowler, Wouter Knoben, Tobias Krueger, Junguo Liu, Elena Macdonald, Hilary McMillan, E. Mario Mendiondo, Alberto Montanari, Marc F. Muller, Saket Pande, Fuqiang Tian, Alberto Viglione, Yongping Wei, Attilio Castellarin, Daniel Peter Loucks, Taikan Oki, María J. Polo, Huub Savenije, Anne F. Van Loon, Ankit Agarwal, Camila Alvarez-Garreton, Ana Andreu, Marlies H. Barendrecht, Manuela Brunner, Louise Cavalcante, Yonca Cavus, Serena Ceola, Pedro Chaffe, Xi Chen, Gemma Coxon, Zhao Dandan, Kamran Davary, Moctar Dembélé, Benjamin Dewals, Tatiana Frolova (Bibikova), Animesh K. Gain, Alexander Gelfan, Mohammad Ghoreishi, Thomas Grabs, Xiaoxiang Guan, David M. Hannah, Joerg Helmschrot, Britta Höllermann, Jean Hounkpè, Elizabeth Koebele, Megan Konar, Frederik Kratzert, Sara Lindersson, Maria Carmen Llasat, Alessia Matanó, Maurizio Mazzoleni, Alfonso Mejia, Pablo Mendoza, Bruno Merz, Jenia Mukherjee, Farzin Nasiri Saleh, Bertil Nlend, Rodric Merime Nonki, Christina Orieschnig, Katerina Papagiannaki, Gopal Penny, Olga Petrucci, Rafael Pimentel, Sandra Pool,

Elena Ridolfi, Maria Rusca, Nivedita Sairam, Adarsh Sankaran Namboothiri, Ana Carolina Sarmiento Buarque, Elisa Savelli, Lukas Schoppa, Kai Schröter, Anna Scolobig, Mojtaba Shafiei, Anna E. Sikorska-Senoner, Magdalena Smigaj, Claudia Teutschbein, Thomas Thaler, Andrijana Todorovic, Faranak Tootoonchi, Roshanak Tootoonchi, Elena Toth, Ronald van Nooijen, Franciele Maria Vanelli, Nicolás Vásquez, David W. Walker, Marthe Wens, David J. Yu, Heidar Zarei, Changrang Zhou & Günter Blöschl (2025) *Panta Rhei: a decade of progress in research on change in hydrology and society*, *Hydrological Sciences Journal*, 70:7, 1210-1236, DOI: [10.1080/02626667.2025.2469762](https://doi.org/10.1080/02626667.2025.2469762)

To link to this article: <https://doi.org/10.1080/02626667.2025.2469762>



© 2025 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.



[View supplementary material](#)



Published online: 03 Apr 2025.



[Submit your article to this journal](#)



Article views: 4786



[View related articles](#)



[View Crossmark data](#)



Citing articles: 1 [View citing articles](#)

Panta Rhei: a decade of progress in research on change in hydrology and society

Heidi Kreibich ^{1a}, Murugesu Sivapalan ^{2b}, Amir AghaKouchak ^{3c}, Nans Addor ^{4d}, Hafzullah Aksoy ^{5e}, Berit Arheimer ^{6f}, Karsten Arnbjerg-Nielsen ^{7g}, Cynthia Vail-Castro ^{8h}, Christophe Cudenneq ⁹ⁱ, Mariana Madruga de Brito ^{10j}, Giuliano Di Baldassarre ^{11k}, David C. Finger ^{12l}, Keirnan Fowler ^{13m}, Wouter Knoben ¹⁴ⁿ, Tobias Krueger ^{15o}, Junguo Liu ^{16p}, Elena Macdonald ^{17q}, Hilary McMillan ^{18r}, E. Mario Mendiondo ^{19s}, Alberto Montanari ^{20t}, Marc F. Muller ^{21u}, Saket Pande ^{22v}, Fuqiang Tian ^{23w}, Alberto Viglione ^{24x}, Yongping Wei ^{25y}, Attilio Castellarin ^{26z}, Daniel Peter Loucks ^{27aa}, Taikan Oki ^{28ab}, María J. Polo ^{29ac}, Huub Savenije ^{30ad}, Anne F. Van Loon ^{31ae}, Ankit Agarwal ^{32af}, Camila Alvarez-Garretón ^{33ag}, Ana Andreu ^{34ah}, Marlies H. Barendrecht ^{35ai}, Manuela Brunner ^{36aj}, Louise Cavalcante ^{37ak}, Yonca Cavus ^{38al}, Serena Ceola ^{39am}, Pedro Chaffe ^{40an}, Xi Chen ^{41ao}, Gemma Coxon ^{42ap}, Zhao Dandan ^{43aq}, Kamran Davary ^{44ar}, Moctar Dembélé ^{45as}, Benjamin Dewals ^{46at}, Tatiana Frolova (Bibikova) ^{47au}, Animesh K. Gain ^{48av}, Alexander Gelfan ^{49aw}, Mohammad Ghoreishi ^{50ax}, Thomas Grabs ^{51ay}, Xiaoxiang Guan ^{52az}, David M. Hannah ^{53ba}, Joerg Helmschrot ^{54bb}, Britta Höllermann ^{55bc}, Jean Hounkè ^{56bd}, Elizabeth Koebele ^{57be}, Megan Konar ^{58bf}, Frederik Kratzert ^{59bg}, Sara Lindersson ^{60bh}, Maria Carmen Llasat ^{61bi}, Alessia Matanó ^{62bj}, Maurizio Mazzoleni ^{63bk}, Alfonso Mejia ^{64bl}, Pablo Mendoza ^{65bm}, Bruno Merz ^{66bn}, Jenia Mukherjee ^{67bo}, Farzin Nasiri Saleh ^{68bp}, Bertil Nlend ^{69bq}, Rodric Merime Nonki ^{70br}, Christina Orieschnig ^{71bs}, Katerina Papagiannaki ^{72bt}, Gopal Penny ^{73bu}, Olga Petrucci ^{74bv}, Rafael Pimentel ^{75bw}, Sandra Pool ^{76bx}, Elena Ridolfi ^{77by}, Maria Rusca ^{78bz}, Nivedita Sairam ^{79ca}, Adarsh Sankaran Namboothiri ^{80cb}, Ana Carolina Sarmiento Buarque ^{81cc}, Elisa Savelli ^{82cd}, Lukas Schoppa ^{83ce}, Kai Schröter ^{84cf}, Anna Scolobig ^{85cg}, Mojtaba Shafiei ^{86ch}, Anna E. Sikorska-Senoner ^{87ci}, Magdalena Smigaj ^{88cj}, Claudia Teutschbein ^{89ck}, Thomas Thaler ^{90cl}, Andrijana Todorovic ^{91cm}, Faranak Tootoonchi ^{92cn}, Roshanak Tootoonchi ^{93co}, Elena Toth ^{94cp}, Ronald van Nooijen ^{95cq}, Franciele Maria Vanelli ^{96cr}, Nicolás Vásquez ^{97cs}, David W. Walker ^{98ct}, Marthe Wens ^{99cu}, David J. Yu ^{100cv}, Heidar Zarei ^{101cw}, Changrang Zhou ^{102cx} and Günter Blöschl ^{103cy}

^aSection Hydrology, GFZ Helmholtz Centre for Geosciences, Potsdam, Germany; ^bThe Grainger College of Engineering, Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA; ^cDepartment of Civil and Environmental Engineering, University of California, Irvine, CA, USA; ^dFathom, Bristol, UK; and Geography, University of Exeter, Exeter, UK; ^eDepartment of Civil Engineering, Istanbul Technical University, Istanbul, Turkey; ^fHydrological Research, Swedish Meteorological and Hydrological Institute (SMHI), Norrköping, Sweden; ^gDanish Meteorological Institute, Copenhagen, Denmark; ^hResearch Applications Laboratory, NSF National Center for Atmospheric Research, Boulder, CO, USA; ⁱInstitut Agro, INRAE, SAS, Rennes, France; and Imperial College – CNRS International Research Center on Transformational Sciences and Technologies, London, UK; ^jDepartment of Urban and Environmental Sociology, Helmholtz Centre for Environmental Research (UFZ), Leipzig, Germany; ^kDepartment of Earth Sciences, Uppsala University, Uppsala, Sweden; ^lDepartment of Engineering, Reykjavik University, Reykjavik, Iceland; ^mUniversity of Melbourne, Melbourne, Australia; ⁿUniversity of Calgary, Calgary, AB, Canada; ^oGeography Department and IRI THESys, Humboldt-Universität zu Berlin, Berlin, Germany; ^pHenan Provincial Key Laboratory of Hydrosphere and Watershed Water Security, North China University of Water Resources and Electric Power, Zhengzhou, China; ^qDepartment of Geography, San Diego State University, San Diego, CA, USA; ^rSao Carlos School of Engineering, University of Sao Paulo, Sao Carlos-SP, Brazil; ^sDepartment of Civil, Chemical, Environmental, and Materials Engineering, Alma Mater Studiorm, Università di Bologna, Bologna, Italy; ^tEawag – Swiss Federal Institute of Aquatic Science and Technology, Dübendorf, Switzerland; ^uDelft University of Technology, Delft, Netherlands; ^vDepartment of Hydraulic Engineering and State Key Laboratory of Hydroscience and Engineering, Tsinghua University, Beijing, China; ^wDepartment of Environment, Land and Infrastructure Engineering, Politecnico di Torino, Torino, Italy; ^xThe University of Queensland, Brisbane, Australia; ^yCivil and Environmental Engineering, Cornell University, Ithaca, NY, USA; ^zGraduate School of Engineering, The University of Tokyo, Tokyo, Japan; ^{aa}Department of Agronomy, Unit of Excellence María de Maeztu (DAUCO), Fluvial Dynamics and Hydrology Research Group, Andalusian Institute for Earth System Research (IISTA), University of Córdoba, Córdoba, Spain; ^{bb}Institute for Environmental Studies (IVM), Vrije Universiteit Amsterdam, Amsterdam, Netherlands; ^{cc}Department of Hydrology, Indian Institute of Technology Roorkee, Roorkee, India; ^{dd}Center for Climate and Resilience Research (CR)2, University of Chile, Santiago, Chile; ^{ee}Department of Geography, King's College London, London, UK; ^{ff}Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland; and WSL Institute for Snow and Avalanche Research SLF, Davos Dorf, Switzerland; ^{gg}Wageningen University, Wageningen, Netherlands; ^{hh}Department of Civil Engineering, Istanbul Beykent University, Istanbul, Turkey; ⁱⁱDepartment of Sanitary and Environmental Engineering, Universidade Federal de Santa Catarina, Florianópolis, Brazil; ^{jj}Department of Geography and Geographic Information Science, University of Cincinnati, Cincinnati, OH, USA; ^{kk}University of Bristol, Bristol, UK; ^{ll}Institute of Surface–Earth System Science, School of Earth System Science, Tianjin University, Tianjin, China; ^{mm}Department of Water Engineering, Ferdowsi University of Mashhad, Mashhad, Iran; ⁿⁿInternational Water Management Institute (IWMI), Accra, Ghana; ^{oo}Urban and Environmental Engineering (UEE), University of Liège, Liège, Belgium; ^{pp}Institute of Geography RAS, Moscow, Russia; ^{qq}School of Environmental and Conservation Sciences, Murdoch University, Murdoch, Australia; ^{rr}Faculty of Geography, Lomonosov Moscow State University, Moscow, Russia; ^{ss}Global Institute for Water Security (GIWS), University of Saskatchewan, Saskatoon, Saskatchewan, Canada; ^{tt}Birmingham Institute for Sustainability and Climate Action, and School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham, UK; ^{uu}Stellenbosch University Water Institute, Stellenbosch, South Africa; ^{vv}Institute of

CONTACT Heidi Kreibich ✉ heidi.kreibich@gfz.de GFHelmholtz Centre for Geosciences, Section Hydrology, Telegrafenberg, Potsdam 14473, Germany
Supplemental data for this article can be accessed online at <https://doi.org/10.1080/02626667.2025.2469762>

© 2025 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.
This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. The terms on which this article has been published allow the posting of the Accepted Manuscript in a repository by the author(s) or with their consent.

Geography, Osnabrueck University, Osnabrück, Germany; ^{www}National Water Institute, University of Abomey Calavi, Abomey-Calavi, Benin; ^{xx}Department of Political Science, University of Nevada, Reno, NV, USA; ^{yy}Google Research, Vienna, Austria; ^{zz}University of Barcelona, Barcelona, Spain; ^{aaa}Department of Civil and Environmental Engineering, The Pennsylvania State University, State College, PA, USA; ^{bbb}Department of Civil Engineering, Universidad de Chile, Santiago, Chile; ^{ccc}Department of Humanities and Social Sciences, Indian Institute of Technology Kharagpur, Kharagpur, India; ^{ddd}Department of Water Engineering, Faculty of Civil and Environmental Engineering, Tarbiat Modares University, Tehran, Iran; ^{eee}University of Douala, Douala, Cameroon; ^{fff}Laboratory for Environmental Modeling and Atmospheric Physics (LEMAP), University of Yaounde 1, Yaounde, Cameroon; ^{ggg}UMR G-EAU, IRD, Montpellier, France; ^{hhh}National Observatory of Athens, Institute for Environmental Research and Sustainable Development, Athens, Greece; ⁱⁱⁱEnvironmental Defense Fund, San Francisco, CA, USA; ^{jjj}CNR-IRPI-Research Institute for Geo-Hydrological Protection, CNR (Italian National Research Council), Cosenza, Italy; ^{kkk}Department of Civil, Constructional and Environmental Engineering, Sapienza Università di Roma, Rome, Italy; ^{lll}University of Manchester, Manchester UK; ^{mmm}Department of Civil Engineering, TKM College of Engineering, Kollam, India; ⁿⁿⁿUniversidade de Sao Paulo, Sao Paulo, Brazil; ^{ooo}Middle East North Africa and Europe Regional Hub, Mercy Corps, Portland, OR, USA; ^{ppp}Leichtweiß-Institute for Hydraulic Engineering and Water Resources, Division Hydrology and River Basin Management, Technische Universität Braunschweig, Braunschweig, Germany; ^{qqq}Institute for Environmental Sciences, University of Geneva, Geneva, Switzerland; ^{rrr}Division of Environment and Natural Resources, Norwegian Institute of Bioeconomy Research (NIBIO), Aas, Norway; ^{sss}Federal Office of Meteorology and Climatology MeteoSwiss, Zurich-Airport, Switzerland; and Center for Climate Systems Modeling C2SM, ETH Zurich, Zurich, Switzerland; ^{ttt}Institute of Landscape Planning, BOKU University, Vienna, Austria; ^{uuu}Faculty of Civil Engineering, Institute for Hydraulic and Environmental Engineering, University of Belgrade, Belgrade, Serbia; ^{vvv}Department of Crop Production Ecology, Swedish University of Agricultural Sciences (SLU), Uppsala, Sweden; ^{www}Department of Civil, Environmental and Mechanical Engineering, University of Trento, Trento, Italy; ^{xxx}Independent researcher, Joinville, Brazil; ^{yyy}Lyles School of Civil and Construction Engineering; Department of Political Science, Purdue University, West Lafayette, IN, USA; ^{zzz}Department of Hydrology and Water Resources, Shahid Chamran University of Ahvaz, Ahvaz, Iran; ^{aaaa}Institute of Hydraulic Engineering and Water Resources Management, Vienna University of Technology, Vienna, Austria; ^{bbbb}Advanced Mining Technology Center (AMTC), Universidad de Chile, Santiago, Chile; ^{cccc}Institute for Environmental Sciences and Geography, University of Potsdam, Potsdam, Germany

ABSTRACT

To better understand the increasing human impact on the water cycle and the feedbacks between hydrology and society, the International Association of Hydrological Sciences (IAHS) organized the scientific decade “Panta Rhei – Everything Flows: Change in hydrology and society” (2013–2022). A key finding is the need to use integrated approaches to assess the co-evolution of human–water systems in order to avoid unintended consequences of human interventions over long periods of time. Additionally, substantial progress has been made in leveraging new data sources on human behaviour, e.g. through text mining of social media posts. Much has been learned about detecting hydrological changes and attributing them to their drivers, e.g. quantifying climate effects on floods. To achieve further progress, we recommend broadening the understanding, the discipline and training activities, while at the same time pursuing synthesis by focusing on key themes, developing innovative approaches and finding sustainable solutions to the world’s water problems.

ARTICLE HISTORY

Received 10 July 2024
Accepted 31 January 2025

EDITOR

A. Fiori

ASSOCIATE EDITOR

(not assigned)

KEYWORDS

socio-hydrology; predictions under change; integrated water resources management; human–water feedbacks; change

1 Introduction

The feedbacks between hydrology and society have accelerated in recent decades, highlighting the need for the hydrological community to better understand the interactions between these systems (Montanari *et al.* 2013, Brondizio *et al.* 2016). Climate change, land use and socio-economic changes significantly alter the water cycle, leading to changes in water availability, quality and distribution, and related hazards. For instance, flood and drought impacts have already significantly increased in many regions and are expected to increase further (IPCC 2012, 2022). Freshwater scarcity is becoming a major limiting factor for societal development and security (United Nations 2018, GCEW 2023). Thus, it is important to understand, assess, predict and manage these accelerating changes in order to mitigate their adverse impacts and to ensure sustainability (Montanari *et al.* 2013, Ceola *et al.* 2016, McMillan *et al.* 2016, Di Baldassarre *et al.* 2019). This review aims to present key scientific advances on change in hydrology and society, with a focus on the feedbacks between humans and water, particularly over decadal to centennial time scales.

1.1 The IAHS scientific decade: Panta Rhei – Everything Flows: Change in hydrology and society

The overall aim of the International Association of Hydrological Sciences (IAHS) science decades is to coordinate efforts in order to accelerate research progress on a particular hydrological problem. The success of the scientific decades PUB – Predictions in Ungauged Basins 2003–2012 and Panta Rhei – Everything Flows: Change in hydrology and society 2013–2022 led to the current scientific decade, “Science for solutions: Hydrology Engaging Local People IN one Global world (HELPING),” 2023–2032 (Arheimer *et al.* 2024). At the close of the PUB scientific decade (Blöschl *et al.* 2013, Hrachowitz *et al.* 2013), the IAHS community started a global discussion to identify the most relevant societal challenges to shape the next IAHS scientific decade. The discussions on a blog, which attracted thousands of visits and many comments, converged on the understanding that “change” was the keyword for hydrological sciences in the 21st century and that a broad perspective on global change is necessary. The new decade should highlight the key role of hydrology in predicting future trends of environmental dynamics shaped by human–water feedbacks (Montanari *et al.* 2013).



Figure 1. Links and cooperation between the Pantar Rhei working groups and the IAHS commissions. International Commission on Snow and Ice Hydrology (ICSIH), International Commission on Continental Erosion (ICCE), International Commission on Groundwater (ICGW), International Commission on Tracers (ICT), International Commission on Coupled Land-Atmosphere Systems (ICCLAS), International Commission on Statistical Hydrology (ICSH), International Commission on Water Quality (ICWQ), International Commission on Remote Sensing (ICRS), International Commission on Surface Water (ICSW), International Commission on Water Resources Systems (ICWRS).

To emphasize the focus on change, this decade was called “Pantar Rhei – Everything Flows: Change in hydrology and society” after the aphorism attributed to the Greek philosopher Heraclitus of Ephesus, which conveys the idea that nature and societies are continuously changing. Supporting a community-based bottom-up organization, an open call for Working Groups (WGs) was issued, which resulted in over 30 groups that initiated joint studies, scientific papers, conference sessions and workshops within the frame of the IAHS scientific decade. An overview of the Pantar Rhei working groups and their cooperation with IAHS commissions (Fig. 1) emphasizes the variety of scientific challenges being addressed and the diversity of approaches to solving them.

During the decade, the substantial increase in the network of hydrologists and scientists in a range of disciplines, including social sciences, stimulated large-scale cooperation based on the exchange of knowledge and data, which was supported

by the emergence of the open science paradigm (UNESCO (United Nations Educational Scientific and Cultural Organization) 2021; Cudennec *et al.* 2022b, Hall *et al.* 2022). Examples are the Pantar Rhei opinion paper series in the *Hydrological Sciences Journal* (Kreibich *et al.* 2017) and the international collaborative effort to collect and analyse the Pantar Rhei benchmark dataset of paired events of floods and droughts, to which more than 90 scientists contributed (Kreibich *et al.* 2022b, 2023). Remarkable progress in understanding interconnected change in hydrology and society has also been made due to relevant research projects and programmes supported by governmental agencies and funding organizations. Furthermore, the long-term partnership of IAHS with several agencies of the United Nations (UN) and the UN Water coordination mechanism allowed strong synergies with, and scientific inputs to, multilateral efforts, including the implementation of Sustainable Development

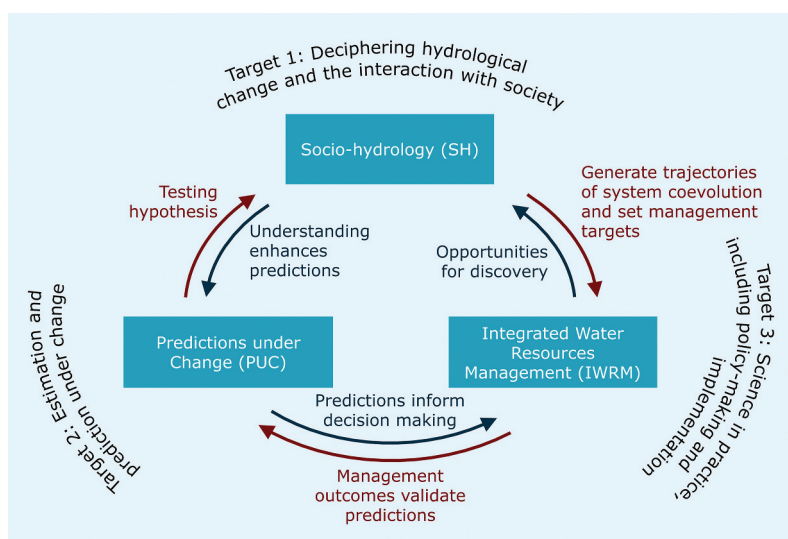


Figure 2. Panta Rhei research encompasses three domains – socio-hydrology (SH), predictions under change (PUC), and integrated water resources management (IWRM) – to achieve its three targets (figure adapted from Montanari *et al.* 2013, Thompson *et al.* 2013).

