Where should hydrology go? An early-career perspective on the next IAHS Scientific Decade: 2023-2032

This manuscript is a non-peer reviewed preprint submitted to EarthArXiv. It has been submitted to the Hydrological Sciences Journal. The twitter handles of the first authors are: @HarroJongen and @tessavanhateren.

Theresa C van Hateren[a,b*] & Harro J Jongen[a,c*], Hadeel Al-Zawaidah[a], Joris GW Beemster[a], Judith Boekee[d], Linda Bogerd[a], Sijia Gao[e], Christin Kannen[f], Ilja van Meerveld[g], Sjoukje I de Lange[a], Felicia Linke[e,h], Rose B Pinto[a], Janneke OE Remmers[a], Jessica Ruijsch[i], Steven R Rusli[a], Roeland C van de Vijsel[a], Jerom PM Aerts[d], Sehouevi MD Agoungbome[d], Markus Anys[e], Sara Blanco Ramírez[g], Tim van Emmerik[a], Luca Gallitelli[j], Gabriela Gesualdo[k], Wendy Gonzalez Otero[f], Sarah Hanus[g], Zixiao He[a,l], Svenja Hoffmeister[f], Ruben O Imhoff[a,m], Tim Kerlin[f], Sumit M Meshram[d], Judith Meyer[b,n], Aline Meyer Oliveira[g], Andreas CT Müller[f], Remko Nijzink[b], Mirjam Scheller[g], Louise Schreyers[a], Dhruv Sehgal[a,b], Paolo F Tasseron[a], Adriaan J Teuling[a], Michele Trevisson[o], Kryss Waldschläger[a], Bas Walraven[d], Chanoknun Wannasin[a], Jan Wienhöfer[f], Marjanne Zander[a,m], Shulin Zhang[a,q], Jingwei Zhou[a], Judith Y Zomer[a], and Bob W Zwartendijk[a,r]

[a]*Hydrology and Quantitative Water Management Group, Wageningen University & Research, Wageningen, The Netherlands;* [b]*Department of Environmental Research and Innovation, Luxembourg Institute of Science and Technology, Belvaux, Luxembourg;* [c]*Meteorology and Air Quality group, Wageningen University & Research, Wageningen, The Netherlands;* [d]*Faculty of Civil Engineering and Geosciences, Department of Water Resources, Delft University of Technology, Delft, the Netherlands;* [e]*Hydrology, Faculty of Environment and Natural Resources, University of Freiburg, Freiburg, Germany;* [f]*Institute for Water and River Basin Management, Karlsruhe Institute of Technology, Karlsruhe, Germany;* [g]*Department of Geography, University of Zürich, Zürich,*

Switzerland; [h]Institute of Earth and Environmental Sciences, University of Freiburg, Freiburg, Germany; [i]Water Systems and Global Change Group, Wageningen University & Research, Wageningen, The Netherlands; [j]Department of Sciences, University of Roma Tre, Rome, Italy; [k]Department of Hydraulics and Sanitation, São Carlos School of Engineering , University of São Paulo, São Paulo, Brazil; [l]School of Ocean Engineering and Technological Sciences, Sun Yat-Sen University, Guangshou, China; [m]Operational Water Management and Early Warning, Department of Inland Water Systems, Deltares, The Netherlands; [n]Faculty of Science, Technology and Medicine, University of Luxembourg, Esch-Sur-Alzette, Luxembourg; [o]Institute for Hydromechanics, Karlsruhe Institute of Technology, Karlsruhe, Germany; [p]Catchment and Urban Hydrology Department, Deltares, Delft, The Netherlands; [q]State Key Laboratory of Hydrology, Water Resources and Hydraulic Engineering, Hohai University, Nanjing, China; [r]Research and Innovation Centre Techniek, Ontwerpen en Informatica, Inholland University of Applied Sciences, Alkmaar, The Netherlands

Corresponding author: harro.jongen@wur.nl.

*These authors contributed equally to this work.

Where should hydrology go? An early-career perspective on the next IAHS Scientific Decade: 2023-2032

This paper shares an early-career perspective on potential themes for the upcoming International Association of Hydrological Sciences (IAHS) scientific decade (SD). This opinion paper synthesizes six discussion sessions in western Europe identifying three themes that all offer a different perspective on the hydrological threats the world faces and could serve to direct the broader hydrological community: “Tipping points and thresholds in hydrology”, “Intensification of the water cycle”, and “Water services under pressure”. Additionally, four trends were distinguished concerning the way in which hydrological research is conducted: big data, bridging science and practice, open science, and inter- and multidisciplinarity. These themes and trends will provide valuable input for future discussions on the theme for the next IAHS SD. We encourage other Early-Career Scientists to voice their opinion by organizing their own discussions sessions and commenting on this paper to make this initiative grow from a regional initiative to a global movement.

Keywords: IAHS scientific decade; early-career scientists; tipping points; water cycle intensification; water services

Introduction

The International Association of Hydrological Sciences (IAHS) Scientific Decades (SDs) aim to formulate science programmes and engage the scientific community to advance the hydrological sciences. The first International Hydrological Decade was formulated in 1965 by UNESCO (Nace, 1965) to highlight the field of hydrology as an independent scientific discipline, but SDs have since grown to boost thematic advances in the field of hydrology. It is now a global movement initiated and coordinated by the IAHS. The past SDs have provided the foundation for scientific collaborations and have been vital in shaping hydrological research around specific themes. Especially the last two SDs have shown that well-organized community efforts can shape the field of hydrology (Hrachowitz et al., 2013; Kreibich et al., 2017; McMillan et al., 2016) . The two most recent decades focused on prediction in ungauged basins (PUB, 2002-2012, Sivapalan et al., 2003) and on change in hydrology and society (*Panta Rhei*, 2012-2022 Montanari et al., 2013). The results from the PUB decade have been summarized by Hrachowitz et al. (2013), and several community papers on *Panta Rhei* research results have already been published (e.g. Kreibich et al., 2017; McMillan et al., 2016) .

Because of increased cooperation between hydrologists, a next SD is likely to have an even bigger impact than the last one. Therefore, it is important to start the discussions on a theme for the next SD. The themes of the past two decades were developed through discussions during symposia, in online blogs, and at specific sessions at IAHS conferences (Montanari et al., 2013; Sivapalan et al., 2003) . The discussions were open to all hydrologists. Due to the international orientation of the IAHS, people from all over the world were involved. However, the author list of the opinion papers predominantly involved well-established researchers. While established researchers are key in shaping research, Early Career Scientists (ECS) are important drivers of many research projects. Although they were invited and encouraged to participate in the discussion sessions, ECS were rarely part of the author list of the resulting opinion papers (Figure 1). Since the gender balance in hydrology differs between established researchers and ECS (Popp et al., 2019), the diversity of the authors was also skewed (Figure 1). We perceive the lower diversity as a major disadvantage of the adopted approach, because the outcomes of the discussions may not have reflected the perspectives of the full spectrum of hydrologists.