Goal (SDG) 6: “Clean Water and Sanitation” and interlinkages within Agenda 2030 (e.g. Young *et al.* 2015, Cudennec *et al.* 2020, 2022a, Mahé *et al.* 2021, Dixon *et al.* 2022, ISC 2023).

1.2 The three domains of Panta Rhei research

The Science Plan of Panta Rhei organized the scientific work around three targets and six science questions (Montanari *et al.* 2013). The three targets are closely related to the three domains: (1) socio-hydrology (Target 1), (2) predictions under change (Target 2), and (3) integrated water resources management (IWRM, Target 3), as Panta Rhei aimed to bridge past developments with new opportunities (Fig. 2).

The domain of socio-hydrology attempts to understand the complex interactions and feedbacks between human and water systems (Sivapalan *et al.* 2012). It contributes to deciphering hydrological change and its interaction with societies (Target 1 in Montanari *et al.* 2013). The innovation of socio-hydrological research is to model the co-evolution of human–water systems with an integrated approach to better understand the above-mentioned feedbacks and unintended consequences of human interventions over long periods of time. Along with empirical research across scales and places, stylized models based on differential equations are promising tools that can help explore socio-hydrological dynamics and contribute to theory development (Di Baldassarre *et al.* 2015). In addition, socio-hydrology draws on tools developed in research on socio-ecological and complex systems to expand socio-hydrological knowledge (Troy *et al.* 2015). With these tools, however, predictability is debatable in view of the contingent nature of some environmental and societal processes, as well as the importance of retroactive loops and the possible presence of tipping points (Sivapalan and Blöschl 2015, Bai *et al.* 2016). The goal is, rather, the projection of alternative, plausible and co-evolving trajectories of the socio-hydrological system, which may help stakeholders identify safe or desirable

operating spaces (Srinivasan *et al.* 2017a). As such, socio-hydrology aims to be a use-inspired science to inform the complex water sustainability challenges faced in the Anthropocene (Sivapalan *et al.* 2014, Sivapalan and Blöschl 2015, Di Baldassarre *et al.* 2019) and be applied to policy-making (Troy *et al.* 2015).

The domain of predictions under change aims to understand and model changes in hydrological systems in response to various environmental and human-induced drivers. It improves the estimation and prediction of hydrological processes under change, including design variables for flood and drought risk mitigation (Target 2 in Montanari *et al.* 2013). The drivers of change include climate change, river regulation, land use change, water abstraction or storage, and others (e.g. Milly *et al.* 2008). Detection and attribution of past changes help to understand trends (IPCC 2022). While detection demonstrates that a change has been observed and is statistically significantly different from what can be explained by natural variability, attribution associates detected changes with the corresponding drivers and rules out alternative explanations that are not causally associated with observed outcomes (Merz *et al.* 2012). On this basis, models and methods are developed to predict future changes in hydrological systems under changing conditions, supporting decision making in the management and planning of water resources.

The domain of integrated water resources management (IWRM) is a holistic approach to managing water resources that considers the multiple uses and users of water within a given area (Biswas 2004, Uysal *et al.* 2024). It has high societal relevance and, therefore, aims for iterative exchanges among science, technology, and societies. It brings science into practice, including policymaking and implementation (Target 3 in Montanari *et al.* 2013). IWRM aims to ensure that water resources are managed in an equitable, sustainable and efficient manner that considers both social and environmental aspects. Key principles of IWRM include a focus on basin-

Table 1. Organization of this review along the Panta Rhei science questions (Montanari *et al.* 2013).

Panta Rhei Science Questions (Montanari <i>et al.</i> 2013)	Sections of review
How can we advance our monitoring and data analysis capabilities to predict and manage hydrological change?	2. Monitoring and data analysis
What are the external drivers and internal system properties of change? How can boundary conditions be defined for the future?	3. Drivers of change
How do changes in hydrological systems interact with, and feedback to, natural and social systems driven by hydrological processes? What are the boundaries of coupled hydrological and societal systems?	4. Understanding socio-hydrological systems
How can we use improved knowledge of coupled hydrological–social systems to improve model predictions, including estimation of predictive uncertainty and assessment of predictability?	5. Modelling and prediction
How can we support societies to adapt to changing conditions by considering the uncertainties and feedbacks between natural and human-induced hydrological changes?	6. Water management and adaptation to change
What are the key gaps in our understanding of hydrological change?	7. Summary of achievements 8. Recommendations

level planning, stakeholder participation, the integration of water management across different sectors, and the consideration of social, economic, and environmental factors. The approach also emphasizes the need for adaptive management, which involves continuously monitoring and assessing water resources, and adapting management strategies as needed to meet changing conditions (Medema *et al.* 2008, Kreibich *et al.* 2014).

This review is organized along the Panta Rhei science questions (Montanari *et al.* 2013), as shown in Table 1. The aim is to present scientific progress and to illustrate it using specific research findings from the scientific decade.

As a basis for this review, a collection of 351 key scientific papers that contribute to answering these science questions was compiled (see Supplementary material). The spreadsheet for the collection of key papers (see Supplementary material) has been made publicly available and the authors of the present article have each contributed up to five key papers. The collection also contains a brief summary of the most important results and scientific advances for each paper, as well as information on which of the scientific questions of Panta Rhei the paper contributes to answering (see Supplementary material). With 58 to 89 papers per question, i.e. with shares between 17% and 25%, the distribution of papers among the questions to be answered is fairly even. This collection demonstrates the recent progress by many experts in the field of change in hydrology and society worldwide.

2 Scientific progress on monitoring and data analysis

Improving our understanding of the long-term co-evolution of hydrological systems has required associating geophysical and anthropogenic processes that have historically been observed at disparate temporal, spatial, and social scales. Improving data interoperability and accessibility to enable interdisciplinary

research was therefore an essential component of the Panta Rhei scientific decade. Many initiatives and approaches have improved data accessibility, discovered new, unconventional data, developed innovative approaches to data integration and analyses, and used citizen science, thus contributing to answering the science question “How can we advance our monitoring and data analysis capabilities to predict and manage hydrological change?” The Panta Rhei collection of key scientific papers contains 58 papers (17%) that contribute to answering this question (see Supplementary material).

2.1 Improved data accessibility

Over the past decade there have been major innovations in data collection, in the combination of disparate data into easy-to-use large-sample datasets, and in data sharing and open-access initiatives that improved the accessibility of hydrological and socio-economic data. For instance, flow monitoring at thousands of stations over decades has been the basis for detecting changes in high flows and seasonality that were attributed to climate change across Europe (Hall *et al.* 2014, Blöschl *et al.* 2019b) and globally (Wang *et al.* 2024). New data have enabled advances in detecting human influence on river flow, for instance by showing that water abstractions aggravate droughts (Van Loon *et al.* 2022) and must be taken into account to successfully predict the baseflow index (Bloomfield *et al.* 2021). Analysis of paired events identified improved governance and high investment in integrated risk management as success factors in managing unprecedented flood and drought events (Kreibich *et al.* 2019, 2022b). Newly released global datasets, such as freshwater withdrawal and consumption rates, enabled Huggins *et al.* (2022) to map socio-ecological vulnerability to freshwater stress and storage loss and identify hotspots for prioritizing interventions such as IWRM practices.

Considerable effort has been spent on making data more accessible and useful via collation across locations and domains (Gupta *et al.* 2014). For example, the Catchment Attributes and Meteorology for Large-sample Studies (CAMELS), Caravan and EStreams datasets combine daily hydro-meteorological time series with landscape attributes (e.g. reservoir type and capacity, water abstraction and return, consumptive water use, and surface and groundwater rights) for more than 20 000 catchments in over 35 countries (Newman *et al.* 2015, Addor *et al.* 2017, Alvarez-Garreton *et al.* 2018, Chagas *et al.* 2020, Coxon *et al.* 2020, Fowler *et al.* 2021, Höge *et al.* 2023, Kratzert *et al.* 2023, Do Nascimento *et al.* 2024). These datasets have been instrumental in demonstrating that wastewater discharges dominate urban hydrology signals across England and Wales (Coxon *et al.* 2024), that water uses exacerbated hydrological drought conditions during the megadrought in central Chile after 2010 (Álamos *et al.* 2024) and that stream water losses are higher in areas of extensive groundwater pumping (Uchôa *et al.* 2024). Other studies target specific environments that are sensitive to change, such as high-mountain snow cover in semi-arid regions (Polo *et al.* 2019); or focus on anthropogenic processes, e.g. storage and release policies for approximately 2000 reservoirs in the US (Turner *et al.* 2021).

Important progress has been made in the last decade through the structured documentation of extreme events and the recording of their impacts in databases (De Groeve *et al.* 2014, Rudari *et al.* 2017). Examples include flood fatality data across 12 territories in Europe and its surroundings (Papagiannaki *et al.* 2022), drought impact data extracted from nearly 5000 reports (Stahl *et al.* 2016), and object-specific flood damage data from fluvial, pluvial and groundwater flooding stored in the Flood Damage Database HOWAS 21 (Kellermann *et al.* 2020).

2.2 New, unconventional data

The increasing availability and volume of digital data have also opened up new opportunities for the prediction and management of hydrological change by including unstructured and qualitative data types in the research design. For example, analysing the minutes of water board committee meetings, Carvalho *et al.* (2024) found that water allocation decisions were increasingly based on seasonal forecasts and data on oceanic indices in Northeast Brazil from 1997 to 2021. An analysis of the number of news articles published about drought revealed that single-family customers reduced their water consumption most quickly following heavy drought-related news coverage (Quesnel and Ajami 2017, Roby *et al.* 2018). Web-scraping and text mining have made social media popular for analysing public opinion on extreme events (Cervone *et al.* 2016, Kryvasheyev *et al.* 2016, Smith *et al.* 2017), improving flood mapping (Fohringer *et al.* 2015, Scotti *et al.* 2020), and monitoring the occurrence of disasters (Kryvasheyev *et al.* 2016). Data collected through car navigation apps such as Waze or Mapbox have been shown to be powerful in estimating the extent of traffic impacts due to flooding (Praharaaj *et al.* 2021, Safaei-Moghadam *et al.* 2023), as well as anomalies in human activity (Farahmand *et al.* 2022). Similarly, Google Trends has emerged as a way to measure public awareness regarding drought (Kam *et al.* 2019, Kim *et al.* 2019, Alencar *et al.* 2024), track flood disasters (Thompson *et al.* 2021), and understand the dynamic social response to past droughts (Gonzales and Ajami 2017).

Earth observation products have become common for assessing key environmental variables at large scale, such as Landsat data employed for surface water dynamics (Pekel *et al.* 2016), Gravity Recovery and Climate Experiment (GRACE) data used for terrestrial water storage evolution (Chen and Rodell 2021, Kvas *et al.* 2024), and the Surface Water and Ocean Topography (SWOT) mission aimed at monitoring river hydraulic properties (Frasson *et al.* 2019). Local-scale monitoring has recently been fostered by low-cost innovative wireless sensor networks (WSN), employed for example in the meteorological, hydrological, agricultural, water management and services sectors (Ojha *et al.* 2015, Marais *et al.* 2016, Pimentel *et al.* 2017, Tauro *et al.* 2018, Bárdossy *et al.* 2021).

2.3 Data integration and machine learning

The combination of datasets with both process-based modelling and machine learning (ML) approaches can be integrated in tools that decision makers can use to investigate the long-term effects of their management decisions (Xia *et al.* 2021).

Furthermore, alongside large-scale or large-sample efforts, there are bespoke small-scale efforts to harness local hydrological understanding for improved social outcomes. For example, Hund *et al.* (2018) developed a data-based drought early warning system for communities dependent on an aquifer in Costa Rica, with predictions based on the local understanding of what climatic conditions typically lead to drought-induced hardship.

Interdisciplinary perspectives that integrate qualitative and quantitative data are needed to understand complex human-water systems (Di Baldassarre *et al.* 2021, Rangelcroft *et al.* 2021, Vanelli *et al.* 2022). While quantitative data allow researchers to identify generalizable patterns and dynamics, qualitative data provide insights into the socio-political drivers of water management through detailed analyses of local contexts (Riedlinger and Berkes 2001, Ruska and Di Baldassarre 2019, Alexander *et al.* 2020). Several innovative approaches have been developed that combine qualitative and quantitative data in a meaningful way, in particular for nexus studies (Liu *et al.* 2017a, Cudennec *et al.* 2018, Heal *et al.* 2022). Another example is provided by Ferdous *et al.* (2018), who triangulated quantitative data from household surveys and qualitative data from focus group discussions in a socio-hydrological study. Sarmiento Buarque *et al.* (2020) present a sequential mixed design, where a modelling-based quantitative analysis was supported by qualitative data obtained from newspapers and photographs. Van Loon *et al.* (2015) analysed quantitative and qualitative data in an iterative manner to investigate the frequency of occurrence of different drought types in cold climates.

With the increasing accessibility of big data from diverse data sources, artificial intelligence (AI) and ML approaches are increasingly used to overcome the challenges posed by the high complexity, non-linearity, and non-stationarity of change in hydrology and society (Kratzert *et al.* 2019, Ke *et al.* 2020, Mao *et al.* 2021, Yu *et al.* 2023). For instance, ML is used to automatically label built-up areas based on night-time lights or buildings and map roads using aerial or satellite imagery (Alshehhi and Marpu 2017, Jia *et al.* 2022). Other examples include real-time identification or mapping of floods based on social media posts (Annis and Nardi 2019), and analyses of flood damage processes using decision tree or Bayesian approaches (Carisi *et al.*, 2018, Schoppa *et al.* 2020, Paprotny *et al.* 2021). Human perceptions and decisions were assessed based on insurance uptake using interpretable ML (Knighton *et al.* 2021, Veigel *et al.* 2023).

2.4 Citizen science

Citizen science and related data acquisition techniques such as volunteered geographic information (VGI), participatory tools and crowdsourcing have emerged to complement observations, raise awareness, promote innovative thinking, and encourage scientist–citizen cooperation in addressing water management issues (Woolley *et al.* 2010, Buytaert *et al.* 2014). Citizen science and related methods have a significant role in improving community sensitivity and engagement with water-related issues. Through citizen science initiatives, people can actively participate in data collection, analysis, and interpretation, promoting universal and equitable access to scientific data and information (de

Sherbinin *et al.* 2021). Additionally, citizen science projects can have educational and outreach aspects, promoting awareness and understanding of water issues among the broader public, and even increasing citizen engagement in local governance processes (Nardi *et al.* 2022).

Citizen science has gained increasing prominence in hydrology, addressing the need for more dispersed and diverse observations of multiple water-related variables (Nardi *et al.* 2022) and is used to collect large amounts of data over wide areas (Buytaert *et al.* 2014, Walker *et al.* 2021). It additionally enables the observation of social, economic, educational, and behavioural dynamics that are difficult to capture (Jollymore *et al.* 2017).

Applications of citizen science in hydrology can range from local-scale studies involving a single volunteer to global-scale studies involving tens of thousands of volunteers (Walker *et al.* 2021). Examples of data commonly acquired include water levels (Lowry and Fienen 2013, Jan *et al.* 2019), water quality (Rangecroft *et al.* 2023, 2024), building footprints obtained from OpenStreetMap (Cerri *et al.* 2021), and meteorological observations (“Met Office WOW – Home Page” n.d.). Comprehensive overviews of citizen science projects in the field of hydrology are provided by Buytaert *et al.* (2014), Anna *et al.* (2019), Njue *et al.* (2019), See (2019), Kelly-Quinn *et al.* (2022), and Nath and Kirschke (2023).

Summary on monitoring and data analysis: Our monitoring and data analysis capabilities to predict and manage hydrological change have advanced significantly: (1) Accessibility and usefulness of (time series) data has increased by sharing and combining data across locations and domains, including quantified human impacts. Examples are the CAMELS datasets (e.g. Alvarez-Garreton *et al.* 2018, Fowler *et al.* 2021, Höge *et al.* 2023), Panta Rhei benchmark datasets (e.g. Kreibich *et al.* 2023) and impact datasets (e.g. Stahl *et al.* 2016, Papagiannaki *et al.* 2022). (2) Repurposing and combining of data and increased exploration of new, unconventional data sources such as social media, novel sensors (e.g. Fohringer *et al.* 2015, Kryvasheyev *et al.* 2016, Scotti *et al.* 2020) and new methods of analysis such as machine learning and text mining (e.g. Knighton *et al.* 2021, Paprotny *et al.* 2021, Veigel *et al.* 2023) have increased the availability and potential of qualitative and quantitative data. (3) Advancements in citizen science have demonstrated its value in monitoring various processes, promoting community engagement and supporting education in hydrology (e.g. Jollymore *et al.* 2017, Nardi *et al.* 2022).

3 Scientific progress on drivers of change

The pace and scope of change of hydrological systems has accelerated, and with them the risks to society and the environment. This has also increased the importance of assessing the drivers of change. Effects of climate, land use and socio-economic changes on freshwater quantity and quality trends were frequently assessed, and new approaches for attribution were developed to answer the following scientific questions: “What are the external drivers and internal system properties of change? How can boundary conditions be defined for the future?” The Panta Rhei collection of key scientific papers contains 67 papers (19%) that contribute to answering these questions (see Supplemental material).

3.1 Climate change

Climate change is expected to significantly influence the water cycle, through changes in the global atmospheric circulation and the larger water-holding capacity of a warmer atmosphere. Using 7250 observations around the world covering the years 1971–2010, Gudmundsson *et al.* (2021) found evidence for the role of anthropogenic climate change as a causal driver of recent trends in river flow. Wang *et al.* (2024) detected a clear trend of weakening seasonality in river flow in high-latitude regions of the Northern Hemisphere, which is closely linked to anthropogenic climate change. Yang *et al.* (2021) showed that, at a global scale, long-term annual streamflow has remained stationary in 79% of catchments with minimal human disturbance, while the percentage is only 38% for those catchments where substantial human interventions have occurred.

Climate change and human behaviour also jointly drive changes in hydrological extremes and exacerbate their effects (Arheimer *et al.* 2017, Caretta *et al.* 2022, Chagas *et al.* 2022). Based on a meta-analysis, Merz *et al.* (2021) found that in more than half of catchments worldwide, floods have increased in recent decades. River floods in Europe have increased in magnitude in the northwest and decreased in the south and east in the last 60 years (Blöschl *et al.* 2019b, Bertola *et al.* 2020). Changing seasonality of floods has been detected, more clearly than for their magnitudes (Blöschl *et al.* (2017) for Europe, Collins (2019) for the US, Chagas *et al.* (2022) for Brazil). These studies usually consider river flooding, but flash flooding is also expected to increase due to increased atmospheric convection in a warmer climate (Llasat *et al.* 2016, Huang *et al.* 2022).

Changes in drought frequency and severity have been detected with various confidence levels depending on the drought type (Van Loon 2015). While meteorological droughts have increased in a few regions of Africa and South America, socio-hydrological droughts have increased in megacities (Souza *et al.* 2022) and agricultural (soil-moisture) droughts have increased in several regions on all continents (IPCC 2022). Brunner *et al.* (2023) find that high-elevation catchments in the Alps have experienced a stronger change in drought type (from rainfall-driven to temperature-driven) and drought severity (shorter and higher deficit) than low-elevation catchments. Brunner and Tallaksen (2019) found that four regions in Europe, i.e. southeast England, southeast France, central Norway, and the Pre-Alpine area, may become more affected by multi-year droughts in the future as streamflow becomes less snow influenced. The increasing trend in drought severity in the Po River basin (Italy) was found to be mainly driven by the type and seasonality of precipitation, rather than its total amount, and the expansion of irrigated areas (Montanari *et al.* 2023).

3.2 Land use and socio-economic change

Land use changes such as deforestation and urbanization have often caused increased surface runoff and a decreased baseflow (Levy *et al.* 2018, Müller *et al.* 2021). This effect, along with the regulation of river flows, e.g. for hydropower production,

industrial use or flood protection, has substantially affected discharge regimes in many parts of the world (Vorogushyn and Merz 2013, Wang *et al.* 2017, Arheimer and Lindström 2019, Shrestha *et al.* 2022).

Considering the combined effects of anthropogenic alterations to natural water streams and changing climate has resulted in a new framework of droughts, that defines anthropogenic drought as a compound multidimensional and multi-scale phenomenon (AghaKouchak *et al.* 2015, Van Loon *et al.* 2016). Anthropogenic droughts are governed by the combination of natural water variability, climate change, human decisions and activities, and altered micro-climatic conditions due to changes in land and water management (AghaKouchak *et al.* 2021). Human activities have a major impact on hydrological droughts as well, in some cases exacerbating the effects of climate change, despite management efforts (Van Loon *et al.* 2022). Alborzi *et al.* (2018) report on the combined effects of meteorological drought and unsustainable water resource management, which contributed to the rapid shrinkage of Lake Urmia in Iran, after it had reached a tipping point. Van Oel *et al.* (2018) document the exacerbating effect of reservoir operations on downstream hydrological drought in a river basin in Brazil, while a continental-scale study in the US shows that reservoirs can also alleviate drought severity in many instances (Brunner 2021). Increasing water demand and decreasing surface water availability are frequent causes of groundwater overexploitation (Nlend *et al.* 2018). Declining groundwater resources are exacerbated by misaligned incentives associated with the common-pool nature of the resource (Mullen *et al.* 2022).

Flood impacts are also strongly influenced by changes in land use and socio-economic processes, next to atmospheric drivers (Formetta and Feyen 2019, Merz *et al.* 2021). Shifts in socio-economic systems foster human encroachment into floodplains and increase flood exposure. Thus, increasing exposure was the main driver of the increase in flood losses during recent decades, in Europe (Stevens *et al.* 2016, Paprotny *et al.* 2018) and elsewhere (Tanoue *et al.* 2016, McAneney *et al.* 2019). It is expected that future flood impacts will continue to increase (Rojas *et al.* 2013, Dottori *et al.* 2018), due to a combination of changes in hazard, exposure and vulnerability (Rojas *et al.* 2013, Vousdoukas *et al.* 2018, Steinhilber *et al.* 2022, Schoppa *et al.* 2024). Sauer *et al.* (2021) quantified hazard, exposure and vulnerability changes for flood events globally, finding that for Europe the increase in flood losses was driven almost entirely by exposure, with some small decline in hazard and vulnerability.

3.3 Changes in water quality

Climate change in terms of rising temperatures, changes in precipitation patterns, and extreme weather events have affected the water cycle, also leading to changes in water quality (e.g. Meier *et al.* 2014, Bartosova *et al.* 2019). In coastal areas, sea level rise, storm surges, drought, land subsidence and erosion were reported to affect salinity and water quality in soils, estuaries and aquifers (Dasgupta *et al.* 2015, Jasechko *et al.* 2020, Phlips *et al.* 2020). Water scarcity also impacts water

quality, as pollution is more concentrated, so that recent scientific advances have been in the direction of quality-related and ecological water scarcity (Liu *et al.* 2016, 2022). Integrated assessments of water quality, quantity, and environmental flows have been widely applied at global, national, and local levels (Liu *et al.* 2017b, van Vliet *et al.* 2017, Ma *et al.* 2020).

Urbanization and changes in land use have resulted in increased impervious surfaces, such as roads, which can lead to higher levels of pollutants, e.g. nutrients and chemicals being washed into water bodies (Dailey *et al.* 2014). Diffuse pollution that remains in the environment for a very long time makes it challenging to achieve water quality goals (Van Meter *et al.* 2018). In particular, new science questions on the use, fate and impacts of persistent anthropogenic chemicals, such as PFAS (Ackerman Grunfeld *et al.* 2024) and microplastics (Eerkes-Medrano *et al.* 2015), were raised during the Panta Rhei scientific decade.

At the same time, traditional water-quality problems due to agricultural activities have not yet been solved, e.g. the use of fertilizers and animal waste that result in nutrient runoff and contamination of water bodies, leading to eutrophication (Finger *et al.* 2013) and intensive irrigation that increases salinity in downstream water bodies (Thorslund *et al.* 2021). Direct implications for human health are expected from industrial discharges, including the release of pollutants and chemicals that contaminate water sources (Ma *et al.* 2020), and mobilization of geogenic contaminants (e.g. arsenic) due to groundwater overuse (Erban *et al.* 2013).

Addressing these complex and interlinked water quality challenges requires a holistic approach that includes sustainable water management, land use planning, pollution control and public awareness (Hipsey and Arheimer 2013, Rahman *et al.* 2019). Modelling was found to be instrumental in planning remedial measures at the catchment scale (Arheimer *et al.* 2015) and regionally (Bartosova *et al.* 2021). Nature-based solutions have proven to be efficient in addressing some of these challenges (Huang *et al.* 2020, Oral *et al.* 2021, Carvalho *et al.* 2022) although their effect at large scale has been questioned, e.g. regarding wetland constructions for nutrient reduction (Arheimer and Pers 2017). Technological advances have contributed to significantly improve both detection and treatment of water contaminants. Stricter environmental policies, regulations and standards are needed to reduce pollution, by improving wastewater treatment, reducing the impact of agricultural practices, and managing landscapes (Hanrahan *et al.* 2018, Cheng *et al.* 2022, Penny *et al.* 2022).

3.4 Methodological advancements in the attribution of change

Hydrological systems are spatially heterogeneous and tightly coupled with human and ecological systems at a variety of spatial and temporal scales (Kingston *et al.* 2020, Bertassello *et al.* 2021). Studying changes in these human–water systems requires addressing the twin challenges of detection and attribution. Detecting hydrological change implies distinguishing persistent changes in hydrological outcomes from the effects of stationary but long-memory climate variability

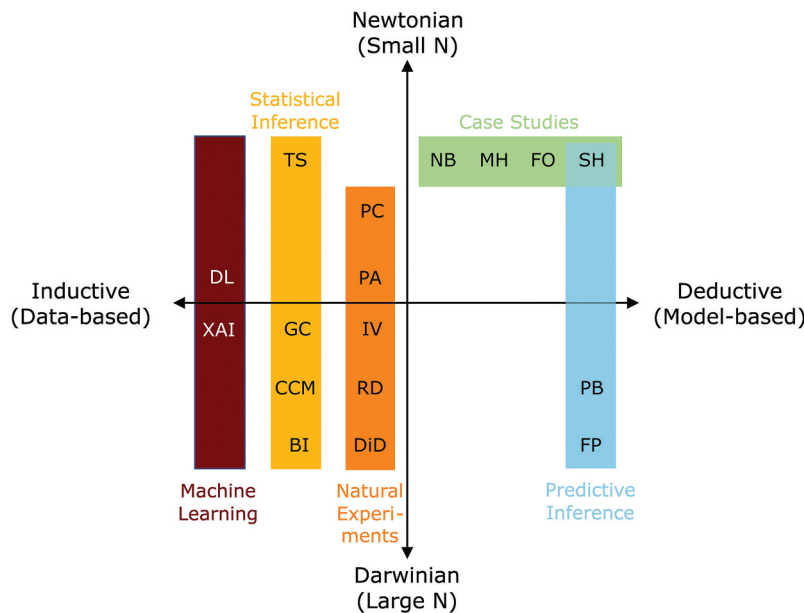


Figure 3. Approximative typology of attribution approaches: DL (diagnostic learning), XAI (explainable artificial intelligence), TS (time series analysis), GC (Granger causality analysis), CCM (convergent cross-mapping), BI (Bayesian inference), PC (paired catchments), PA (panel analysis), IV (instrumental variable), RD (regression discontinuity), DiD (difference-in-difference), NB (narrative-based analysis), MH (multiple hypotheses), FO (field observation), SH (socio-hydrological modelling), PB (process-based or physical modelling), FP (fingerprinting).

and random observation errors (Hall *et al.* 2014, Koutsoyiannis and Montanari 2015, Milly *et al.* 2015, Serinaldi and Kilsby 2015, Yang *et al.* 2019, Villarini and Wasko 2021). Much methodological development during the *Panta Rhei* decade has focused on addressing the second challenge of attribution, which investigates the causal relationship between changes and their hypothesized drivers (Merz *et al.* 2012). Elucidating such causal relationships is necessary to improve predictions (Srinivasan *et al.* 2017a, Müller and Levy 2019) and to develop and evaluate policies to avert or mitigate these changes (Thompson *et al.* 2013). This subsection discusses current attribution approaches with regard to their deductive (model-based) vs. inductive (data-based) nature and their focus on internal “Newtonian” (small sample size) vs. external “Darwinian” (large sample size) variability (Fig. 3).

Deductive process-based models are developed, calibrated and validated to test causal hypotheses about the key physical processes assumed to govern hydrological dynamics (Ferraro *et al.* 2019), such as hydroclimatic change (Chiang *et al.* 2021), changes in streamflow (Hundecha and Merz 2012, Duethmann *et al.* 2015, Badjana *et al.* 2017, Mao and Liu 2019, Collar *et al.* 2022) and flood risk (Metin *et al.* 2018). In a related approach, hydrological change is analysed by identifying a fingerprint: specific signatures of changes in the hypothesized drivers (Viglione *et al.* 2016, Arheimer and Lindström 2019, Bertola *et al.* 2019, 2021, Kemter *et al.* 2020). For example, Viglione *et al.* (2016) leverage the fact that different processes govern floods in catchments of different sizes to identify the most likely drivers of changing flood characteristics. Challenges to this approach are related to data scarcity and the complexity of systems, where feedbacks with social and ecological processes can be both drivers and outcomes of hydrological change (Srinivasan *et al.* 2017b, Duethmann *et al.* 2020).

Data-based inductive approaches use statistical models that rely on the detection and interpretation of statistical relationships, in time (Arheimer and Lindström 2019, Lan *et al.* 2020) or with observable covariates (Khazaei *et al.* 2019, Shao *et al.* 2022), or both (Chagas and Chaffe 2018, Franceschinis *et al.* 2021, Müller *et al.* 2021). In terms of attribution, three alternative strategies are deployed. First, the structure of the data themselves can be used to infer causal relationships, for instance through time series analysis such as Granger causality analysis (Singh and Borrok 2019) or convergent cross-mapping (Bonotto *et al.* 2022). Second, the characteristics of the data-generating process can be leveraged by identifying so-called natural experiments (Müller and Levy 2019), for instance through panel regression analysis (Blum *et al.* 2020, Davenport *et al.* 2020, Mondino *et al.* 2021) or covariate matching (Wagenaar *et al.* 2018, Brunner 2021). Third, ML can be leveraged to explicitly control for all plausible sources of variations, for instance using explainable AI (Althoff *et al.* 2021, Veigel *et al.* 2023) or autoencoders (Bassi *et al.* 2024).

Complementary to the previously described Darwinian (large sample) approaches are the Newtonian (small sample) ones that tackle attribution by seeking to reconstruct a plausible narrative to explain the observed phenomena for a limited number of cases (internal validity) (Harman and Troch 2014). Approaches seeking to elucidate the internal mechanics of a small number of units, through either statistical analysis or process-based modelling, fall under the latter category, along with other approaches, including comparative case studies (Kreibich *et al.* 2017, Garcia *et al.* 2019), socio-hydrological or agent-based models (Kandasamy *et al.* 2014, Mustafa *et al.* 2018, Penny *et al.* 2021, Schoppa *et al.* 2022) and narrative-based approaches (Treuer *et al.* 2017, Leong 2018).

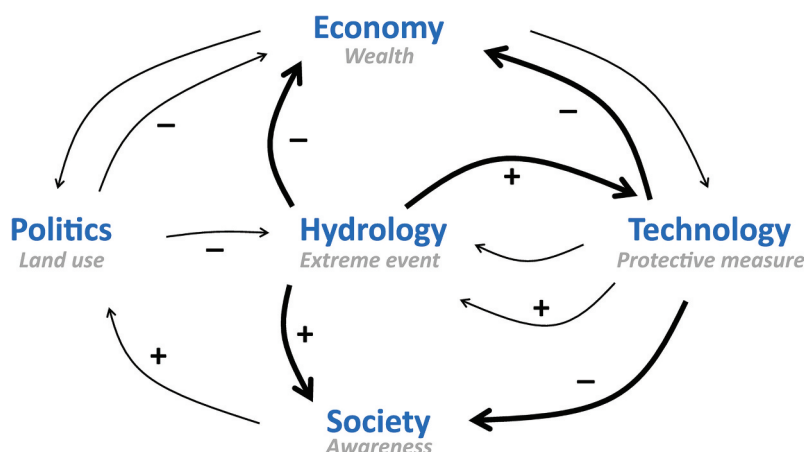


Figure 4. Causal loop diagram showing how hydrological, economic, political, technological, and social processes are all interlinked and gradually coevolve (continuous thin arrows), while being abruptly altered (continuous thick arrows) by the sudden occurrence of an extreme event. Depending on the choice of specific state variables and feedback mechanisms it can help simulate phenomena, e.g. unintended consequences such as the levee effect (figure adapted from Di Baldassarre *et al.* 2013, Sivapalan and Blöschl 2015).

Summary on drivers of change: Significant advancements were achieved in detecting and attributing hydrological changes: (1) Climate change leads to both increasing and decreasing trends of hydrological extremes in different regions of the world (e.g. Blöschl *et al.* 2019b, Merz *et al.* 2021, Brunner and Tallaksen 2019) and for different types of events (e.g. Van Loon 2015, Huang *et al.* 2022). (2) Land use and socio-economic change, such as the construction of hydraulic structures, were also identified as drivers of change, particularly in terms of flood and drought impacts (e.g. Vorogushyn and Merz 2013, Nlend *et al.* 2018, Paprotny *et al.* 2018). (3) Climate and global change, e.g. urbanization, leads to higher levels of pollutants and changes in water quality (e.g. Dailey *et al.* 2014, Meier *et al.* 2014, Bartosova *et al.* 2019). (4) The development of various attribution approaches, e.g. deductive (model-based) vs. inductive (data-based) ones, led to a better quantification of the interactions between drivers and a better separation of the individual contributions of drivers to change (e.g. Viglione *et al.* 2016, Arheimer and Lindström 2019, Ferraro *et al.* 2019).

4 Scientific progress on socio-hydrological systems

The impact of humans on water systems has increased and with it the need to understand the interactions and feedbacks between social and hydrological systems. To this end, new socio-hydrological concepts and approaches were developed to answer the following questions: “How do changes in hydrological systems interact with, and feedback to, natural and social systems driven by hydrological processes? What are the boundaries of coupled hydrological and societal systems?” The Panta Rhei collection of key scientific papers contains 89 papers (25%) that contribute to answering these questions (see Supplementary material).

4.1 Concepts for socio-hydrological systems

It is well known that human societies increasingly influence the hydrological regime, deliberately or otherwise, by: (a) building dams and reservoirs to store water for different purposes; (b) diverting water flows for urban, industrial or agricultural use; (c) changing the characteristics of watersheds via land use change, including deforestation, urbanization, or

drainage of wetlands; and (d) altering the regional or global climate via greenhouse gas emissions (Savenije *et al.* 2014).

Concurrently, changes in the hydrological regime, including the occurrence of extreme events, influence human societies. Water crises, droughts and floods impact societies in multiple ways, and can cause serious human and economic losses. Moreover, individuals, communities, and societies adapt and respond to extreme events by changing policies or social contracts (Adger *et al.* 2013) as well as collective behaviour, or patterns of human settlements (Mård *et al.* 2018).

An important scientific advancement in relation to the change in hydrology and society is the concept of socio-hydrological systems, which is based on a two-way coupling between human actions and water quantity and quality (Sivapalan *et al.* 2012, Sivapalan and Blöschl 2015). To illustrate this, Fig. 4 shows a causal loop diagram, consisting of system states and feedbacks. It illustrates how hydrological, economic, political, technological and social processes are all interlinked and either gradually co-evolve or are abruptly altered by the sudden occurrence of an extreme event, e.g. a flood (Di Baldassarre *et al.* 2013, Sivapalan and Blöschl 2015). In general, while humans influence hydrological flows, water storage, and the distribution of floods and droughts, they also respond to hydrological risk by changing (deliberately or not) demography, behaviour, water governance and infrastructure. Thus, human influences on and adaptive responses to hydrological processes are changing in space and time, indicating that simulations without sufficient inclusion of human interaction tend to underestimate temporal dynamics of human awareness and actions that alter hydrology (Di Baldassarre *et al.* 2015, Van Loon *et al.* 2016, AghaKouchak *et al.* 2021).

These complex interactions and feedbacks between human and water systems (e.g. Fig. 4) can generate socio-hydrological phenomena, i.e. patterns across places or even across contexts (Sivapalan and Blöschl 2015, Di Baldassarre *et al.* 2019). These phenomena consist of actual outcomes, paradoxical dynamics, or unintended consequences that arise from water management to achieve a desired societal objective (Table 2). The large range of socio-hydrological phenomena was organized into a

Table 2. Examples of archetypes and socio-hydrological phenomena (adapted from Di Baldassarre *et al.* 2019).

Archetype	Archetype definition	General phenomenon	Characteristics of phenomenon	Sub-phenomena
Fixes that fail	Shortcut solutions might seem to work in the short term, but often fail in the long run. In this way, they will aggravate the original problem or create even more challenging problems.	Safe-development paradox (Kates <i>et al.</i> 2006, Fusinato <i>et al.</i> 2024)	Protection measures generate a false sense of security that reduces coping capacities thereby increasing social vulnerability.	<i>Levee effect</i> (White 1945) <i>Reservoir effect</i> (Di Baldassarre <i>et al.</i> 2018)
		Rebound effect (Alcott 2005)	Increasing efficiency leads to higher consumption.	<i>Irrigation efficiency paradoxes</i> (Dumont <i>et al.</i> 2013)
Limits to growth	Continuous and accelerating growth of demand makes the system go beyond the limits unintentionally, thus experiencing a subsequent decline.	Supply–demand cycle (Kallis 2010)	Increasing supply enables growth that in turn generates higher demands.	<i>Fixes that backfire</i> (Gohari <i>et al.</i> 2013)
		Adaptation effect (Di Baldassarre <i>et al.</i> 2015)	Frequent extreme events increase coping capacities, thereby reducing social vulnerability. Adaptation to drought can worsen flood losses, and vice versa.	<i>Flood risk adaptation</i> Kreibich <i>et al.</i> (2017) <i>Sequence effect</i> (Di Baldassarre <i>et al.</i> 2017)
		Pendulum swing (Kandasamy <i>et al.</i> 2014)	Changing priorities from pursuing economic prosperity or environmental protection.	<i>Peak water paradoxes</i> Gleick and Palaniappan (2010) <i>Environmental Kuznets curve</i> (Dinda 2004)
Success to the successful	Good performance secures more resources relative to others, enabling the generation of further success which in turn secures still more resources.	Aggregation effect	Undesirable outcomes at the system scale from aggregated optimal decisions at the individual scale. Desirable outcomes at the system scale from aggregated inequalities at the individual scale.	<i>Collective action</i> (Olson 1965, Ostrom 1990) <i>Water injustice</i> (Zwarteveen <i>et al.</i> 2017)
		Institutional complexity	Trade-off between resilience and efficiency or between resilience to different disturbance regimes.	<i>Robustness–fragility trade-off</i> (Csete and Doyle 2002)

small number of system archetypes (Table 2). For instance, the most common example of the “fixes that fail” archetype is the levee effect (Di Baldassarre *et al.* 2018, 2019).

4.2 Approaches for assessing human–water systems

The Panta Rhei initiative has successfully contributed to a societal impact assessment that goes beyond project evaluation to include, for example, feedback mechanisms and the legacy of past and projected future changes based on implemented or proposed actions on a multi-decadal or centennial scale. Many conceptualizations of mechanisms and potential boundaries have been suggested (e.g. Elshafei *et al.* 2014, Müller *et al.* 2024). System dynamics models based on causal loop diagrams seem to be a promising way to study and validate long-term dynamics (Di Baldassarre *et al.* 2015, Barendrecht *et al.* 2017, Schoppa *et al.* 2022).

Models for large-scale studies primarily focus on the water–energy–food nexus or other aspects within the framework of the SDGs and have been adopted by institutional investors such as the World Bank (Liu *et al.* 2017a, Payet-Burin *et al.* 2019). Recently we have seen the development of models with very fine resolutions based on agent-based modelling (Wens *et al.* 2020, Ghoreishi *et al.* 2021) or various applications of statistical or ML methods to study interactions on the micro-scale. The purpose of modelling has shifted, to some degree, from finding universal modelling paradigms to finding suitable boundaries that ensure a simplicity that enables decision making while having the complexity that allows for robust assessment of the main impacts (Arnbjerg-Nielsen *et al.* 2022). Approaches have been developed to integrate

quantitative and qualitative information in order to better understand the hydrological, socio-political, economic, and cultural contexts in different locations (Rangecroft *et al.* 2018, Vanelli *et al.* 2022), supported by socio-hydrology (Sivapalan and Blöschl 2015).

In detail, conceptual models have been proposed to demonstrate that demographic and socio-economic characteristics such as income levels or social status further differentiate population vulnerabilities to water and livelihood insecurities (Haeffner *et al.* 2017, Teweldebrhan *et al.* 2020, Savelli *et al.* 2021, Savelli and Mazzoleni 2023). Understanding and modelling the co-evolution of water institutions has shown that vulnerabilities interact with livelihood insecurity in cities and floodplains (Yu *et al.* 2017, Munepeerakul *et al.* 2020).

The Panta Rhei community has progressed our understanding of drought through the lens of human influences and coupled system co-evolution (Park *et al.* 2018, Cavus and Aksoy 2020, Wens *et al.* 2020). Such studies have revealed a strong linkage between human behaviour and drought effects across increasing time scales, which help to form a foundation for understanding and communicating such complexities within operational drought management (Cavus *et al.* 2022). Similarly, the conceptual basis for connecting social processes (adaptation, management) with flood events has been strengthened by incorporating, for instance, bounded rationality and prospect theories (Di Baldassarre *et al.* 2015, Kreibich *et al.* 2017, Michaelis *et al.* 2020). Progress has continuously been made in predicting basin-scale socio-hydrological dynamics of water use for agricultural and environmental

purposes and its effects on societal conditions such as migration into agricultural basins and flood plains (Di Baldassarre *et al.* 2017, Roobavannan *et al.* 2018). There has also been progress in simulating the interplay between multiple hazards, water management, and societies. For example, Mazzoleni *et al.* (2021) showed that changes in flood and drought awareness can help contribute to the emergence of multiple human–water phenomena (e.g. sequence effect, reservoir effect, supply–demand cycle, and levee effect).

Comparative studies across socio-economic and cultural gradients of human water relations as well as hydroclimatic gradients provided a better understanding of the interplay between water hazards and societal responses, e.g. with respect to flood protection and poor water quality (Gupta *et al.* 2014, Kreibich *et al.* 2017, 2022a, Daniel *et al.* 2022). An example of this is disentangling the effect of social norms on the way water is abstracted for intensive agriculture from the effect the latter has on the formation of norms that encourage such water use (Troy *et al.* 2015, Alam *et al.* 2022). Another example is provided by Zhao *et al.* (2019), who introduced comparative advantage theory to track the driving forces of virtual water trade based on the spatial-temporal distribution of resource productivity and opportunity costs of land, labour and water use in agricultural and non-agricultural sectors across Chinese provinces.

Summary on understanding socio-hydrological systems: Significant advancements were achieved in conceptualizing and assessing socio-hydrological systems: (1) A better understanding of the feedbacks between hydrology and society has been achieved, based on the concept of a two-way coupling between human actions and water quantity and quality (e.g. Sivapalan *et al.* 2012, Sivapalan and Blöschl 2015). These complex feedbacks can generate phenomena such as the levee effect (e.g. Di Baldassarre *et al.* 2013, 2018). The generic and transferable descriptions of socio-hydrological phenomena and their organization into system archetypes should be considered in decision making (e.g. Di Baldassarre *et al.* 2019). (2) Integrated approaches were developed to assess the co-evolution of human–water systems in order to avoid unintended consequences of human interventions over long periods of time, described as phenomena. The development of socio-hydrological models made it possible to simulate long-term developments, including future projections (e.g. Barendrecht *et al.* 2017, Schoppa *et al.* 2022). Synthesis studies stressed the importance of space-time aspects as well as of understanding causalities to even better address important societal challenges (e.g. Van Loon *et al.* 2016, Zhao *et al.* 2019).

5 Scientific progress on modelling and prediction

The evolution of hydrological systems motivates the need to improve modelling and prediction to support better risk assessment, planning, and infrastructure design. Various approaches and models were developed in response to the following question: “How can we use improved knowledge of coupled hydrological–social systems to improve model predictions, including estimation of predictive uncertainty and assessment of predictability?” The Panta Rhei collection of key scientific papers contains 61 papers (17%) that contribute to answering this question (see Supplementary material).