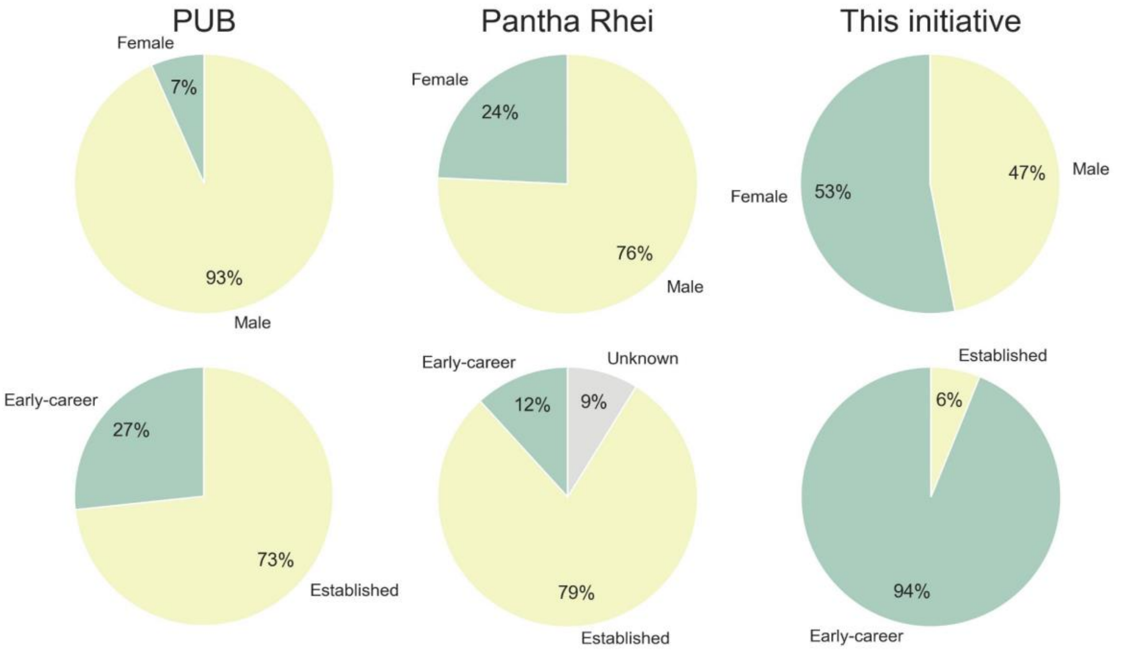

Figure 1: Gender (top) and career-stage (bottom) diversity in co-authors of initial publications of PUB (Sivapalan et al., 2003), Panta Rhei (Montanari et al., 2013), and this initiative. For the publications of Sivapalan et al. (2003) and Montanari et al. (2013), the numbers are based on publicly available, online information. Early career scientists in these charts are defined as having received their latest degree (BSc, MSc, PhD) less than five years before publication of the paper. This definition was chosen to enable an unambiguous classification.

We believe that actively involving a more complete representation of hydrological researchers early on in the discussion could lead to an SD theme that is supported by a larger part of the hydrological community. This broad backing of the theme will further increase the impact of the upcoming SD. To boost ECS involvement in SD discussions, we organized discussion sessions in western Europe targeting ECS. This resulted in a gender-balanced group of co-authors consisting of mostly ECS (Figure 1). Due to the regional character of this initiative, a spatial bias is inherently present in the presented work. We therefore urge other groups of ECS to actively share their own opinions, for example as comments on this paper or in future IAHS discussion sessions.

We present three potential themes for the upcoming SD that all offer a different perspective on the hydrological threats the world faces: “Tipping points and thresholds in hydrology”, “Intensification of the water cycle”, and “Water services under pressure”. We acknowledge that, even though the *Panta Rhei* decade comes to an end, change in hydrology and society is as important as it was ten years ago (Blöschl et al., 2019). However, a new theme will boost hydrology and give the opportunity to incorporate the knowledge gained in the last decade within a new focus. In addition, four key trends are presented: big data, bridging science and practice, open science, and inter- and multidisciplinarity. The trends are beyond the scope of a possible theme, as they concern the fashion in which hydrological research is or is expected to be conducted. These themes and trends can provide valuable input for future discussions on a theme for the next IAHS SD.

Methods

We aimed to involve a more diverse group of the hydrological scientific community, in particular ECS, in the discussion on the new SD theme, for which we adopted a different approach than was applied for previous SDs. For this initiative, ECS were not strictly defined by years since their last graduation, but we welcomed anyone identifying as ECS to create an inclusive atmosphere. We organized ECS discussion sessions to identify potential themes for the upcoming SD in a joint effort led by early-career hydrologists from Wageningen University and Research (WUR). In the spring of 2022, discussion sessions took place at WUR and five other institutes in four countries: the Karlsruhe Institute of Technology (KIT), the Luxembourg Institute of Science and Technology (LIST), the Delft University of Technology (TUD), the University of Freiburg (UoF), and the University of Zürich (UZH). Additionally, researchers from the Swiss Federal Institute of Technology in Zürich (ETH), and the Dutch branch of the Young Hydrologic Society (YHS-NL) were invited to join. PhD candidates made up the majority of the participants complemented by postdoctoral researchers and assistant professors. No master’s students joined the discussions. While these sessions have greatly improved the influence of ECS in such discussions (Figure 1), the session's geographic locations have inevitably led to a spatial bias towards high-income countries. Although the participants' countries of origin were more diverse than the affiliated institutes, future efforts should aim to further broaden the diversity by including a larger geographical region.

All discussion sessions followed a similar format, but the content evolved during the series of discussions. Each session started with a short presentation of the history of the SDs and the aim of our initiative. Subsequently, the participants were split into groups of 4-6 people to broaden the discussion and involve all opinions. The division was targeted to create diverse groups mixing institutes and subdisciplines of hydrology. These group conversations were guided by a set of questions that were prepared in advance. The questions developed over the sessions starting from a brainstorming level (i.e., "What do you expect to be key words for hydrology in the near future?") towards more detailed questions at the later sessions (i.e., "What would be the research questions tackled in the proposed themes?"). All questions can be found in the supporting information. Finally, each group summarized their answers to the questions at the plenary discussion that followed. ECS were encouraged to voice their opinion on the theme of the next SD by being in small groups of peers without their voices being unintentionally overshadowed by the presence of senior scientists.

Potential themes for the next IAHS scientific decade

Hydrological threats arise from pressures of the environment (e.g. climate change, ecosystem degradation, and biodiversity loss) and society (e.g. population, industrial, and economic growth). We see these threats as the central problem for hydrology in the coming decade. Hydrological threats thus should be studied, but this can be done starting from different perspectives. Three themes emerged from the discussion sessions that all postulate a perspective on how hydrology could tackle the hydrological threats faced by the environment and society. For the next IAHS Scientific Decade, we suggest that hydrological research could focus on one of the themes below:

- Tipping points and thresholds in hydrology
- Intensification of the hydrological cycle
- Water services under pressure

Tipping points and thresholds in hydrology

Tipping points are critical thresholds in complex systems such as the hydrological system. Once critical thresholds are exceeded, the system's state heavily changes, referred to as a regime shift. These regime shifts can be either reversible or irreversible. A reversible tipping point indicates that the system can restore under the same environmental circumstances, whereas an irreversible tipping point indicates that the system can only restore after circumstances have been reversed beyond the original point, known as hysteresis (Scheffer et al., 2009). Both reversible and irreversible tipping points occur in hydrology. Examples of reversible tipping points are the Horton and Dunne principles of overland flow generation (Dunne and Black, 1970a, 1970b; Horton, 1945), and an example of an irreversible tipping point is a landslide due to heavy rainfall (Keefer et al., 1987).

As mentioned before, the hydrological cycle is affected by climate change and human interventions. Therefore, hydrology needs to advance the understanding and prediction of systems under change (Ehret et al., 2014) with particular attention to tipping points and their critical thresholds (Blöschl et al., 2019). The concept of tipping points gained momentum over the past decades, because hydrological threats have resulted in water systems being pushed beyond their sustainable level. For instance, deforestation has led to soil erosion and karstification (Gams and Gabrovec, 1999). Recently, warnings have repeatedly been issued that deforestation in the Amazon is likely to hit a tipping point greatly reducing precipitation (e.g. Amigo, 2020; Lovejoy and Nobre, 2018). Another example is groundwater abstraction that jeopardizes groundwater-dependent vegetation (Barron et al., 2013).