5.1 Recognition of the change in hydrology and society led to advances In Modelling

Although we know that “stationarity is dead” (Milly *et al.* 2008) due to the changes observed over time in hydrological response (Montanari *et al.* 2013, Ceola *et al.* 2016, McMillan *et al.* 2016), it can still be useful to model hydrological processes under known conditions to make reliable predictions, such as for the design of civil structures (Koutsoyiannis 2011, Lins and Cohn 2011, Matalas 2012, Koutsoyiannis and Montanari 2015). Nevertheless, gradual and sudden changes in the form of a trend, a jump or a shift (Fowler *et al.* 2022, Volpi *et al.* 2024) due to the natural variation of a hydrological process or anthropogenic interventions should not be ignored, as, for instance, they have the potential to increase the frequency and intensity of extreme hydrological events. Similarly, in the more complex context of human–water systems, inertia in culture and institutions, poor governance and the hierarchical and cross-sectoral size of organizations influence human decision making. Roobavannan *et al.* (2018) and Amirkhani *et al.* (2022) incorporated changing beliefs about how important the environment is with respect to agricultural production as a function of community sensitivity to environmental degradation. Statistical techniques such as breakpoint analysis have been used, for example, to evaluate the impact on flow from human-induced changes in catchment characteristics (Arheimer and Lindström 2019) or to identify changes in reservoir operating rules and to develop amended rules using inverse modelling (Giuliani and Castelletti 2016).

5.2 Quantitative and qualitative human–water systems modelling

Traditional hydrological models are best suited for simulation and prediction in natural catchments, assuming that conditions have not been influenced by societal interaction. Human influences were often only included as management scenarios during the simulation, frequently at a specific point in time (Montanari *et al.* 2013). The predictive capabilities of traditional hydrological models are based on empirical observations, with which the models are calibrated and validated (Aguilar *et al.* 2017). However, complex human–water system models must reflect human and social dynamics such as changing water institutions. The data needed to calibrate such models often include observations of choices made by humans or the evolution of institutions (Sarmiento-Buarque *et al.* 2020). Further, modelling concepts have gone beyond the physics-based principles to include the governing principles behind human actions such as rules based on behavioural theories and evolutions of water institutions and governance that are a result of long-term slow-moving processes of values, norms and culture (Sivapalan and Blöschl 2015, Wesselink *et al.* 2017, Bartosova *et al.* 2021, Schrieks *et al.* 2021). For instance, a system-of-systems regional flood model was used to quantify the effect of changes in various risk components, including changes in land use, assets, and vulnerability, on flood risk (Metin *et al.* 2018). Recent models of human–water decision making have benefited from the novel

application of concepts that exist in the social sciences domain, such as game theoretic concepts, agent-based models, and behavioural models (Bartosova *et al.* 2021, Schrieks *et al.* 2021). For example, heterogeneous decision making of farmers has been extensively modelled using agent-based models (Tamburino *et al.* 2020, Wens *et al.* 2020, 2022). Yu *et al.* (2017) used game theoretic concepts to incorporate collective action in a stylized human–water system model of flood resilience. The model rules which describe how humans interact with their water environment were also inspired by behavioural theories such as the theory of planned behaviour, so that the models provided realistic predictions of societal inequities and unintended consequences of agricultural water interventions (Pouladi *et al.* 2020, Alam *et al.* 2022). Integrating empirical data, e.g. from recorded events, into socio-hydrological models supports the simulation of real, long-term processes in human–flood systems, including future projections (Schoppa *et al.* 2024). Using Bayesian inference allows models to be calibrated with qualitative and quantitative data and even to include expert knowledge as a prior (Barendrecht *et al.* 2019).

The application of hydrological models as well as human–water system models is not objective and models' subjectivity should be better recognized (Lane 2014, Merz *et al.* 2015, Beck and Krueger 2016, Melsen *et al.* 2018, Addor and Melsen 2019, Yu *et al.* 2022). It is now acknowledged that the predictability of human–water systems is affected by factors such as biased selection in choosing stakeholders for model co-development, social effects that stem from model results, mutual reinforcement of model development and model shaping by the involved parties (modellers, scientists, stakeholders), a lack of neutrality in political implications, and difficulties with transdisciplinary collaboration between academic and non-academic actors (Melsen *et al.* 2018). Yu *et al.* (2022) have highlighted that the complexities of human–water systems, such as decision making at various spatial, temporal and organizational scales, affect system predictability.

In line with the modelling traditions of social sciences, where mixed methods are often used, models have been calibrated on narratives or narratives are built on model predictions (Leong 2018, Mostert and Mostert 2018, Rangelcroft *et al.* 2018, Yu *et al.* 2022). Such an interplay of qualitative and quantitative methods to improve predictions and their significance for societies is important in the coupled modelling of human–water systems.

It is increasingly acknowledged that human–water models developed to capture extremely long-term phenomena should be explicit about their uncertainty when applied to short-term decision making (Srinivasan *et al.* 2017a). Merz *et al.* (2015) argue that surprise is particularly important in attempting to overcome potential cognitive biases within coupled human–water management. Techniques such as behavioural experiments and surveys have been proposed to test hypotheses about human behaviour and biases in decision making (Tian *et al.* 2019, Yu *et al.* 2022). As such, the concept of scale, and how human–water processes may shift according to the lens through which they are studied and by whom, are of importance in bridging the gap between

understanding human–water co-evolution and utilizing such insights for prediction. In this light, a means for defining, capturing, and communicating human–water model uncertainty, especially in narratives or qualitative causal loop diagrams developed for diverse decision makers, is essential (e.g. Höllermann and Evers 2019). Formal Bayesian and other methods have been proposed to analyse uncertainty in such models. Barendrecht *et al.* (2019) incorporated survey data in a human–flood systems model and provided quantitative uncertainty information based on Bayesian statistics.

5.3 Approaches to predict future trajectories

A spectrum of data and modelling methods were developed, to unravel complex human–societal phenomena in order to predict future trajectories of human–water systems in diverse contexts. For instance, novel concepts describing community sensitivity to drought and flood events were used to understand vulnerability dynamics in the past and predict possible future trajectories (Di Baldassarre *et al.* 2017, Roobavannan *et al.* 2018, Wens *et al.* 2021, Rusca *et al.* 2023).

Several socio-hydrological studies, mostly in human–agricultural and human–flood systems, have used diverse data sources to simultaneously calibrate social parameters, such as perception of risk to flooding, alongside hydrological parameters of the models using novel calibration strategies (Roobavannan *et al.* 2018, Barendrecht *et al.* 2019, Schoppa *et al.* 2024). Such calibrated models were then used to identify conditions under which the coupled system would sustainably evolve. For example, using a lumped socio-hydrological model at basin scale, Roobavannan *et al.* (2018) found that a higher level of diversification in the basin economy increases sustainability and makes it less reliant on water availability. Schoppa *et al.* (2024) calibrated a socio-hydrological model for flood risk assessment with survey data and simulated a wide range of potential futures. Results showed that integrated adaptation strategies (i.e. combined structural and non-structural measures) can reduce the average flood risk by up to 60%.

Summary on modelling and prediction: Progress in modelling and predicting future trajectories was achieved: (1) Various powerful socio-hydrological model approaches were developed which describe feedbacks; examples are stylized models, system-of-systems models and agent-based models (e.g. Yu *et al.* 2017, Metin *et al.* 2018, Wens *et al.* 2020). These approaches allow, for example, the incorporation of changes in risk perceptions, beliefs and community sensitivities into (long-term) modelling (e.g. Giuliani and Castelletti 2016, Amirkhani *et al.* 2022). (2) Using Bayesian inference, qualitative and quantitative data as well as expert knowledge can be used for model parameterization (e.g. Rangelcroft *et al.* 2018, Yu *et al.* 2022). The combination of socio-hydrological modelling and empirical data provides additional insights into human–water systems to realistically explore possible system evolutions comprehensively, including unlikely futures (e.g. Barendrecht *et al.* 2019, Schoppa *et al.* 2024). (3) Calibrated socio-hydrological models are used to predict future trajectories of human–water systems in diverse contexts and to identify conditions under which the systems would sustainably evolve (e.g. Roobavannan *et al.* 2018, Wens *et al.* 2021, Schoppa *et al.* 2024).

6 Scientific progress on water management and adaptation to change

Since it is not possible to plan under stable hydrological conditions, adaptive management approaches need to be developed that are more flexible to changing conditions. The development of realistic long-term scenarios, adaptive management and participatory governance are suggested approaches to answer the following question: “How can we support societies to adapt to changing conditions by considering the uncertainties and feedbacks between natural and human-induced hydrological changes?” The Panta Rhei collection of key scientific papers contains 76 papers (22%) that contribute to answering this question (see Supplementary material).

6.1 Scenarios and possibility spaces

Prediction is central to water resources management and planning. Socio-hydrological models aim to show under what circumstances sustainable development or a “lock-in” situation can arise (Ceola *et al.* 2016, Schoppa *et al.* 2024). Various socio-hydrological models have been developed to describe possible consequences of both “hard” infrastructure and “soft-path” solutions (Garcia *et al.* 2022, Genova and Wei 2023).

The predictions obtained from the socio-hydrological models are not mere scenarios that represent snapshots of the world at some specific future points in time, as is usual in conventional water resources planning. Predictions produced from the socio-hydrological models are alternative, plausible and co-evolving trajectories of coupled human–water systems. Collectively, these trajectories map out the future possibility space of socio-hydrological systems (Sivapalan and Blöschl 2015, Srinivasan *et al.* 2016). The possibility space creates a range of options by exploring the future more independently of initial views regarding probability and desirability. It covers future pathways involving disruptive changes, i.e. changes that do not necessarily follow the pattern of past transitions and are impossible to obtain through scenario analyses, and it greatly expands the possibility range by simulating various combinations of multiple variables within the system boundaries of the models. This possibility space makes it easier to be imaginative, systematic and explicit about hypothetical “What if?” questions. It can assist in identifying safe or desirable solutions for water availability and use while warning against maladaptive actions for socio-hydrological systems with alternate stable states of multiple variables (Rockström *et al.* 2009). The possibility space provides the basis for developing adaptive and participatory water governance.

6.2 Adaptive water management

Adaptive water management is a planning process that is decidedly adaptive, aims to keep multiple pathways to the future open, and incorporates the knowledge and perspectives of stakeholders (Versteeg *et al.* 2021). In this way, it aims to avoid the following three problems that often lead to the failure of planning processes in water management: (1) traditional planning

processes often emphasize the technical aspects of water management while ignoring the practices and knowledge of water users and other stakeholders; (2) they are based on an overly rational and linear ideal of the controllability of hydrology and infrastructure, which is untenable in a time of environmental change, non-stationarity and uncertainty; and (3) the planning processes are often not suitable for balancing the competing interests of stakeholders while keeping an eye on the feasibility and economic viability of the measures now and in the future (Butsch *et al.* 2022b, Conallin *et al.* 2022, Pham *et al.* 2022, Ward *et al.* 2020).

The Panta Rhei initiative has supported adaptive water management through inter- and transdisciplinary research and collaboration between hydrologists, social scientists, and a range of stakeholders, considering non-stationarity, uncertainty and change in hydrology and society. Furthermore, new ideas and advancements are created by meeting changing social needs (Sivapalan and Blöschl 2017). In the community paper that launched the IAHS Prague statement on the adaptation of water resource systems, Ceola *et al.* (2016) promote resilient, adaptive water resources systems management and advocate for a bottom-up approach that starts with analysing the vulnerabilities of a particular system in context and with stakeholders, rather than adopting a one-size-fits-all (“top-down”) perspective. van Nooijen and Kolechkina (2021) applied control theory for a water resources control system with time-varying delays in the feedback loop in a changing and unpredictable environment. Garcia *et al.* (2020) modelled reservoir dynamics before proposing a multi-level approach to flood and drought management which includes consideration of cognitive biases and systematic errors in decision making (Garcia *et al.* 2022). Kreibich *et al.* (2014) suggested integrating the cost assessment cycle into the risk management cycle so that continuous monitoring of the costs associated with natural hazards and their management enables early identification of inefficient risk mitigation strategies and supports adaptation. Such solutions provide tools to support the planning, monitoring, implementation and evaluation of adaptive water management under changing climatic and socio-economic conditions over long periods of time.

6.3 Participatory water governance

Participatory water governance approaches are particularly suited to managing complex, integrated, dynamic human–water systems. These approaches are adaptive and nested, and span scales of problems and jurisdictions; they actively involve communities and stakeholders, and incorporate all kinds of knowledge to inform decision making (Lemos 2015, Carnohan *et al.* 2020). The growing importance of participation in water management can generally be attributed to its potential to initiate social learning processes and build capacity (Evers *et al.* 2016). Understanding the conflicting demands and views of stakeholders can strengthen trust between them and enables the inclusion of local knowledge and different values, interests and perspectives in planning and management processes, which promotes acceptance of the proposed measures (Gooch and Huitema 2008, Evers *et al.* 2016).

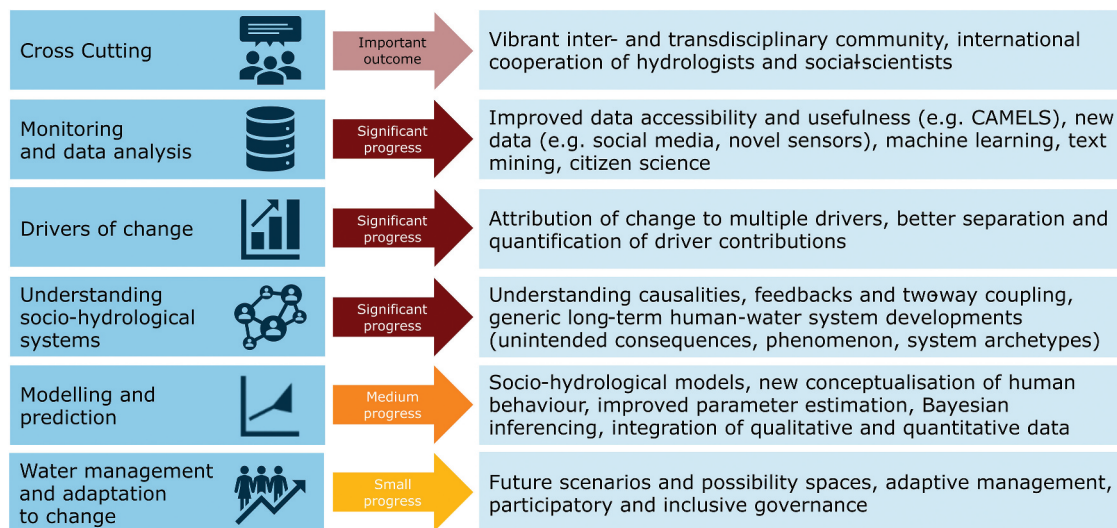


Figure 5. Summary of progress in research on change in hydrology and society in terms of hydrological science and practical water management.

As the following examples demonstrate, the Panta Rhei initiative's contributions to supporting participatory water governance range from novel approaches to theoretical frameworks, inclusion and quantification of social variables and the participatory implementation of water management. Rangecroft *et al.* (2021) developed a working approach for bridging the gap between hydrologists and social scientists by embracing the concepts of research ethics, power dynamics and communication barriers. Di Baldassarre *et al.* (2019) discuss the role of socio-hydrology as a disciplinary framework to accommodate social heterogeneity, power relations, cultural beliefs and cognitive biases. Godinez-Madriral *et al.* (2020) have shown how scientists were involved in the long-standing controversies surrounding the Zapotillo dam and water transfer project in Mexico, and how a participatory approach to hydrological modelling can give voice to previously marginalized concerns and proposals.

An implementation example is the transdisciplinary restoration of the damaged aquatic ecosystem in the Heihe River catchment area in China. Experts in hydrology, social development and ecosystem health together with authorities and other stakeholders implemented an interdisciplinary network approach leading to satisfactory restoration results (Liu *et al.* 2019).

In another case, hydrologists worked with the Scottish government to develop a web-based tool to help prioritize the location of riparian tree planting to provide shade for preventing water temperature extremes and protect fisheries as a climate change adaptation strategy (Jackson *et al.* 2018, 2021). Many other examples demonstrate how co-design with potential end-users from the public and private sector as well as civil society organizations lead to improved preparedness, early warning and resilience to floods and droughts (Löschner *et al.* 2016, Rangecroft *et al.* 2018, Lienert *et al.* 2022).

However, caution needs to be taken, as social learning can be characterized by power differences and strategic behaviour (Bou Nassar *et al.* 2021, Nicollier *et al.* 2022), and foregrounding integration, consensus and neutrality in transdisciplinary research may reinforce differences in value, knowledge and power (Ruska and Di Baldassarre 2019, Brelsford *et al.* 2020, Hayashi *et al.* 2021).

Summary on water management and adaptation to change: (1) Water management can consider future scenarios that consist of plausible, co-evolving trajectories of human–water systems and form possibility spaces that enable an assessment of the circumstances under which sustainable development may arise (e.g. Sivapalan and Blöschl 2015, Srinivasan *et al.* 2016). (2) Adaptive management concepts, which anticipate changes over time, keep multiple pathways to the future open, and incorporate the perspectives of stakeholders, have been developed (e.g. Garcia *et al.* 2020, Versteeg *et al.* 2021). Water management is seen as a continuous process with regular monitoring and revisiting management decisions, e.g. via the integrated cost assessment cycle (Kreibich *et al.* 2014). (3) Participatory and inclusive governance is needed as it initiates social learning processes, builds capacity, enables the inclusion of local knowledge and promotes acceptance of the proposed measures (e.g. Evers *et al.* 2016, Godinez-Madriral *et al.* 2020). Advice from the scientific community should also play an essential role in participatory governance, as promoted in the Prague statement of the International Association of Hydrological Sciences in 2015 (Ceola *et al.* 2016).

7 Summary of scientific achievements

Inter- and transdisciplinary collaboration has generated concepts, methods, results and applications that have filled many important gaps in our understanding of change in hydrology and society and led to progress in science and practical water management, as presented in the different sections of this review, which we visualize in Fig. 5 and summarize as follows.

7.1 Cross-cutting

In addition to the creation of knowledge, an important outcome of the Panta Rhei initiative is non-tangible, namely the large and diverse community that formed during the decade, in line with the IAHS mandate. Cooperation of hydrologists, social scientists, and practitioners at local, regional, and international levels led to mutual benefits and new outcomes. Transdisciplinary project teams transformed our understanding of human–water systems, improving predictions and decision making. Close communication between scientists and stakeholders was essential, as new ideas and advancements

are often generated by addressing changing societal needs with new approaches and technologies. The co-alignment of research with the UNESCO Intergovernmental Hydrological Programme (IHP) priorities for a water secure world in a changing environment, and with the efforts of the World Meteorological Organization (WMO) to support operational hydrology, enabled more stakeholders to participate in the creation of a new and sustainable water culture through co-creative knowledge and transformative education actions at several scales of governance.

7.2 Monitoring and data analysis

The accessibility and usefulness of data have increased significantly, particularly due to increasing community data-sharing initiatives, which match hydrological data with socio-economic and behavioural data, e.g. CAMELS initiatives or Panta Rhei benchmark data compilations. Open and equitable data sharing is supported by international principles such as the FAIR data principles of findability, accessibility, interoperability, and reusability (FAIR) (Wilkinson *et al.* 2016), the CARE Principles for Indigenous Data Governance which are Collective benefit, Authority to control, Responsibility, and Ethics (CARE) (Carroll *et al.* 2020) and open science principles (Ramachandran *et al.* 2021).

New methods of analysis (e.g. ML, text mining), repurposing of data and increased exploration of new, unconventional data sources (e.g. social media, novel sensors) have increased the availability of data in general, but especially of data on socio-economic aspects and human behaviour. The value of citizen science for monitoring, but also in terms of community sensitization, educational aspects and knowledge generation through the involvement of multiple points of view, was further confirmed and consolidated.

7.3 Drivers of change

Significant advancements have been achieved in detecting and attributing hydrological changes, particularly on the basis of monitoring and data analyses. Especially, the effects of climate change and land use change were quantified for past and potential future developments. Additionally, other socio-economic processes, such as urbanization, the construction of hydraulic structures or groundwater exploitation, have also been identified as drivers of change.

In particular, assessments that considered many, in some cases all, relevant drivers of change led to a better quantification of the interactions between drivers and a better separation of their individual contributions to change. These comprehensive, mainly model-based (deductive), but occasionally also data-based (inductive) analyses improved our understanding of the long-term developments of complex human–water systems, and stressed the importance of human actions, e.g. to mitigate flood and drought risks.

7.4 Understanding socio-hydrological systems

Socio-hydrological research, based on both the analysis of long time series and the in-depth assessment of case studies, has led

to a better understanding of the processes in human–water systems. It is crucial to understand and consider the causalities and feedbacks that can lead to phenomena such as the levee effect. The development of socio-hydrological models made it possible to simulate long-term developments, including future projections. Combinations of model- and data-based approaches increase the relevance for practical water management.

Comparative studies enabled the identification of commonalities and differences between places and the recognition of patterns. As such, generic and transferable descriptions of long-term changes that involve a two-way coupling between human actions and water quantity or quality were developed, which also led to organizing the range of socio-hydrological phenomena into a small number of system archetypes (e.g. fixes that fail). Archetypes are expressed in terms of generic causal loop diagrams. Syntheses and meta-analyses across socio-hydrological studies stressed the importance of space and space-time aspects as well as of understanding causalities to even better address important societal challenges.

7.5 Modelling and prediction

Various powerful socio-hydrological model approaches have been developed which describe feedbacks, e.g. causal loops, and include new conceptualizations of human behaviour such as risk awareness and community sensitivity. Examples are stylized models (i.e. system characteristics simplified into a set of differential equations), system-of-systems models (spatially explicit coupled models that capture different hydrological and socio-economic processes of the system) and agent-based models (theory-based models that describe the decisions and interactions between agents).

Significant progress in parameter estimation has been achieved thanks to improved accessibility as well as new, unconventional data that also describe new parameters like community sensitivity. The use of Bayesian inference allows modellers to introduce their degree of belief in certain processes as priors. Further, it opens up the possibility to integrate empirical qualitative and quantitative data. Both these advancements in modelling improved the simulation of past and future complex pathways, e.g. including tipping points and non-linear system dynamics.

7.6 Water management and adaptation to change

Future scenarios (and partly possibility spaces) are now commonly considered in water management, e.g. as required by the EU Water Framework Directive and the Floods Directive. Adaptive management concepts, which do not rely on design values but anticipate changes over time, have been developed. Water management is seen as a continuous process with regular monitoring and revisiting management decisions. Preferences for a particular measure are not only determined by cost–benefit analyses, but the flexibility and adaptability of the measures are also considered.

Participatory and inclusive governance is needed, involving all relevant stakeholders (users, planners and policymakers) at all levels, in particular at the river basin scale, thus from

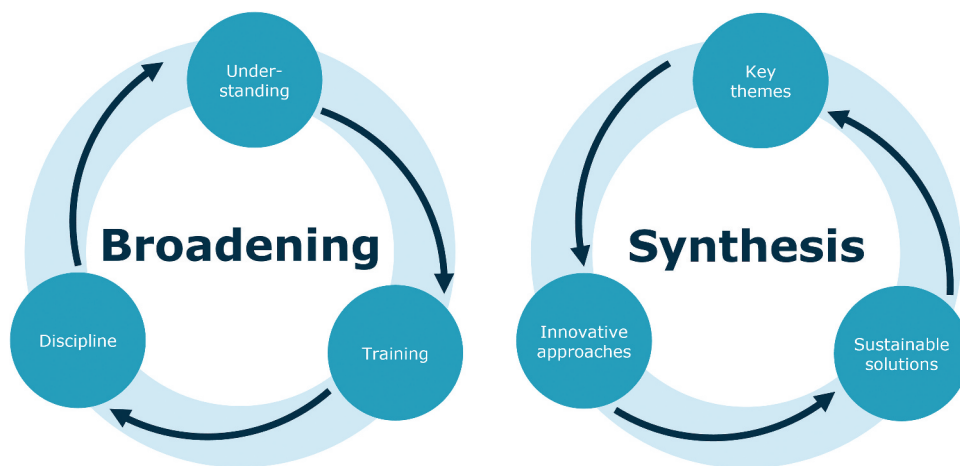


Figure 6. Recommendations to make progress by broadening understanding, discipline and training while synthesizing and focusing on key themes, the development of innovative approaches and sustainable solutions.

different countries if relevant). Advice from the scientific community should also play an essential role in participatory governance as promoted in the IAHS' 2015 Prague statement.

8 Recommendations

The IAHS Panta Rhei scientific decade has ended, but change is still ongoing – everything is still flowing, literally. We understand flow and change better now than in 2013. However, we also realize that the more our knowledge of nature and humans increases, the larger is the number of relevant interactions and feedbacks that will come to our attention, and as such the greater the complexity and uncertainty in our understanding and predictions. We continue our endeavour to answer the question “What are the key gaps in our understanding of hydrological change” and to fill these gaps. Thus, we need both continued excellent science on change in hydrology and society and a pragmatic and holistic approach to translating scientific innovation into policy and practice.

The Panta Rhei scientific decade inspired worldwide research efforts on change in hydrology and society that have created a vibrant and productive community of natural, social and interdisciplinary scientists and practitioners (Pande *et al.* 2022), which is an important and lasting outcome of this initiative. Intensive transdisciplinary collaboration on changes in hydrology and society has resulted in many new concepts, approaches, results and applications that have already improved practical water management for the benefit of societies, as illustrated in this review. We recommend continued effort and support for transdisciplinary collaboration in this field, by providing mid- to long-term funding for transdisciplinary research, supporting improved interdisciplinary education, improving the mechanisms to assess the value of scholarly work, and bringing together scientists and practitioners from various disciplines within the framework of IAHS and beyond (Kreibich *et al.* 2022a). These are all recommendations geared towards a broadening of our activities.

As we expand knowledge, we should also equally consolidate and synthesize, to avoid fragmentation of the field.

We need a clear science agenda for future research on water and societies, which the new IAHS International Commission on Human–Water Feedbacks (ICHWF) is designed to spearhead. We must synthesize knowledge to identify patterns in the apparent disorder and high complexity, using both scientific discourse and targeted efforts such as periodic meta-analyses. Finally, our improved knowledge and predictive capabilities regarding human–water systems should be leveraged to solve water problems in a way that accounts for the long-term feedbacks between humans and water.

We therefore recommend that the community takes a broader view of the hydrological sciences in three dimensions, while at the same time pursuing synthesis, also in three dimensions (Fig. 6).

Broadening:

- **Broadening the understanding** of hydrological sciences by promoting comparative studies across spatial gradients of socio-economic and hydro-climatic systems, which can be supported by making data freely available.
- **Broadening the discipline** by mainstreaming the concept of coupled human–water systems in hydrology, because people are affected by, and affecting, all aspects of water systems.
- **Broadening the training** and education in hydrology towards more interdisciplinary understanding of integrated systems.

Synthesis:

- **Focusing on key themes**, e.g. as proposed by the Unsolved Problems in Hydrology initiative (UPH; Blöschl *et al.* 2019a), in order to strengthen the coherence within the discipline and its impact on other disciplines and societies.
- **Developing innovative approaches** by drawing upon new ideas and technologies (e.g. inter- and

transdisciplinary approaches; analysing new data with ML and AI) in order to advance the hydrological sciences even further in a coherent way.

- **Finding sustainable solutions** as proposed by the new IAHS scientific decade (2023–2032) on “Science for solutions: Hydrology Engaging Local People IN one Global world (HELPING)” (Arheimer *et al.* 2024).

Disclosure statement

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

ORCID

Heidi Kreibich  <http://orcid.org/0000-0001-6274-3625>
 Murugesu Sivapalan  <http://orcid.org/0000-0003-3004-3530>
 Amir AghaKouchak  <http://orcid.org/0000-0003-4689-8357>
 Nans Addor  <http://orcid.org/0000-0002-6057-3930>
 Hafzullah Aksoy  <http://orcid.org/0000-0001-5807-5660>
 Berit Arheimer  <http://orcid.org/0000-0001-8314-0735>
 Karsten Arnbjerg-Nielsen  <http://orcid.org/0000-0002-6221-9505>
 Cynthia Vail-Castro  <http://orcid.org/0000-0002-8825-9900>
 Christophe Cudennec  <http://orcid.org/0000-0002-1707-8926>
 Mariana Madruga de Brito  <http://orcid.org/0000-0003-4191-1647>
 Giuliano Di Baldassarre  <http://orcid.org/0000-0002-8180-4996>
 Wouter Knoben  <http://orcid.org/0000-0001-8301-3787>
 Tobias Krueger  <http://orcid.org/0000-0002-4559-6667>
 Junguo Liu  <http://orcid.org/0000-0002-5745-6311>
 Hilary McMillan  <http://orcid.org/0000-0002-9330-9730>
 E. Mario Mendiondo  <http://orcid.org/0000-0003-2319-2773>
 Alberto Montanari  <http://orcid.org/0000-0001-7428-0410>
 Marc F. Muller  <http://orcid.org/0000-0001-6406-8184>
 Fuqiang Tian  <http://orcid.org/0000-0001-9414-7019>
 Alberto Viglione  <http://orcid.org/0000-0002-7587-4832>
 Attilio Castellarin  <http://orcid.org/0000-0002-6111-0612>
 Daniel Peter Loucks  <http://orcid.org/0000-0001-8095-3474>
 Taikan Oki  <http://orcid.org/0000-0003-4067-4678>
 María J. Polo  <http://orcid.org/0000-0002-6296-2198>
 Anne F. Van Loon  <http://orcid.org/0000-0003-2308-0392>
 Ankit Agarwal  <http://orcid.org/0000-0001-8572-7046>
 Ana Andreu  <http://orcid.org/0000-0001-8346-5417>
 Manuela Brunner  <http://orcid.org/0000-0001-8824-877X>
 Yonca Cavus  <http://orcid.org/0000-0002-0528-284X>
 Serena Ceola  <http://orcid.org/0000-0003-1757-509X>
 Pedro Chaffe  <http://orcid.org/0000-0002-9918-7586>
 Xi Chen  <http://orcid.org/0000-0002-0293-7417>
 Zhao Dandan  <http://orcid.org/0000-0002-9797-2046>
 Moctar Dembélé  <http://orcid.org/0000-0002-0689-2033>
 Animesh K. Gain  <http://orcid.org/0000-0003-3814-693X>
 Mohammad Ghoreishi  <http://orcid.org/0000-0002-5051-2763>
 David M. Hannah  <http://orcid.org/0000-0003-1714-1240>
 Britta Höllermann  <http://orcid.org/0000-0001-5545-3515>
 Elizabeth Koebele  <http://orcid.org/0000-0001-9133-2710>
 Frederik Kratzert  <http://orcid.org/0000-0002-8897-7689>
 Sara Lindersson  <http://orcid.org/0000-0001-9359-6218>
 Maurizio Mazzoleni  <http://orcid.org/0000-0002-0913-9370>
 Alfonso Mejia  <http://orcid.org/0000-0003-3891-1822>
 Pablo Mendoza  <http://orcid.org/0000-0002-0263-9698>
 Bruno Merz  <http://orcid.org/0000-0002-5992-1440>
 Bertil Nlend  <http://orcid.org/0000-0001-7961-1901>
 Rodric Merime Nonki  <http://orcid.org/0000-0003-2466-6272>
 Christina Orieschnig  <http://orcid.org/0000-0001-5182-7110>
 Katerina Papagiannaki  <http://orcid.org/0000-0003-4433-5841>
 Gopal Penny  <http://orcid.org/0000-0001-6628-1026>
 Olga Petrucci  <http://orcid.org/0000-0001-6918-1135>
 Rafael Pimentel  <http://orcid.org/0000-0001-6990-4874>

Sandra Pool  <http://orcid.org/0000-0001-9399-9199>
 Elena Ridolfi  <http://orcid.org/0000-0002-4714-2511>
 Nivedita Sairam  <http://orcid.org/0000-0003-4611-9894>
 Adarsh Sankaran Namboothiri  <http://orcid.org/0000-0001-8223-043X>
 Ana Carolina Sarmiento Buarque  <http://orcid.org/0000-0002-9489-4214>
 Elisa Savelli  <http://orcid.org/0000-0002-8948-0316>
 Lukas Schoppa  <http://orcid.org/0000-0002-3443-4603>
 Kai Schröter  <http://orcid.org/0000-0002-3173-7019>
 Mojtaba Shafiei  <http://orcid.org/0000-0001-8894-1208>
 Anna E. Sikorska-Senoner  <http://orcid.org/0000-0002-5273-1038>
 Magdalena Smigaj  <http://orcid.org/0000-0002-2763-4666>
 Claudia Teutschbein  <http://orcid.org/0000-0002-3344-2468>
 Thomas Thaler  <http://orcid.org/0000-0003-3869-3722>
 Andrijana Todorovic  <http://orcid.org/0000-0002-1001-9739>
 Faranak Tootoonchi  <http://orcid.org/0000-0001-5262-1712>
 Elena Toth  <http://orcid.org/0000-0002-9652-7901>
 Ronald van Nooijen  <http://orcid.org/0000-0001-7783-487X>
 Franciele Maria Vanelli  <http://orcid.org/0000-0001-8763-5786>
 Nicolás Vásquez  <http://orcid.org/0000-0002-4651-8935>
 David W. Walker  <http://orcid.org/0000-0002-2486-4677>
 Marthe Wens  <http://orcid.org/0000-0002-0133-5924>
 David J. Yu  <http://orcid.org/0000-0001-9929-1933>
 Changrang Zhou  <http://orcid.org/0000-0001-8466-192X>
 Günter Blöschl  <http://orcid.org/0000-0003-2227-8225>

References

- Ackerman Grunfeld, D., *et al.*, 2024. Underestimated burden of per- and polyfluoroalkyl substances in global surface waters and groundwaters. *Nature Geoscience*, 17 (4), 340–346. doi:10.1038/s41561-024-01402-8.
- Addor, N., *et al.*, 2017. The CAMELS data set: catchment attributes and meteorology for large-sample studies, *Hydrol. Earth System Science*, 21 (10), 5293–5313. doi:10.5194/hess-21-5293-2017.
- Addor, N., *et al.*, 2019. Large-sample hydrology: recent progress, guidelines for new datasets and grand challenges. *Hydrological Sciences Journal*, 65 (5), 712–725. doi:10.1080/02626667.2019.1683182.
- Addor, N. and Melsen, L.A., 2019. Legacy, rather than adequacy, drives the selection of hydrological models. *Water Resources Research*, 55 (1), 378–390. doi:10.1029/2018WR022958.
- Adger, W.N., *et al.*, 2013. Changing social contracts in climate-change adaptation. *Nature Climate Change*, 3 (4), 330–333. doi:10.1038/nclimate1751.
- AghaKouchak, A., *et al.*, 2021. Anthropogenic drought: definition, challenges, and opportunities. *Reviews of Geophysics*, 59 (2), e2019RG000683. doi:10.1029/2019RG000683.
- AghaKouchak, A. *et al.*, 2015. Water and climate: recognize anthropogenic drought. *Nature*, 524 (7566), 409–411. doi:10.1038/524409a.
- Aguilar, C., Montanari, A., and Polo, M.J., 2017. Real-time updating of the flood frequency distribution through data assimilation. *Hydrology and Earth System Sciences*, 21 (7), 3687–3700. doi:10.5194/hess-21-3687-2017.
- Alam, M.F., *et al.*, 2022. Understanding human–water feedbacks of interventions in agricultural systems with agent based models: a review. *Environmental Research Letters*, 17 (10), 103003. doi:10.1088/1748-9326/ac91e1.
- Álamos, N., *et al.*, 2024. The influence of human activities on streamflow reductions during the megadrought in central Chile, *Hydrol. Earth System Science*, 28 (11), 2483–2503. doi:10.5194/hess-28-2483-2024.
- Alborzi, A., *et al.*, 2018. Climate-informed environmental inflows to revive a drying lake facing meteorological and anthropogenic droughts. *Earth System Science*, 13 (8), 084010. doi:10.1088/1748-9326/aad246.
- Alcott, B., 2005. Jevons’ paradox. *Ecological Economics*, 54 (1), 9–21. doi:10.1016/j.ecolecon.2005.03.020.
- Alencar, P.H., *et al.*, 2024. Flash droughts and their impacts—using newspaper articles to assess the perceived consequences of rapidly emerging

- droughts. *Environmental Research Letters*, 19, 074048. doi:10.1088/1748-9326/ad58fa.
- Alexander, S.M., et al., 2020. Qualitative data sharing and synthesis for sustainability science. *Nature Sustainability*, 3 (2), 81–88. doi:10.1038/s41893-019-0434-8.
- Alshehhi, R. and Marpu, P.R., 2017. Hierarchical graph-based segmentation for extracting road networks from high-resolution satellite images. *ISPRS Journal of Photogrammetry and Remote Sensing*, 126, 245–260. doi:10.1016/j.isprsjprs.2017.02.008.
- Althoff, D., Bazame, H.C., and Nascimento, J.G., 2021. Untangling hybrid hydrological models with explainable artificial intelligence. *H2Open Journal*, 4 (1), 13–28. doi:10.2166/h2oj.2021.066.
- Alvarez-Garretón, C., et al., 2018. The CAMELS-CL dataset: catchment attributes and meteorology for large sample studies – chile dataset. *Hydrol Earth Syst. Sci*, 22 (11), 5817–5846. doi:10.5194/hess-22-5817-2018.
- Amirkhani, M., et al., 2022. An operational sociohydrological model to understand the feedbacks between community sensitivity and environmental flows for an endorheic lake basin, lake Bakhtegan, Iran. *Journal of Hydrology*, 605 (2022), 127375. doi:10.1016/j.jhydrol.2021.127375.
- Anna, H., et al., September 2019. Global mapping of citizen science projects for disaster risk reduction. *Frontiers of Earth Science*, 7. doi:10.3389/feart.2019.00226.
- Annis, A. and Nardi, F., 2019. Integrating VGI and 2D hydraulic models into a data assimilation framework for real time flood forecasting and mapping. *Geo-Spatial Information Science*, 22 (4), 223–236. doi:10.1080/10095020.2019.1626135.
- Arheimer, B., et al., 2020. Global catchment modelling using World-Wide HYPE (WWH), open data and stepwise parameter estimation. *Hydrol. Earth System Science*, 24 (2), 535–559. doi:10.5194/hess-24-535-2020
- Arheimer, B., et al., 2024. The IAHS science for solutions decade, with hydrology engaging local people in one global world (HELPING). *Hydrological Sciences Journal*, 69 (11), 1417–1435. doi:10.1080/02626667.2024.2355202.
- Arheimer, B., Donnelly, C., and Lindström, G., 2017. Regulation of snow-fed rivers affects flow regimes more than climate change. *Nature Communications*, 8 (1). doi:10.1038/s41467-017-00092-8.
- Arheimer, B. and Lindström, G., 2019. Detecting changes in river flow caused by wildfires, storms, urbanization, regulation, and climate across Sweden. *Water Resources Research*, 55 (11), 8990–9005. doi:10.1029/2019WR024759.
- Arheimer, B., Nilsson, J., and Lindström, G., 2015. Experimenting with coupled hydro-ecological models to explore measure plans and water quality goals in a semi-enclosed swedish bay. *Water*, 7 (7), 3906–3924. doi:10.3390/w7073906.
- Arheimer, B. and Pers, B.C. 2017. Lessons learned? Effects of nutrient reductions from constructing wetlands in 1996–2006 across Sweden. *Ecological Engineering*, 103, 404–414. doi:10.1016/j.ecoleng.2016.01.088
- Arnbjerg-Nielsen, K., et al., 2022. To what extent should we ensure the explicit inclusion of water quality within the WEF nexus? Discussion of “Water quality: the missing dimension of water in the water–energy–food nexus. *Hydrological Sciences Journal*, 67 (8), 1287–1290. doi:10.1080/02626667.2022.2077651.
- Badjana, H.M., et al., 2017. Hydrological system analysis and modelling of the Kara River Basin (West Africa) using a lumped metric conceptual model. *Hydrological Sciences Journal*, 62 (7), 1094–1113. doi:10.1080/02626667.2017.1307571.
- Bai, X., et al., 2016. Plausible and desirable futures in the Anthropocene: a new research agenda. *Global Environmental Change*, 39, 351–362. doi:10.1016/j.gloenvcha.2015.09.017.
- Baldassarre, D., et al., 2021. Integrating multiple research methods to unravel the complexity of human-water systems. *AGU Advances*, 2 (3), 3. doi:10.1029/2021av000473.
- Bárdossy, A., Seidel, J., and El Hachem, A., 2021. The use of personal weather station observations to improve precipitation estimation and interpolation. *Hydrol. Earth System Science*, 25 (2), 583–601. doi:10.5194/hess-25-583-2021.
- Barendrecht, M.H., et al., 2019. The value of empirical data for estimating the parameters of a sociohydrological flood risk model. *Water Resources Research*, 55 (2), 1312–1336. doi:10.1029/2018WR024128.
- Barendrecht, M.H., Viglione, A., and Blöschl, G., 2017. A dynamic framework for flood risk. *Water Security*, 1, 3–11. doi:10.1016/j.wasec.2017.02.001.
- Bartosova, A., et al., 2019. Future socioeconomic conditions may have a larger impact than climate change on nutrient loads to the Baltic Sea. *Ambio*, 48 (11), 1325–1336. doi:10.1007/s13280-019-01243-5.
- Bartosova, A., et al., 2021. Large-scale hydrological and sediment modeling in nested domains under current and changing climate. *Journal of Hydrologic Engineering*, 26 (5). doi:10.1061/(ASCE)HE.1943-5584.0002078.
- Bassi, A., et al., 2024. Learning landscape features from streamflow with autoencoders. *Hydrology and Earth System Sciences Discussions*, 2024, 1–30.
- Beck, M. and Krueger, T., 2016. The epistemic, ethical, and political dimensions of uncertainty in integrated assessment modeling. *WIREs Climate Change*, 7, 627–645. doi:10.1002/wcc.415.
- Berg, P., Donnelly, C., and Gustafsson, D., 2018. Near-real-time adjusted reanalysis forcing data for hydrology. *Hydrology Earth Systemic Sciences*, 22 (2), 989–1000. doi:10.5194/hess-22-989-2018.
- Bertassello, L., Levy, M.C., and Müller, M.F., 2021. Sociohydrology, ecohydrology, and the space-time dynamics of human-altered catchments. *Hydrological Sciences Journal*, 66 (9), 1393–1408. doi:10.1080/02626667.2021.1948550.
- Bertola, M., et al., 2020. Flood trends in Europe: are changes in small and big floods different? *Hydrology and Earth System Sciences*, 24 (4), 1805–1822. doi:10.5194/hess-24-1805-2020.
- Bertola, M., et al., 2021. Do small and large floods have the same drivers of change? A regional attribution analysis in Europe. *Hydrology and Earth System Sciences*, 25 (3), 1347–1364. doi:10.5194/hess-25-1347-2021.
- Bertola, M., Viglione, A., and Blöschl, G., 2019. Informed attribution of flood changes to decadal variation of atmospheric, catchment and river drivers in Upper Austria. *Journal of Hydrology*, 577, 123919. doi:10.1016/j.jhydrol.2019.123919.
- Biswas, A.K., 2004. Integrated water resources management: a reassessment. *Water International*, 29 (2), 248–256. doi:10.1080/02508060408691775.
- Bloomfield, J.P., et al., 2021. How is Baseflow Index (BFI) impacted by water resource management practices?, *Hydrol. Earth Systemic Sciences*, 25 (10), 5355–5379. doi:10.5194/hess-25-5355-2021.
- Blöschl, G., et al., 2013. *Runoff predictions in ungauged basins – synthesis across processes, places and scales*. Cambridge, UK: Cambridge University Press, 465.
- Blöschl, G., et al., 2017. Changing climate shifts timing of European floods. *Science*, 357 (6351), 588–590. doi:10.1126/science.aan2506.
- Blöschl, G., et al., 2019a. Twenty-three unsolved problems in hydrology (UPH) - a community perspective. *Hydrological Sciences Journal*, 64 (10), 1141–1158. doi:10.1080/02626667.2019.1620507
- Blöschl, G., et al., 2019b. Changing climate both increases and decreases European river floods. *Nature*, 573 (7772), 108–111. doi:10.1038/s41586-019-1495-6.
- Blum, A.G., et al., 2020. Causal effect of impervious cover on annual flood magnitude for the United States. *Geophysical Research Letters*, 47 (5), no–no. doi:10.1029/2019GL086480.
- Bonotto, G., et al., 2022. Identifying causal interactions between ground-water and streamflow using convergent cross-mapping. *Water Resources Research*, 58 (8), e2021WR030231. doi:10.1029/2021WR030231.
- Bou Nassar, J.A., et al., 2021. Multi-level storylines for participatory modeling – involving marginalized communities in Tz’olöj Ya. *Mayan Guatemala Hydrology Earth Systemic Sciences*, 25 (3), 1283–1306. doi:10.5194/hess-25-1283-2021.
- Brelsford, C., et al., 2020. Developing a sustainability science approach for water systems. *Ecology & Society*, 25 (2). doi:10.5751/ES-11515-250223.

- Brondizio, E.S., *et al.*, 2016. Re-conceptualizing the Anthropocene: a call for collaboration. *Global Environmental Change*, 39, 318–327. doi:10.1016/j.gloenvcha.2016.02.006.
- Brunner, M.I., 2021. Reservoir regulation affects droughts and floods at local and regional scales. *Environmental Research Letters*, 16 (12), 124016. doi:10.1088/1748-9326/ac36f6.
- Brunner, M.I., *et al.*, 2023. Hydrological drought generation processes and severity are changing in the Alps. *Geophysical Research Letters*, 50 (2), e2022GL101776. doi:10.1029/2022GL101776.
- Brunner, M.I. and Tallaksen, L.M., 2019. Proneness of European catchments to multiyear streamflow droughts. *Water Resources Research*, 55 (11), 8881–8894. doi:10.1029/2019WR025903.
- Buarque, S., *et al.*, 2020. Using historical source data to understand urban flood risk: a socio-hydrological modelling application at gregório creek, Brazil. *Hydrological Sciences Journal*, 65 (7), 1075–1083. doi:10.1080/02626667.2020.1740705.
- Burt, T.P. and McDonnell, J.J., 2015b. Whither field hydrology? The need for discovery science and outrageous hydrological hypotheses. *Water Resources Research*, 51 (8), 5919–5928. doi:10.1002/2014WR016839.
- Butsch, C., *et al.*, 2022b. Editorial: actors and adaptive planning in water management. *Frontiers in Water*, 4, 991338. doi:10.3389/frwa.2022.991338.
- Buytaert, W., *et al.*, 2014. Citizen science in hydrology and water resources: opportunities for knowledge generation, ecosystem service management, and sustainable development. *Frontiers of Earth Science*, 2 October. 10.3389/feart.2014.00026.
- Caretta, M.A., *et al.*, 2022. Water. In: D.C. Roberts, eds. *Climate change 2022: impacts, adaptation and vulnerability. contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change*. Cambridge, UK and New York, NY, USA: Cambridge University Press, 551–712. doi:10.1017/9781009325844.006.
- Carisi, F., *et al.*, 2018. Development and assessment of uni- and multi-variable flood loss models for Emilia-Romagna (Italy). *NHESS*, 18, 2057–2079. doi:10.5194/nhess-18-2057-2018
- Carnohan, S.A., *et al.*, 2020. Climate change adaptation in rural South Africa: using stakeholder narratives to build system dynamics models in data-scarce environments. *Journal of Simulation*, 15 (1–2), 5–22. doi:10.1080/17477778.2020.1762516.
- Carroll, S.R., *et al.*, 2020. The CARE Principles for Indigenous Data Governance. *Data Science Journal*, 19 (1), 43. doi:10.5334/dsj-2020-043
- Carvalho, P.N., *et al.*, 2022. Nature-based solutions addressing the water-energy-food nexus: review of theoretical concepts and urban case studies. *Journal of Cleaner Production*, 338, 130652. doi:10.1016/j.jclepro.2022.130652.
- Carvalho, T.M.N., de Souza Filho, F.D.A., and de Brito, M.M., 2024. Unveiling water allocation dynamics: a text analysis of 25 years of stakeholder meetings. *Environmental Research Letters*, 19 (4), 044066. doi:10.1088/1748-9326/ad37cd.
- Cavus, Y. and Aksoy, H., 2020. Critical drought severity/intensity-duration-frequency curves based on precipitation deficit. *Journal of Hydrology*, 584, 124312. doi:10.1016/j.jhydrol.2019.124312.
- Cavus, Y., Stahl, K., and Aksoy, H., 2022. Revisiting major dry periods by rolling time series analysis for human-water relevance in drought. *Water Resources Management*, 36 (8), 2725–2736. doi:10.1007/s11269-022-03171-8.
- Ceola, S., *et al.*, 2016. Adaptation of water resources systems to changing society and environment: a statement by the International association of hydrological sciences. *Hydrological Sciences Journal*, 61 (16), 2803–2817. doi:10.1080/02626667.2016.1230674.
- Cerri, M., *et al.*, 2021. Are openstreetmap building data useful for flood vulnerability modelling? *Natural Hazards and Earth System Sciences*, 21 (2), 643–662. doi:10.5194/nhess-21-643-2021.
- Cervone, G., *et al.*, 2016. Using twitter for tasking remote-sensing data collection and damage assessment: 2013 Boulder flood case study. *International Journal of Remote Sensing*, 37 (1), 100–124. doi:10.1080/01431161.2015.1117684.
- Chagas, V.B., Chaffe, P.L., and Blöschl, G., 2022. Climate and land management accelerate the Brazilian water cycle. *Nature Communications*, 13 (1), 5136. doi:10.1038/s41467-022-32580-x.
- Chagas, V.B.P., *et al.*, 2020. CAMELS-BR: hydrometeorological time series and landscape attributes for 897 catchments in Brazil. *Earth System Science Data*, 12 (3), 2075–2096. doi:10.5194/essd-12-2075-2020.
- Chagas, V.B.P. and Chaffe, P.L.B., 2018. The role of land cover in the propagation of rainfall into streamflow trends. *Water Resources Research*, 54 (9), 5986–6004. doi:10.1029/2018WR022947.
- Chen, J. and Rodell, M., 2021. Applications of gravity recovery and climate experiment (GRACE) in global groundwater study. In: A. Mukherjee, B. R. Scanlon, A. Aureli, S. Langan, H. Guo, A.A. McKenzie, eds. *Global Groundwater*. London: Elsevier, 531–543. doi:10.1016/B978-0-12-818172-0.00039-6.
- Cheng, C., *et al.*, 2022. What is the relationship between land use and surface water quality? A review and prospects from remote sensing perspective. *Environ Sci Pollut Res*, 29 (38), 56887–56907. doi:10.1007/s11356-022-21348-x.
- Chiang, F., Mazdiyasi, O., and AghaKouchak, A., 2021. Evidence of anthropogenic impacts on global drought frequency, duration, and intensity. *Nature Communications*, 12 (1), 2754. doi:10.1038/s41467-021-22314-w.
- Collar, N.M., *et al.*, 2022. Linking fire-induced evapotranspiration shifts to streamflow magnitude and timing in the western United States. *Journal of Hydrology*, 612, 128242. doi:10.1016/j.jhydrol.2022.128242.
- Collins, M.J., 2019. River flood seasonality in the Northeast United States: characterization and trends. *Hydrological Processes*, 33 (5), 687–698. doi:10.1002/hyp.13355
- Conallin, J., *et al.*, 2022. A review of the applicability of the motivations and abilities (MOTA) framework for assessing the implementation success of water resources management plans and policies. *Hydrol. Earth Syst. Sci*, 26 (5), 1357–1370. doi:10.5194/hess-26-1357-2022.
- Coxon, G., *et al.*, 2020. CAMELS-GB: hydrometeorological time series and landscape attributes for 671 catchments in Great Britain. *Earth Syst. Sci. Data*, 12 (4), 2459–2483. doi:10.5194/essd-12-2459-2020.
- Coxon, G. *et al.*, 2024. Wastewater discharges and urban land cover dominate urban hydrology signals across England and Wales. *Environmental Research Letters*, 19, 084016. doi:10.1088/1748-9326/ad5bf.
- Csete, M.E. and Doyle, J.C., 2002. Reverse engineering of biological complexity. *Science*, 295 (5560), 1664–1669. doi:10.1126/science.1069981.
- Cudennec, C., *et al.*, 2018. Epistemological dimensions of the water-energy-food nexus approach. *Hydrological Sciences Journal*, 63 (12), 1868–1871. doi:10.1080/02626667.2018.1545097.
- Cudennec, C., *et al.*, 2020. Towards FAIR and SQUARE hydrological data. *Hydrological Sciences Journal*, 65 (5), 681–682. doi:10.1080/02626667.2020.1739397.
- Cudennec, C., *et al.*, 2022a. Operational, epistemic and ethical value chaining of hydrological data to knowledge and services: a watershed moment. *Hydrological Sciences Journal*, 67 (16), 2363–2368. doi:10.1080/02626667.2022.2150380.
- Cudennec, C., Sud, M., and Boulton, G., 2022b. Governing Open Science. *Hydrological Sciences Journal*, 67 (16), 2359–2362. doi:10.1080/02626667.2022.2086462.
- Dailey, K.R., Welch, K.A., and Lyons, W.B., 2014. Evaluating the influence of road salt on water quality of Ohio rivers over time. *Applied Geochemistry*, 47, 25–35. doi:10.1016/j.apgeochem.2014.05.006.
- Daniel, D., Pande, P., and Rietveld, L., 2022. Endogeneity in water use behaviour across case studies of household water treatment adoption in developing countries. *World Development Perspectives*, 25, 100385. doi:10.1016/j.wdp.2021.100385.
- Dasgupta, S., *et al.*, 2015. Climate change and soil salinity: the case of coastal Bangladesh. *Ambio*, 44 (8), 815–826. doi:10.1007/s13280-015-0681-5.
- Davenport, F.V., *et al.*, 2020. Flood size increases nonlinearly across the western United States in response to lower snow-precipitation ratios. *Water Resources Research*, 56 (1), e2019WR025571. doi:10.1029/2019WR025571.
- De Groeve, T., 2014. Current status and best practices for disaster loss data recording in EU member states: a comprehensive overview of

- current practice in the EU member states. JRC Scientific and Policy Report (Report JRC92290).
- Di Baldassarre, G., et al., 2013. Socio-hydrology: conceptualising human-flood interactions, *Hydrol. Earth System Science*, 17 (8), 3295–3303. doi:10.5194/hess-17-3295-2013.2013.
- Di Baldassarre, G., et al., 2015. Debates - Perspectives on socio-hydrology: capturing feedbacks between physical and social processes. *Water Resources Research*, 51 (6), 4770–4781. doi:10.1002/2014WR016416.
- Di Baldassarre, G., et al., 2017. Drought and flood in the Anthropocene: feedback mechanisms in reservoir operation. *Earth Syst. Dynam.*, 8 (1), 225–233. doi:10.5194/esd-8-225-2017.
- Di Baldassarre, G., et al., 2018. Water shortages worsened by reservoir effects. *Nature Sustainability*, 1 (11), 617–622. doi:10.1038/s41893-018-0159-0.
- Di Baldassarre, G., et al., 2019. Sociohydrology: scientific challenges in addressing the sustainable development goals. *Water Resources Research*, 55 (8), 6327–6355. doi:10.1029/2018WR023901.
- Dinda, S., 2004. Environmental Kuznets curve hypothesis: a survey. *Ecological Economics*, 49 (4), 431–455. doi:10.1016/j.ecolecon.2004.02.011.
- Dixon, H., et al., 2022. Intergovernmental cooperation for hydrometry – what, why and how? *Hydrological Sciences Journal*, 67 (16), 2552–2566. doi:10.1080/02626667.2020.1764569.
- Do Nascimento, T.V.M., et al., 2024. EStreams: an integrated dataset and catalogue of streamflow, hydro-climatic and landscape variables for Europe. *scientific Data*, 11 (1), 879. doi:10.1038/s41597-024-03706-1.
- Dottori, F., et al., 2018. Increased human and economic losses from river flooding with anthropogenic warming. *Nature Climate Change*, 8 (9), 781–786. doi:10.1038/s41558-018-0257-z.
- Duethmann, D., et al., 2015. Attribution of streamflow trends in snow and glacier melt-dominated catchments of the Tarim River, Central Asia. - *Water Resources Research*, 51 (6), 4727–4750. doi:10.1002/2014WR016716.
- Duethmann, D., Blöschl, G., and Parajka, J., 2020. Why does a conceptual hydrological model fail to correctly predict discharge changes in response to climate change? *Hydrology and Earth System Sciences*, 24 (7), 3493–3511. doi:10.5194/hess-24-3493-2020.
- Dumont, A., Mayor, B., and López-Gunn, E., 2013. Is the rebound effect or Jevons paradox a useful concept for better management of water resources? Insights from the irrigation modernisation process in Spain. *Aquatic procedia*, 1, 64–76. doi:10.1016/j.aqpro.2013.07.006.
- Eerkes-Medrano, D., Thompson, R.C., and Aldridge, D.C., 2015. Microplastics in freshwater systems: a review of the emerging threats, identification of knowledge gaps and prioritisation of research needs. *Water Research*, 75, 63–82. doi:10.1016/j.watres.2015.02.012.
- Elshafei, Y., et al., 2014. A prototype framework for models of socio-hydrology: identification of key feedback loops and parameterization approach, *Hydrol. Earth System Science*, 18 (6), 2141–2166. doi:10.5194/hess-18-2141-2014.
- Erban, L.E., et al., 2013. Release of arsenic to deep groundwater in the Mekong Delta, Vietnam, linked to pumping-induced land subsidence. *Proceedings of the National Academy of Sciences*, 110 (34), 13751–13756. doi:10.1073/pnas.1300503110.
- Evers, M., et al., 2016. Collaborative decision making in sustainable flood risk management: a socio-technical approach and tools for participatory governance. *Environmental Science & Policy*, 55 (2), 335–344. doi:10.1016/j.envsci.2015.09.009.
- Farahmand, H., et al., 2022. Anomalous human activity fluctuations from digital trace data signal flood inundation status. *Environment and Planning. B, Urban Analytics and City Science*, 49 (7), 1893–1911. doi:10.1177/23998083211069990.
- Ferdous, M.R., et al., 2018. Socio-hydrological spaces in the jamuna river floodplain in Bangladesh. *Hydrology and Earth System Sciences*, 22 (10), 5159–5173. doi:10.5194/hess-22-5159-2018.
- Ferraro, P.J., Sanchirico, J.N., and Smith, M.D., 2019. Causal inference in coupled human and natural systems. *Proceedings of the National Academy of Sciences*, 116(12), 5311–5318. doi:10.1073/pnas.1805563115.
- Finger, D., Wüest, A., and Bossard, P., 2013. Effects of oligotrophication on primary production in peri-alpine lakes. *Water Resour. Res.*, 49 (8), 4700–4710. doi:10.1002/wrcr.20355.
- Fohringer, J., et al., 2015. Social media as an information source for rapid flood inundation mapping. *NHESS*, 15, 2725–2738. doi:10.5194/nhess-15-2725-2015.
- Formetta, G. and Feyen, L., 2019. Empirical evidence of declining global vulnerability to climate-related hazards. *Global Environmental Change*, 57, 101920.
- Fowler, K., et al., 2022. Hydrological shifts threaten water resources. *Water Resources Research*, 58 (8), e2021WR031210. doi:10.1029/2021WR031210.
- Fowler, K., et al., 2022b. Explaining changes in rainfall–runoff relationships during and after Australia’s Millennium Drought: a community perspective. *Hydrology and Earth System Sciences*, 26 (23), 6073–6120. doi:10.5194/hess-26-6073-2022.
- Fowler, K.J.A., et al., 2021. CAMELS-AUS: hydrometeorological time series and landscape attributes for 222 catchments in Australia. *Earth Syst. Sci. Data*, 13 (8), 3847–3867. doi:10.5194/essd-13-3847-2021.
- Franceschinis, C., et al., 2021. Heterogeneity in flood risk awareness: a longitudinal, latent class model approach. *Journal of Hydrology*, 599, 126255. doi:10.1016/j.jhydrol.2021.126255.
- Frasson, R.P.D.M., et al., 2019. Will the surface water and ocean topography (SWOT) satellite mission observe floods? *Geophysical Research Letters*, 46 (17–18), 10435–10445. doi:10.1029/2019GL084686.
- Frota, R.L., et al., 2021. Network³ socio-hydrology: a case study of causal factors that shape the Jaguaribe River Basin, Ceará-Brazil. *Hydrological Sciences Journal*, 66 (6), 935–950. doi:10.1080/02626667.2021.1913282.
- Fusinato, E., 2024. Safe development paradox: evidence and methodological insights from a systematic review. *Nat Hazards*, 120, 13693–13714. doi:10.1007/s11069-024-06774-z.
- Garcia, M., et al., 2019. Towards urban water sustainability: analyzing management transitions in Miami, Las Vegas, and Los Angeles. *Global Environmental Change*, 58, 101967. doi:10.1016/j.gloenvcha.2019.101967.
- Garcia, M., et al., 2022. Weathering water extremes and cognitive biases in a changing climate. *Water Security*, 15, 100110. doi:10.1016/j.wasec.2022.100110.
- Garcia, M., Ridolfi, E., and Di Baldassarre, G., 2020. The interplay between reservoir storage and operating rules under evolving conditions. *Journal of Hydrology*, 590, 125270. doi:10.1016/j.jhydrol.2020.125270.
- GCEW (Global Commission on the Economics of Water), 2023. *The What, Why and How of the World Water Crisis*. Paris, France: OECD Environment Directorate Climate, Biodiversity and Water Division. <https://watercommission.org/wp-content/uploads/2023/03/Why-What-How-of-Water-Crisis-Web.pdf> [Accessed 20 March 2025].
- Genova, P. and Wei, Y.P., 2023. A socio-hydrological model for assessing water resource allocation and water environmental regulations in the Maipo River Basin. *Journal of Hydrology*, 617 (2023), 129159. doi:10.1016/j.jhydrol.2023.129159.
- Genova, P., Wei, Y.P., and Olivares, M., 2022. Evolution of water environmental regulations in Chile since 1900. *Water Policy*, 24 (8), 1306–1324.
- Ghoreishi, M., et al., 2021. Peering into agricultural rebound phenomenon using a global sensitivity analysis approach. *Journal of Hydrology*, 602, 126739. doi:10.1016/j.jhydrol.2021.126739.
- Giuliani, M. and Castelletti, A., 2016. Is robustness really robust? How different definitions of robustness impact decision-making under climate change. *Clim. Change*, 135 (3–4), 409–424. doi:10.1007/s10584-015-1586-9.
- Gleick, P.H. and Palaniappan, M. (2010). Peak water limits to freshwater withdrawal and use. *Proceedings of the National Academy of Sciences*, 107(25), 11155–11162.
- Godinez-Madriral, J., Van Cauwenbergh, N., and van der Zaag, P., 2020. Unraveling intractable water conflicts: the entanglement of science and politics in decision-making on large hydraulic infrastructure.

- Hydrol. Earth Syst. Sci.*, 24 (10), 4903–4921. doi:10.5194/hess-24-4903-2020.
- Gohari, A., et al., 2013. Water transfer as a solution to water shortage: a fix that can backfire. *Journal of Hydrology*, 491, 23–39. doi:10.1016/j.jhydrol.2013.03.021.
- Gonzales, P. and Ajami, N., 2017. Social and structural patterns of drought-related water conservation and rebound. *Water Resources Research*, 53 (12), 10619–10634. doi:10.1002/2017wr021852.
- Gooch, G. and Huitema, D., 2008. Participation in water management: theory and practice. In: J.G. Timmerman, C. Pahl-Wostl, and J. Moltgen eds. *The adaptiveness of IWRM: Analysing european iwrms research. international water association publishing*. London, UK: IWA Publishing, 27–44 doi:10.2166/9781780401911.
- Gudmundsson, L., et al., 2021. Globally observed trends in mean and extreme river flow attributed to climate change. *Science*, 371 (6534), 1159–1162. doi:10.1126/science.aba3996.
- Gupta, H.V., et al., 2014. Large-sample hydrology: a need to balance depth with breadth. *Hydrol. Earth Syst. Sci.*, 18, 463–477. doi:10.5194/hess-18-463-2014.
- Haeflner, M., et al., 2017. Accessing blue spaces: social and geographic factors structuring familiarity with, use of, and appreciation of urban waterways. *Landscape and Urban Planning*, 167, 136–146. doi:10.1016/j.landurbplan.2017.06.008.
- Hall, C.A., et al., 2022. A hydrologist's guide to open science. *Hydrology and Earth System Sciences*, 26 (3), 647–664. doi:10.5194/hess-26-647-2022.
- Hall, J., et al., 2014. Understanding flood regime changes in Europe: a state-of-the-art assessment. *Hydrology and Earth System Sciences*, 18 (7), 2735–2772. doi:10.5194/hess-18-2735-2014.
- Hanrahan, B.R., et al., 2018. Winter cover crops reduce nitrate loss in an agricultural watershed in the central US. *Agriculture, Ecosystems & Environment*, 265, 513–523. doi:10.1016/j.agee.2018.07.004.
- Harman, C. and Troch, P.A., 2014. What makes Darwinian hydrology “Darwinian”? Asking a different kind of question about landscapes. *Hydrology and Earth System Sciences*, 18 (2), 417–433. doi:10.5194/hess-18-417-2014.
- Hayashi, Y., et al., 2021. A transdisciplinary engagement with Australian Aboriginal water and the hydrology of a small bedrock island. *Hydrological Sciences Journal*, 66 (13), 1845–1856. doi:10.1080/02626667.2021.1974025.
- Heal, K.V., et al., 2021. Water quality: the missing dimension of water in the water–energy–food nexus. *Hydrological Sciences Journal*, 66 (5), 745–758. doi:10.1080/02626667.2020.1859114.
- Heal, K.V., et al., 2022. Ensuring consideration of water quality in nexus approaches in the science–practice continuum. *Hydrological Sciences Journal*, 67 (8), 1291–1293. doi:10.1080/02626667.2022.2077652.
- Hersbach, H., et al., 2020. The ERA5 global reanalysis. *Meteorology Social*, 146 (730), 1999–2049. doi:10.1002/QJ.3803.
- Hipsey, M.R. and Arheimer, B., 2013. Challenges for water-quality research in the new IAHS decade on hydrology under societal and environmental change. *IAHS Publishing*, 361, 17–29.
- Höge, M., et al., 2023. CAMELS-CH: hydro-meteorological time series and landscape attributes for 331 catchments in hydrologic Switzerland. *Earth Systemic Science Data*, 15 (12), 5755–5784. doi:10.5194/essd-15-5755-2023.
- Höllermann, B. and Evers, M., 2019. Coping with uncertainty in water management: qualitative system analysis as a vehicle to visualize the plurality of practitioners' uncertainty handling routines. *Journal of Environmental Management*, 235, 213–223. doi:10.1016/j.jenvman.2019.01.034.
- Hou, X., et al., 2022. Global mapping reveals increase in lacustrine algal blooms over the past decade. *Nature Geoscience*, 15 (2), 130–134. doi:10.1038/s41561-021-00887-x
- Hrachowitz, M., et al., 2013. A decade of Predictions in Ungauged Basins (PUB) – a review. *Hydrological Sciences Journal*, 58 (6), 1198–1255. doi:10.1080/02626667.2013.803183.
- Huang, H., et al., 2022. Changes in mechanisms and characteristics of western US floods over the last sixty years. *Geophysical Research Letters*, 49 (3), e2021GL097022. doi:10.1029/2021GL097022.
- Huang, Y., et al., 2020. Nature-based solutions for urban pluvial flood risk management. *Wiley Interdisciplinary Reviews: Water*, 7 (3), e1421. doi:10.1002/wat2.1421.
- Huggins, X., et al., 2022. Hotspots for social and ecological impacts from freshwater stress and storage loss. *Nat Commun*, 13 (1), 439. doi:10.1038/s41467-022-28029-w.
- Hund, S.V., et al., 2018. Groundwater recharge indicator as tool for decision makers to increase socio-hydrological resilience to seasonal drought. *Journal of Hydrology*, 563, 1119–1134. doi:10.1016/j.jhydrol.2018.05.069.
- Hundechea, Y. and Merz, B., 2012. Exploring the relationship between changes in climate and floods using a model-based analysis. *Water Resources Research*, 48 (4). doi:10.1029/2011WR010527.
- IPCC, 2012. In: C.B. Field, ed. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. Cambridge, England: Cambridge Univ. Press, 582.
- IPCC, 2022: Climate Change 2022: impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.
- ISC, 2023. *UN 2023 Water Conference: ISC Policy Brief*. Paris: International Science Council. <https://council.science/publications/water-policy-brief/>
- Jackson, F.L., et al., 2018. A spatio-temporal statistical model of maximum daily river temperatures to inform the management of Scotland's Atlantic salmon rivers under climate change. *Science of the Total Environment*, 612, 1543–1558. doi:10.1016/j.scitotenv.2017.09.010.
- Jackson, F.L., et al., 2021. A deterministic river temperature model to prioritize management of riparian woodlands to reduce summer maximum river temperatures. *Hydrological Processes*, 35 (8), e14314. doi:10.1002/hyp.14314.
- Jan, S., et al., April 2019. Virtual Staff Gauges for Crowd-Based Stream Level Observations. *Frontiers of Earth Science*, 7. doi:10.3389/feart.2019.00070.
- Jasechko, S., et al., 2020. Groundwater level observations in 250,000 coastal US wells reveal scope of potential seawater intrusion. *Nature Communications*, 11 (1), 3229. doi:10.1038/s41467-020-17038-2.
- Jia, J., Cui, W., and Liu, J., 2022. Urban catchment-scale blue-green-gray infrastructure classification with unmanned aerial vehicle images and machine learning algorithms. *Frontiers in Environmental Science*, 9, 778598. doi:10.3389/fevs.2021.778598.
- Jollymore, A., et al., 2017. Citizen science for water quality monitoring: data implications of citizen perspectives. *Journal of Environmental Management*, 200 (September), 456–467. doi:10.1016/j.jenvman.2017.05.083.
- Kallis, G., 2010. Coevolution in water resource development: the vicious cycle of water supply and demand in Athens, Greece. *Ecological Economics*, 69 (4), 796–809. doi:10.1016/j.ecolecon.2008.07.025.
- Kam, J., Stowers, K., and Kim, S., 2019. Monitoring of drought awareness from google trends: a case study of the 2011–17 California drought. *Weather, Climate, and Society*, 11 (2), 419–429. doi:10.1175/wcas-d-18-0085.1.
- Kandasamy, J., et al., 2014. Socio-hydrologic drivers of the pendulum swing between agricultural development and environmental health: a case study from Murrumbidgee River basin, Australia. *Hydrology and Earth System Sciences*, 18 (3), 1027–1041. doi:10.5194/hess-18-1027-2014.
- Kates, R.W., et al., (2006). Reconstruction of New Orleans after Hurricane Katrina: a research perspective. *Proceedings of the national Academy of Sciences*, 103(40), 14653–14660.
- Ke, Q., et al., 2020. Urban pluvial flooding prediction by machine learning approaches – a case study of Shenzhen city, China. *Advances in Water Resources*, 145, 103719. doi:10.1016/j.advwatres.2020.103719.
- Kellermann, P., et al., 2020. The object-specific flood damage database HOWAS 21. - *Natural Hazards and Earth System Sciences (NHES)*, 20 (9), 2503–2519. doi:10.5194/nhess-20-2503-2020.
- Kelly-Quinn, M., et al., 2022. Opportunities, Approaches and Challenges to the Engagement of Citizens in Filling Small Water Body Data Gaps. *Hydrobiologia*. August, 1–21. doi:10.1007/s10750-022-04973-y.

- Kemter, M., et al., 2020. Joint trends in flood magnitudes and spatial extents across Europe. *Geophysical Research Letters*, 47 (7), e2020GL087464. doi:10.1029/2020GL087464.
- Khazaie, B., et al., 2019. Climatic or regionally induced by humans? Tracing hydro-climatic and land-use changes to better understand the Lake Urmia tragedy. *Journal of Hydrology*, 569, 203–217. doi:10.1016/j.jhydrol.2018.12.004.
- Kim, S., Shao, W., and Kam, J., 2019. Spatiotemporal Patterns of US Drought Awareness. *Palgrave Communications*, 5 (1). doi:10.1057/s41599-019-0317-7.
- Kingston, D., et al., 2020. Moving beyond the catchment scale: value and opportunities in large-scale hydrology to understand our changing world. *Hydrological Processes*, 34 (10), 2292–2298. doi:10.1002/hyp.13729.
- Knighton, J., et al., (2021). Flood risk behaviors of United States riverine metropolitan areas are driven by local hydrology and shaped by race. *Proceedings of the National Academy of Sciences*, 118(13), e2016839118.
- Koutsoyiannis, D., 2011. Hurst-Kolmogorov dynamics and uncertainty. *Journal of the American Water Resources Association*, 47 (3), 481–495. doi:10.1111/j.1752-1688.2011.00543.x.
- Koutsoyiannis, D. and Montanari, A., 2015. Negligent killing of scientific concepts: the stationarity case. *Hydrological Sciences Journal*, 60 (7–8), 7–1183. doi:10.1080/02626667.2014.959959.
- Kratzert, F., et al., 2019. Towards learning universal, regional, and local hydrological behaviors via machine learning applied to large-sample datasets. *Hydrol. Earth System Science*, 23 (12), 5089–5110. doi:10.5194/hess-23-5089-2019.
- Kratzert, F., et al., 2023. Caravan - A global community dataset for large-sample hydrology. *Sci Data*, 10 (1), 61. doi:10.1038/s41597-023-01975-w.
- Kreibich, H., et al., 2014. Costing natural hazards. - *Nature Climate Change*, 4 (5), 303–306. doi:10.1038/nclimate2182.
- Kreibich, H., et al., 2017. Adaptation to flood risk - results of international paired flood event studies. *Earth's Future*, 5 (10), 953–965. doi:10.1002/2017EF000606.
- Kreibich, H., et al., 2019. How to improve attribution of changes in drought and flood impacts. *Hydrological Sciences Journal*, 64 (1), 1–18. doi:10.1080/02626667.2018.1558367.
- Kreibich, H., et al., 2022a. Critical research in the water-related multi-hazard field. *Nature Sustainability*, 5 (2), 90–91. doi:10.1038/s41893-021-00833-0.
- Kreibich, H., et al., 2022b. The challenge of unprecedented floods and droughts in risk management. - *Nature*, 608 (7921), 80–86. doi:10.1038/s41586-022-04917-5
- Kreibich, H., et al., 2023. Panta Rhei benchmark dataset: socio-hydrological data of paired events of floods and droughts. - *Earth System Science Data*, 15 (5), 2009–2023. doi:10.5194/essd-15-2009-2023.
- Kryvasheyev, Y., et al., 2016. Rapid Assessment of Disaster Damage Using Social Media Activity. *Science Advances*, 2 (3), e1500779. doi:10.1126/sciadv.1500779.
- Kvas, A., et al., 2024. Evaluating long-term water storage trends in small catchments and aquifers from a joint inversion of 20 years of GRACE/GRACE-FO mission data. - *Geophysical Journal International*, 236 (2), 1002–1012. doi:10.1093/gji/ggad468.
- Lan, T., et al., 2020. Detection and attribution of abrupt shift in minor periods in human-impacted streamflow. *Journal of Hydrology*, 584, 124637. doi:10.1016/j.jhydrol.2020.124637.
- Lane, S.N., 2014. Acting, predicting and intervening in a socio-hydrological world. *Hydrology and Earth System Sciences*, 18 (3), 927–952. doi:10.5194/hess-18-927-2014.
- Lemos, M.C., 2015. Usable climate knowledge for adaptive and co-managed water governance. *Current Opinion in Environmental Sustainability*, 12, 48–52. doi:10.1016/j.cosust.2014.09.005.
- Leong, C., 2018. The role of narratives in sociohydrological models of flood behaviors. *Water Resources Research*, 54 (4), 3100–3121. doi:10.1002/2017WR022036.
- Levy, M.C., et al., 2018. Land use change increases streamflow across the arc of deforestation in Brazil. *Geophysical Research Letters*, 45 (8), 3520–3530. doi:10.1002/2017GL076526.
- Lienert, J., et al., 2022. The role of multi-criteria decision analysis in a transdisciplinary process: co-developing a flood forecasting system in western Africa. *Hydrol. Earth Syst. Sci*, 26 (11), 2899–2922. doi:10.5194/hess-26-2899-2022.
- Lins, H.F. and Cohn, T.A., 2011. Stationarity: wanted dead or alive? *Journal of the American Water Resources Association*, 47 (3), 475–480. doi:10.1111/j.1752-1688.2011.00542.x.
- Liu, J., et al., 2017a. Challenges in operationalizing the water-energy-food nexus. *Hydrological Sciences Journal*, 62 (11), 1714–1720. doi:10.1080/02626667.2017.1353695.
- Liu, J., et al., 2017b. Water scarcity assessments in the past, present, and future. *Earth's Future*, 5 (6), 545–559. doi:10.1002/2016EF000518.
- Liu, J., et al., 2019. On knowledge generation and use for sustainability. *Nature Sustainability*, 2 (2), 80–82. doi:10.1038/s41893-019-0229-y.
- Liu, J., Liu, Q., and Yang, H., 2016. Assessing water scarcity by simultaneously considering environmental flow requirements, water quantity, and water quality. *Ecological Indicators*, 60, 434–441. doi:10.1016/j.ecolind.2015.07.019.
- Liu, K., et al., 2022. Assessment of ecological water scarcity in China. *Environmental Research Letters*, 17 (10), 104056. doi:10.1088/1748-9326/ac95b0.
- Llasat, M.C., et al., 2016. Trends in flash flood events versus convective precipitation in the Mediterranean region: the case of Catalonia. *Journal of Hydrology*, 541, 24–37. doi:10.1016/j.jhydrol.2016.05.040.
- Löschner, L., et al., 2016. Scientist–stakeholder workshops: a collaborative approach for integrating science and decision-making in Austrian flood-prone municipalities. *Environmental Science & Policy*, 55, 345–352. doi:10.1016/j.envsci.2015.08.003.
- Lowry, C.S. and Fioren, M.N., 2013. CrowdHydrology: crowdsourcing Hydrologic Data and Engaging Citizen Scientists. *Ground Water*, 51 (1), 151–156. doi:10.1111/j.1745-6584.2012.00956.x.
- Ma, T., et al., 2020. Pollution exacerbates China's water scarcity and its regional inequality. *Nature Communications*, 11 (1), 1–9. doi:10.1038/s41467-019-13993-7.
- Mahé, G., et al., 2021. The UNESCO FRIEND-Water program: accelerates, shares and transfers knowledge and innovation in hydrology across the world in the frame of the Intergovernmental Hydrological Program (IHP. *PIAHS*, 384, 5–18. doi:10.5194/piahs-384-5-2021.
- Mao, G., et al., 2021. Comprehensive comparison of artificial neural networks and long short-term memory networks for rainfall-runoff simulation. *Physics and Chemistry of the Earth*, 123, 103026. doi:10.1016/j.pce.2021.103026.
- Mao, G. and Liu, J., 2019. WAYS v1: a hydrological model for root zone water storage simulation on a global scale. *Geoscientific Model Development*, 12 (12), 5267–5289. doi:10.5194/gmd-12-5267-2019.
- Marais, J., et al., 2016. A Review of the Topologies Used in Smart Water Meter Networks: a Wireless Sensor Network Application. *Journal of Sensors*, 2016, 9857568. doi:10.1155/2016/9857568.
- Mård, J., Di Baldassarre, G., and Maxxoleni, M., 2018. Nighttime light data reveal how flood protection shapes human proximity to rivers. *Scientific Advances*, 4, eaar5779. doi:10.1126/sciadv.aar5779.
- Matalas, N.C., 2012. Comment on the announced death of stationarity. *Journal of Water Resources Planning and Management*, 138 (4), 311–312. doi:10.1061/(ASCE)WR.1943-5452.0000215.
- Mazzoleni, M., et al., 2021. Water management, hydrological extremes, and society: modeling interactions and phenomena. *Ecology and Society*, 26 (4). doi:10.5751/ES-12643-260404.
- McAneney, J., et al., 2019. Normalised insurance losses from Australian natural disasters: 1966–2017. *Environmental Hazards*, 18 (5), 414–433. doi:10.1080/17477891.2019.1609406.
- McMillan, H., et al., 2016. PantaRhei 2013–2015: global perspectives on hydrology, society and change. *Hydrological Sciences Journal*, 61 (7), 1174–1191. doi:10.1080/02626667.2016.1159308.
- Medema, W., McIntosh, B.S., and Jeffrey, P.J., 2008. From Premise to Practice: a Critical Assessment of Integrated Water Resources Management and Adaptive Management Approaches in the Water

- Sector. *ECOLOGY AND SOCIETY*, 13 (2), 29. doi:10.5751/ES-02611-130229.
- Meier, M.H.E., et al., 2014. Ensemble Modeling of the Baltic Sea Ecosystem to Provide Scenarios for Management. *AMBIO*, 43 (1), 37–48. doi:10.1007/s13280-013-0475-6.
- Melsen, L.A., Vos, J., and Boelens, R., 2018. What is the role of the model in socio-hydrology? Discussion of “Prediction in a socio-hydrological world”*. *Hydrological Sciences Journal*, 63 (9), 1435–1443. doi:10.1080/02626667.2018.1499025.
- Merz, B., et al., 2012. HESS Opinions ‘More efforts and scientific rigour are needed to attribute trends in flood time series’. - *Hydrology and Earth System Sciences*, 16 (5), 1379–1387. doi:10.5194/hess-16-1379-2012.
- Merz, B., et al., 2015. Charting unknown waters - On the role of Surprise in flood risk assessment and management. *Water Resources Research*, 51 (8), 6399–6416. doi:10.1002/2015WR017464.
- Merz, B., et al., 2021. Causes, impacts and patterns of disastrous river floods. - *Nature Reviews Earth & Environment*, 2 (9), 592–609. doi:10.1038/s43017-021-00195-3.
- Metin, A.D., et al., 2018. How do changes along the risk chain affect flood risk? - *Natural Hazards and Earth System Sciences (NHES)*, 18 (11), 3089–3108. doi:10.5194/nhess-18-3089-2018.
- Michaelis, T., Brandimarte, L., and Mazzoleni, M., 2020. Capturing flood-risk dynamics with a coupled agent-based and hydraulic modelling framework. *Hydrological Sciences Journal*, 65 (9), 1458–1473. doi:10.1080/02626667.2020.1750617.
- Milly, P.C., et al., 2015. On critiques of “Stationarity is dead: whither water management?”. *Water Resources Research*, 51 (9), 7785–7789. doi:10.1002/2015WR017408.
- Milly, P.C.D., et al., 2008. Stationarity Is Dead: whither Water Management? *Science*, 319 (5863), 573–574. doi:10.1126/science.1151915.
- Mondino, E., et al., 2021. Longitudinal survey data for diversifying temporal dynamics in flood risk modelling. *Nat. Hazards Earth Syst. Sci.*, 21 (9), 2811–2828. doi:10.5194/nhess-21-2811-2021.
- Montanari, A., et al., 2013. “Panta Rhei-Everything Flows”: change in hydrology and society-The IAHS Scientific Decade 2013-2022. *Hydrological Sciences Journal*, 58 (6), 1256–1275. doi:10.1080/02626667.2013.809088.
- Montanari, A., et al., 2023. Why the 2022 Po River drought is the worst in the past two centuries. *Science Advances*, 9 (32), 8304. doi:10.1126/sciadv.adg8304.
- Mostert, and Mostert, E., 2018. An alternative approach for socio-hydrology: case study research. *Hydrol. Earth Syst. Sci.*, 22 (1), 317–329. doi:10.5194/hess-22-317-2018.
- Mullen, C., et al., 2022. Hydro economic asymmetries and common-pool overdraft in transboundary aquifers. *Water Resources Research*, 58 (11), e2022WR032136. doi:10.1029/2022WR032136.
- Müller, M.F., et al., 2016. Impact of the Syrian refugee crisis on land use and transboundary freshwater resources. *Proceedings of the national academy of sciences*, 113(52), pp.14932–14937.
- Müller, M.F., et al., 2024. Mapping the landscape of water and society research: promising combinations of compatible and complementary disciplines. *Wiley Interdisciplinary Reviews: Water*, 11 (2), e1701. doi:10.1002/wat2.1701.
- Müller, M.F. and Levy, M.C., 2019. Complementary vantage points: integrating hydrology and economics for sociohydrologic knowledge generation. *Water Resources Research*, 55 (4), 2549–2571. doi:10.1029/2019WR024786.
- Müller, M.F., Roche, K.R., and Dralle, D.N., 2021. Catchment processes can amplify the effect of increasing rainfall variability. *Environmental Research Letters*, 16 (8), 084032. doi:10.1088/1748-9326/ac153e.
- Muneepeerakul, R., John, M.A., and M, J., 2020. The emergence and resilience of self-organized governance in coupled infrastructure systems. *PNAS*, 117 (9), 4617–4622. doi:10.1073/pnas.1916169117.
- Mustafa, A., et al., 2018. Effects of spatial planning on future flood risks in urban environments. *Journal of Environmental Management*, 225, 193–204. doi:10.1016/j.jenvman.2018.07.090.
- Nardi, F., et al., 2022. Citizens AND Hydrology (CANDHY): conceptualizing a transdisciplinary framework for citizen science addressing hydrological challenges. *Hydrological Sciences Journal*, 67 (16), 2534–2551. doi:10.1080/02626667.2020.1849707.
- Nath, S. and Kirschke, S., 2023. Ground Water Monitoring through Citizen Science: a Review of Project Designs and Results. *Ground Water*, 61 (4), 481–493. February. doi:10.1111/gwat.13298.
- Newman, A.J., et al., 2015. Development of a large-sample watershed-scale hydrometeorological data set for the contiguous USA: data set characteristics and assessment of regional variability in hydrologic model performance. *Hydrol. Earth System Science*, 19 (1), 209–223. doi:10.5194/hess-19-209-2015.
- Nicollier, V., Cordeiro Bernardes, M.E., and Kiperstok, A., 2022. What governance failures reveal about water resources management in a municipality of Brazil. *Sustainability*, 14, 2144. doi:10.3390/su14042144.
- Njue, N., et al., 2019. Citizen Science in Hydrological Monitoring and Ecosystem Services Management: state of the Art and Future Prospects. *The Science of the Total Environment*, 693 (November), 133531. doi:10.1016/j.scitotenv.2019.07.337.
- Nlend, B., et al., 2018. The impact of urban development on aquifers in large coastal cities of West Africa: present status and future challenges. *Land Use Policy*, 75, 352–363. doi:10.1016/j.landusepol.2018.03.007
- Ojha, T., Misra, S., and Raghuvanshi, N.S., 2015. Wireless sensor networks for agriculture: the state-of-the-art in practice and future challenges. *Computers and Electronics in Agriculture*, 118, 66–84. doi:10.1016/j.compag.2015.08.011.
- Olson, M., 1965. *The logic of collective action: public goods and the theory of groups*. Cambridge, MA: Harvard University Press.
- Oral, H.V., et al., 2021. Management of Urban Waters with Nature-Based Solutions in Circular Cities—Exemplified through Seven Urban Circularity Challenges. *Water*, 13 (23), 3334. doi:10.3390/w13233334.
- Ostrom, E., 1990. *Governing the commons: the evolution of institutions for collective action*. New York, US: Cambridge university press.
- Pande, S. et al., 2022. Never ask for a lighter rain but a stronger umbrella. *Frontiers in Water*, 3, 822334. doi:10.3389/frwa.2021.822334.
- Papagiannaki, K., et al., 2022. Developing a large-scale dataset of flood fatalities for territories in the Euro-Mediterranean region, FFEM-DB. - *Scientific Data*, 9 (1), 166. doi:10.1038/s41597-022-01273-x.
- Paprotny, D., et al., 2018. Trends in flood losses in Europe over the past 150 years. *Nature Communications*, 9 (1), 1985. doi:10.1038/s41467-018-04253-1.
- Paprotny, D., et al., 2021. A probabilistic approach to estimating residential losses from different flood types. - *Natural Hazards*, 105 (3), 2569–2601. doi:10.1007/s11069-020-04413-x.
- Park, C.E., et al., 2018. Keeping global warming within 1.5°C restrains emergence of aridification. *Nature Climate Change*, 8 (1), 70–74. doi:10.1038/s41558-017-0034-4.
- Payet-Burin, R., et al., 2019. WHAT-IF: an open-source decision support tool for water infrastructure investment planning within the water-energy-food-climate nexus. *Hydrology and Earth System Sciences*, 23 (10), 4129–4152. doi:10.5194/hess-23-4129-2019.
- Pekel, J.-F., et al., 2016. High-resolution mapping of global surface water and its long-term changes. *Nature*, 540 (7633), 418–422. doi:10.1038/nature20584.
- Penny, G., et al., 2021. Trust and incentives for transboundary groundwater cooperation. *Advances in Water Resources*, 155, 104019. doi:10.1016/j.advwatres.2021.104019.
- Penny, G., Bolster, D., and Müller, M.F., 2022. Social dilemmas and poor water quality in household water systems. *Hydrology and Earth System Sciences*, 26 (4), 1187–1202. doi:10.5194/hess-26-1187-2022.
- Pham, L.D.M.H., et al., 2022. Socio-hydrological approach for farmer adaptability to hydrological changes: a case study in salinity-controlled areas of the Vietnamese Mekong Delta. *Hydrological Sciences Journal*, 67 (4), 495–507. doi:10.1080/02626667.2022.2030865.

- Phlips, E.J., et al., 2020. Hurricanes, El Niño and harmful algal blooms in two sub-tropical Florida estuaries: direct and indirect impacts. *Scientific Reports*, 10 (1), 1910. doi:10.1038/s41598-020-58771-4
- Pimentel, R., Herrero, J., and Polo, M.J., 2017. Quantifying snow cover distribution in semiarid regions combining satellite and terrestrial imagery. *Remote Sensing*, 9 (10), 995. doi:10.3390/rs9100995.
- Polo, M.J., et al., 2019. The Guadalfeo Monitoring Network (Sierra Nevada, Spain): 14 years of measurements to understand the complexity of snow dynamics in semiarid regions. *Earth System Science Data*, 11 (1), 393–407. doi:10.5194/essd-11-393-2019.
- Pouladi, P., et al., 2020. Socio-hydrological framework for investigating farmers' activities affecting the shrinkage of Urmia Lake; hybrid data mining and agent-based modelling *Hydrol. Sci. J.*, 65, 1249–1261.
- Praharaj, S., et al., 2019. Estimating Impacts of Recurring Flooding on Roadway Networks: a Norfolk, Virginia Case Study. *Natural Hazards*, 107 (3), 2363–2387. doi:10.1007/s11069-020-04427-5.
- Quesnel, K.J. and Ajami, N.K., 2017. Changes in Water Consumption Linked to Heavy News Media Coverage of Extreme Climatic Events. *Science Advances*, 3 (10), e1700784. doi:10.1126/sciadv.1700784.
- Rahman, M.M., et al., 2019. Salinization in large river deltas: drivers, impacts and socio-hydrological feedbacks. *Water Security*, 6, 100024. doi:10.1016/j.wasec.2019.100024.
- Ramachandran, R., Bugbee, K., and Murphy, K., 2021. From Open Data to Open Science. *Earth & Space Science*, 8 (5), e2020EA001562. doi:10.1029/2020EA001562.
- Rangecroft, S., et al., 2018. Hydrological modelling as a tool for interdisciplinary workshops on future drought. *Progress in Physical Geography: Earth and Environment*, 42 (2), 237–256. doi:10.1177/0309133318766.
- Rangecroft, S., et al., 2021. Guiding principles for hydrologists conducting interdisciplinary research and fieldwork with participants. *Hydrological Sciences Journal*, 66 (2), 214–225. doi:10.1080/02626667.2020.1852241.
- Rangecroft, S., et al., 2023. Unravelling and understanding local perceptions of water quality in the Santa basin, Peru. *Journal of Hydrology*, 625, 129949. doi:10.1016/j.jhydrol.2023.129949.
- Rangecroft, S., et al., 2024. GC Insights: lessons from participatory water quality research in the upper Santa River basin, Peru. *Geoscience Communication*, 7 (2), 145–150. doi:10.5194/gc-7-145-2024.
- Riedlinger, D. and Berkes, F., 2001. Contributions of Traditional Knowledge to Understanding Climate Change in the Canadian Arctic. *The Polar Record*, 37 (203), 315–328. doi:10.1017/S0032247400017058.
- Roby, N.A., et al., 2018. A Novel Search Algorithm for Quantifying News Media Coverage as a Measure of Environmental Issue Salience. *Environmental Modelling & Software*, 101, 249–255. doi:10.1016/j.envsoft.2017.12.012.
- Rockström, J., et al., 2009. A safe operating space for humanity. *Nature*, 461 (7263), 472–475. doi:10.1038/461472a.
- Rojas, R., Feyen, L., and Watkiss, P., 2013. Climate change and river floods in the European Union: socio-economic consequences and the costs and benefits of adaptation. *Global Environmental Change*, 23 (6), 1737–1751. doi:10.1016/j.gloenvcha.2013.08.006.
- Roobavannan, M., et al., 2018. Norms and values in sociohydrological models. *Hydrology and Earth System Sciences*, 22 (2), 1337–1349. doi:10.5194/hess-22-1337-2018.
- Rudari, R. et al., 2017. Overview of loss data storage at global scale. In: D. Molinari, Menoni, S., Ballio, F., eds. *Flood Damage Survey and Assessment*, 3, 31–51. doi:10.1002/9781119217930.ch3. Geoph. Monog. Series, chap.
- Ruska, M., et al., 2023. Unprecedented droughts are expected to exacerbate urban inequalities in Southern Africa. *Nature Climate Change*, 13 (1), 98–105. doi:10.1038/s41558-022-01546-8.
- Ruska, M. and Di Baldassarre, G., 2019. Interdisciplinary critical geographies of water: capturing the mutual shaping of society and hydrological flows. *Water*, 11 (10), 1973. doi:10.3390/w11101973.
- Safaei-Moghadam, A., Tarboton, D., and Minsker, B., 2023. Estimating the Likelihood of Roadway Pluvial Flood Based on Crowdsourced Traffic Data and Depression-Based DEM Analysis. *Natural Hazards and Earth System Sciences*, 23 (1), 1–19. doi:10.5194/nhess-23-1-2023.
- Sauer, I.J., et al., 2021. Climate signals in river flood damages emerge under sound regional disaggregation. *Nature Communications*, 12 (1), 2128. doi:10.1038/s41467-021-22153-9.
- Savelli, E., et al., 2021. Don't blame the rain: social power and the 2015–2017 drought in Cape Town. *Journal of Hydrology*, 594, 125953. doi:10.1016/j.jhydrol.2020.125953.
- Savelli, E. and Mazzoleni, M., 2023. Urban water crises driven by elites' unsustainable consumption. *Nature Sustainability*, 6 (8), 929–940. doi:10.1038/s41893-023-01100-0.
- Savenije, H.H.G., Hoekstra, A.Y., and van der Zaag, P., 2014. Evolving water science in the Anthropocene. *Hydrology and Earth System Sciences*, 18 (1), 319–332. doi:10.5194/hess-18-319-2014.
- Schoppa, L., et al., 2020. Probabilistic Flood Loss Models for Companies. - *Water Resources Research*, 56 (9), e2020WR027649. doi:10.1029/2020WR027649.
- Schoppa, L., et al., 2022. Augmenting a socio-hydrological flood risk model for companies with process-oriented loss estimation. *Hydrological Sciences Journal*, 67 (11), 1623–1639. doi:10.1080/02626667.2022.2095207.
- Schoppa, L., et al., 2024. Projecting flood risk dynamics for effective long-term adaptation. - *Earth's Future*, 12 (3), e2022EF003258. doi:10.1029/2022EF003258.
- Schrieks, T., et al., 2021. Integrating behavioral theories in agent-based models for agricultural drought risk assessments. *Frontiers in Water*, 3, 686329. doi:10.3389/frwa.2021.686329.
- Scotti, V., Giannini, M., and Cioffi, F., 2020. Enhanced flood mapping using synthetic aperture radar (SAR) images, hydraulic modelling, and social media: a case study of Hurricane Harvey (Houston, TX). *J. Flood Risk Manag.*, 13 (4), e12647. doi:10.1111/jfr3.12647.
- See, L., March 2019. A Review of Citizen Science and Crowdsourcing in Applications of Pluvial Flooding. *Frontiers of Earth Science*, 7. doi:10.3389/feart.2019.00044.
- Serinaldi, F. and Kilsby, C.G., 2015. Stationarity is undead: uncertainty dominates the distribution of extremes. *Advances in Water Resources*, 77, 17–36. doi:10.1016/j.advwatres.2014.12.013.
- Shao, S., et al., 2022. Nonstationary analysis of hydrological drought index in a coupled human-water system: application of the GAMLSS with meteorological and anthropogenic covariates in the Wuding River basin, China. *Journal of Hydrology*, 608, 127692. doi:10.1016/j.jhydrol.2022.127692.
- Sherbinin, A.D., et al., 2021. The Critical Importance of Citizen Science Data. *Frontiers in Climate*, 3March. 10.3389/fclim.2021.650760.
- Shrestha, A., et al., 2022. Socio-hydrological modeling of the tradeoff between flood control and hydropower provided by the Columbia River Treaty, Hydrol. *Earth System Science*, 26 (19), 4893–4917. doi:10.5194/hess-26-4893-2022.
- Singh, N.K. and Borrok, D.M., 2019. A Granger causality analysis of groundwater patterns over a half-century. *Scientific Reports*, 9 (1), 12828. doi:10.1038/s41598-019-49278-8.
- Sivapalan, M., et al., 2014. Sociohydrology: use-inspired water sustainability science for the Anthropocene. *Earth's Future*, 2 (4), 225–230. doi:10.1002/2013EF000164.
- Sivapalan, M. and Blöschl, G., 2015. Time scale interactions and the coevolution of humans and water. *Water Resour. Res.*, 51 (9), 6988–7022. doi:10.1002/2015WR017896.
- Sivapalan, M. and Blöschl, G., 2017. The growth of hydrological understanding: technologies, ideas, and societal needs shape the field. *Water Resources Research*, 53 (10), 8137–8146. doi:10.1002/2017WR021396.
- Sivapalan, M., Savenije, H.H.G., and Blöschl, G., 2012. Socio-hydrology: a new science of people and water. *Hydrological Processes*, 26 (8), 1720–1276. doi:10.1002/hyp.8426.
- Smith, L., et al., 2017. Assessing the Utility of Social Media as a Data Source for Flood Risk Management Using a Real-Time Modelling Framework. *Journal of Flood Risk Management*, 10 (3), 370–380. doi:10.1111/jfr3.12154.
- Souza, F.A.A., et al., 2022. Droughts in São Paulo: challenges and lessons for a water-adaptive society. *Urban Water Journal*, 20 (10), 1682–1694. doi:10.1080/1573062X.2022.2047735.

- Srinivasan, V., *et al.*, 2016. Prediction in a socio-hydrological world. *hydrological Sciences Journal*, 1–8. doi:10.1080/02626667.2016.1253844.
- Srinivasan, V., *et al.*, 2017a. Prediction in a socio-hydrological world. *Hydrological Sciences Journal*, 62 (3), 338–345. doi:10.1080/02626667.2016.1253844.
- Srinivasan, V., *et al.*, 2017b. A dynamic framework for water security. *Water Security*, 1, 12–20. doi:10.1016/j.wasec.2017.03.001
- Stahl, K., *et al.*, 2016. Impacts of European drought events: insights from an international database of text-based reports. *Natural Hazards and Earth System Sciences*, 16 (3), 801–819. doi:10.5194/nhess-16-801-2016
- Steinhausen, M., *et al.*, 2022. Drivers of future fluvial flood risk change for residential buildings in Europe. - *Global Environmental Change*, 76, 102559. doi:10.1016/j.gloenvcha.2022.102559.
- Stevens, A.J., Clarke, D., and Nicholls, R.J., 2016. Trends in reported flooding in the UK: 1884–2013. *Hydrological Sciences Journal*, 61 (1), 50–63. doi:10.1080/02626667.2014.950581.
- Tamburino, L., Di Baldassarre, G., and Vico, G., 2020. Water management for irrigation, crop yield and social attitudes: a socio-agricultural agent-based model to explore a collective action problem. *Hydrological Sciences Journal*, 65 (11), 1815–1829. doi:10.1080/02626667.2020.1769103.
- Tanoue, M., Hirabayashi, Y., and Ikeuchi, H., 2016. Global-scale river flood vulnerability in the last 50 years. *Scientific Reports*, 6 (1), 36021. doi:10.1038/srep36021.
- 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.
- Teweldebrihan, M.D., Pande, S., and McClain, M., 2020. The dynamics of farmer migration and resettlement in the Dhidhessa River Basin, Ethiopia. *Hydrological Sciences Journal*, 65 (12), 1985–1993. doi:10.1080/02626667.2020.1789145.
- Thompson, J.J., *et al.*, 2021. The Utility of Google Trends as a Tool for Evaluating Flooding in Data-scarce Places. *Area*. doi:10.1111/area.12719.
- Thompson, S.E., *et al.*, 2013. Developing predictive insight into changing water systems: use-inspired hydrologic science for the Anthropocene. *Hydrology and Earth System Sciences*, 17 (12), 5013–5039. doi:10.5194/hess-17-5013-2013.
- Thorslund, J., *et al.*, 2021. Common irrigation drivers of freshwater salinisation in river basins worldwide. *Nature Communications*, 12 (1), 4232. doi:10.1038/s41467-021-24281-8.
- Tian, F., *et al.*, 2019. Dynamics and driving mechanisms of asymmetric human water consumption during alternating wet and dry periods. *Hydrol. Sci. J*, 64 (5), 507–524. doi:10.1080/02626667.2019.1588972.
- Treuer, G., *et al.*, 2017. A narrative method for analyzing transitions in urban water management: the case of the Miami- Dade Water and Sewer Department. *Water Resources Research*, 53 (1), 891–908. doi:10.1002/2016wr019658.
- Troy, T.J., *et al.*, 2015. Moving sociohydrology forward: a synthesis across studies. *Hydrol. Earth Syst. Sci*, 19 (8), 3667–3679. doi:10.5194/hess-19-3667-2015.
- Turner, S.W.D., *et al.*, 2021. Water storage and release policies for all large reservoirs of conterminous United States. *Journal of Hydrology*, 603A, 126843. doi:10.1016/j.jhydrol.2021.126843.
- Uchôa, J.G.S.M., *et al.*, 2024. Widespread potential for streamflow leakage across Brazil. *Nat Commun*, 15 (1), 10211. doi:10.1038/s41467-024-54370-3
- UNESCO (United Nations Educational Scientific and Cultural Organization). 2021. Recommendation on open science. <https://unesdoc.unesco.org/ark:/48223/pf0000379949.locale=en> [Accessed 5 July 2024]
- United Nations (2018). Sustainable Development Goal 6 Synthesis Report 2018 on Water and Sanitation. New York.
- 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.
- Vanelli, F.M., Kobiyama, M., and Mariana Madruga, D.B., 2022. To Which Extent Are Socio-Hydrology Studies Truly Integrative? The Case of Natural Hazards and Disaster Research. *Hydrology and Earth System Sciences*, 26 (8), 2301–2317. doi:10.5194/hess-26-2301-2022.
- Van Loon, A.F., 2015. Hydrological drought explained. *Wiley Interdisciplinary Reviews: Water*, 2 (4), 359–392. doi:10.1002/wat2.1085.
- Van Loon, A.F., *et al.*, 2015. Hydrological Drought Types in Cold Climates: quantitative Analysis of Causing Factors and Qualitative Survey of Impacts. *Hydrology and Earth System Sciences*, 19 (4), 1993–2016. doi:10.5194/hess-19-1993-2015.
- Van Loon, A.F., *et al.*, 2016. Drought in a human-modified world: reframing drought definitions, understanding, and analysis approaches. *Hydrology and Earth System Sciences*, 20 (9), 3631–3650. doi:10.5194/hess-20-3631-2016.
- Van Loon, A.F., *et al.*, 2022. Streamflow droughts aggravated by human activities despite management. *Environ. Res. Lett*, 17 (4), 044059. doi:10.1088/1748-9326/ac5def.
- Van Meter, K.J., Van Cappellen, P., and Basu, N.B., 2018. Legacy nitrogen may prevent achievement of water quality goals in the Gulf of Mexico. *Science*, 360 (6387), 427–430. doi:10.1126/science.aar4462.
- van Nooijen, R.R.P. and Kolechkina, A.G., 2021. Stability analysis of non-linear sampled data systems with time varying sample period and delay in the feedback loop. *IFAC-PapersOnLine*, 54 (9), 776–782. doi:10.1016/j.ifacol.2021.06.138.
- Van Oel, P.R., *et al.*, 2018. Diagnosing drought using the downstreamness concept: the effect of reservoir networks on drought evolution. *Hydrological Sciences Journal*, 63 (7), 979–990. doi:10.1080/02626667.2018.1470632.
- van Vliet, M., Flörke, M., and Wada, Y., 2017. Quality matters for water scarcity. *Nature Geosci*, 10 (11), 800–802. doi:10.1038/ngeo3047.
- Veigel, N., Kreibich, H., and Cominola, A., 2023. Interpretable Machine Learning Reveals Potential to Overcome Reactive Flood Adaptation in the Continental US. - *Earth's Future*, 11 (9), e2023EF003571. doi:10.1029/2023EF003571.
- Versteeg, N., *et al.*, 2021. Adaptive Planning, Monitoring, and Evaluation for Long-Term Impact: insights From a Water Supply Case in Bangladesh. *Frontiers in Water*, 2, 621971. doi:10.3389/frwa.2020.621971.
- Viglione, A., *et al.*, 2016. Attribution of regional flood changes based on scaling fingerprints. *Water Resources Research*, 52 (7), 5322–5340. doi:10.1002/2016WR019036.
- Villarini, G. and Wasko, C., 2021. Humans, climate and streamflow. *Nature Climate Change*, 11 (9), 725–726. doi:10.1038/s41558-021-01137-z.
- Volpi, E., *et al.*, 2024. The legacy of STAHY: milestones, achievements, challenges, and open problems in statistical hydrology. *Hydrological Sciences Journal*, 69 (14), 1913–1949. doi:10.1080/02626667.2024.2385686.
- Vorogushyn, S. and Merz, B., 2013. Flood trends along the Rhine: the role of river training. - *Hydrology and Earth System Sciences*, 17 (10), 3871–3884. doi:10.5194/hess-17-3871-2013.
- Vousdoukas, M.I., *et al.*, 2018. Climatic and socioeconomic controls of future coastal flood risk in Europe. *Nature Climate Change*, 8 (9), 776–780. doi:10.1038/s41558-018-0260-4.
- Wagenaar, D., *et al.*, 2018. Regional and Temporal Transferability of Multivariable Flood Damage Models. - *Water Resources Research*, 54 (5), 3688–3703. doi:10.1029/2017WR022233.
- Walker, D.W., Smigaj, M., and Tani, M., 2021. The Benefits and Negative Impacts of Citizen Science Applications to Water as Experienced by Participants and Communities. *WIREs. Water*, 8 (1). doi:10.1002/wat2.1488.

- Wang, H., *et al.*, 2017. Impacts of the dam-orientated water-sediment regulation scheme on the lower reaches and delta of the Yellow River (Huanghe): a review. *Global and Planetary Change*, 157, 93–113. doi:10.1016/j.gloplacha.2017.08.005.
- Wang, H., *et al.*, 2024. Anthropogenic climate change has influenced global river flow seasonality. *Science*, 383 (6686), 1009–1014. doi:10.1126/science.adi9501.
- Ward, P.J., *et al.*, 2020. The need to integrate flood and drought disaster risk reduction strategies. *Water Security*, 11, 100070. doi:10.1016/j.wasec.2020.100070
- Wens, M., *et al.*, 2020. Simulating Small-Scale Agricultural Adaptation Decisions in Response to Drought Risk: an empirical agent-based Model for Semi-Arid Kenya. *Frontiers in Water*, 2. doi:10.3389/frwa.2020.00015.
- Wens, M.L.K., *et al.*, 2022. Education, financial aid, and awareness can reduce smallholder farmers' vulnerability to drought under climate change. *Natural Hazards and Earth System Sciences*, 22 (4), 1201–1232. doi:10.5194/nhess-22-1201-2022.
- Wens, M.L.K. *et al.*, 2021. Complexities of drought adaptive behaviour: linking theory to data on smallholder farmer adaptation decisions. *International Journal of Disaster Risk Reduction*, 63, 102435. doi:10.1016/j.ijdrr.2021.102435.
- Wesselink, A., Kooy, M., and Warner, J., 2017. Socio-hydrology and hydrosocial analysis: toward dialogues across disciplines. *Wiley Interdiscip. Rev. Water*, 4 (2), e1196. doi:10.1002/wat2.1196.
- White, G.F., 1945. Human adjustment to floods. *Research Paper*, 29. Department of Geography. University of Chicago. 225.
- Wilkinson, M., *et al.*, 2016. The FAIR guiding principles for scientific data management and stewardship. *Scientific Data*, 3 (1), 160018. doi:10.1038/sdata.2016.18
- Woolley, A.W., *et al.*, 2010. Evidence for a Collective Intelligence Factor in the Performance of Human Groups. *Science*, 330 (6004), 686–688. doi:10.1126/science.1193147.
- Xia, J., *et al.*, 2021. Perspectives on eco-water security and sustainable development in the Yangtze River Basin. *Geosci. Lett.*, 8 (18). doi:10.1186/s40562-021-00187-7.
- Yang, Y., *et al.*, 2021. Streamflow stationarity in a changing world. *Environmental Research Letters*, 16 (6), 064096. doi:10.1088/1748-9326/ac08c1.
- Yasinskii, S.V., *et al.*, 2018. Current Problems in Organizing Water Protection Zones at Water Bodies: case Study of the Uglich Reservoir. *Water Resour.*, 45 (4), 490–502. doi:10.1134/S0097807818040206
- Young, G., *et al.*, 2015. Hydrological sciences and water security: an overview. *PIAHS*, 366, 1–9. doi:10.5194/piahs-366-1-2015.
- Yu, D.J., *et al.*, 2017. Incorporating institutions and collective action into a sociohydrological model of flood resilience. *Water Resources Research*, 53 (2), 1–18. doi:10.1002/2016WR019746.
- Yu, D.J., *et al.*, 2022. On capturing human agency and methodological interdisciplinarity in socio-hydrology research. *Hydrol. Sci. J.*, 67 (13), 1905–1916. doi:10.1080/02626667.2022.2114836.
- Yu, Q., *et al.*, 2023. Enhancing streamflow simulation using hybridized machine learning models in a semi-arid basin of the Chinese Loess Plateau. *Journal of Hydrology*, 617, 129115. doi:10.1016/j.jhydrol.2023.129115.
- Zhao, D., *et al.*, 2019. Explaining virtual water trade: a spatial-temporal analysis of the comparative advantage of land, labor and water in China. *Water Research*, 153, 304–314. doi:10.1016/j.watres.2019.01.025.