These examples show that tipping points link the hydrological system with landscapes as well as ecosystems. In related scientific fields, tipping points are already a well-established concept. They are fundamental to the Intergovernmental Panel on Climate Change (IPCC) reports and the Planetary Boundaries framework (IPCC, 2021; Rockström et al., 2009; Steffen et al., 2015). Based on the IPCC report, the Planetary Boundaries framework and tipping point research, warnings are frequently issued stating that passing these tipping points poses risks and will have severe impacts (Lenton et al., 2019; Otto et al., 2020; Steffen et al., 2018). Given the complexity and connectivity of the entire Earth system, tipping points in other scientific areas will affect hydrology and vice versa.

Next to external tipping points affecting the hydrological cycle, tipping points have also been observed in different parts of the hydrological cycle itself. Hydrological disciplines in which tipping points have been identified include surface runoff (Dijkstra et al., 2019; Dunne and Black, 1970a; Horton, 1945), groundwater (Bailey, 2011; Figura et al., 2011), hydrometeorology (Buitink et al., 2020; Denissen et al., 2020; Krishnamurthy R et al., 2020), ecohydrology (Hirota et al., 2011; Mayor et al., 2019), and water quality (Dakos et al., 2019; Dijkstra et al., 2019). Moreover, these tipping points manifest themselves in all places: from arctic (Devoie et al., 2019; Rosier et al., 2021) to temperate climates (Kupec et al., 2021; van der Velde et al., 2021), from wet

(Loverde-Oliveira et al., 2009; Verbesselt et al., 2016) to arid regions (Bailey, 2011; Bernardino et al., 2020), and from hydrological source (Marty, 2008) to sink (Kirwan and Megonigal, 2013).

While tipping points have been found, they remain difficult to identify and are often not well represented in models. Predicting and identifying hydrological tipping points is particularly challenging since the positive feedbacks that induce regime shifts originate from complex interactions and occur in heterogeneous landscapes with high connectivity (Nijp et al., 2019; Scheffer et al., 2012). In addition, modelled tipping points can only be verified after they occur (Denissen et al., 2020; Krishnamurthy R et al., 2020). The impossibility of verifying unobserved tipping points is problematic since their occurrence comes with the drastic consequences of irreversible tipping behaviour on hydrological systems (e.g. Dakos et al., 2019; Drijfhout et al., 2015). Unravelling how known tipping points cause hydrological regime shifts requires the integration of different research approaches. Experiments in a controlled setting can help to identify the underlying feedback mechanisms (van de Vijsel et al., 2021; Webster et al., 2016). With conceptual models capturing the key processes, it is possible to test whether this feedback mechanism indeed causes the observed regime shift (Bailey, 2011; Dijkstra et al., 2019). At the same time, high-complexity models capturing the processes as completely as possible can be used to reproduce the conceptual simulations in settings closer to physical reality (Drijfhout et al., 2015). These high-complexity simulations assist with interpreting field observations and extrapolating results to future climate scenarios. In practice, integrating these scientific approaches is not straightforward. Identifying tipping points in increasingly large amounts of data is tedious and “scanning” for tipping points with models is computationally expensive. Efficiently integrating these approaches may greatly advance our scientific understanding of hydrological regime shifts and can help us to not only identify, but also successfully predict tipping points.

Given the potentially catastrophic consequences of hydrological tipping points, improving our process understanding and predictive capacity should be a focal point of future hydrological research. This is summarized in the following research questions that the theme “Tipping points and thresholds in hydrology” would address:

- How can hydrological tipping points and thresholds be identified?
- At what scales are the identified tipping points and thresholds relevant and how do these scales interact?
- Which non-hydrological tipping points affect hydrological systems?
- What needs to be included in hydrological models to simulate and predict tipping points and thresholds? How reliable are modelled tipping points and thresholds?
- How can we use our knowledge of tipping points and complex systems to mitigate the impacts of environmental and climate change?

Intensification of the water cycle

As global warming directly influences water fluxes, the hydrological cycle is strongly affected by climate change (e.g. Koutsoyiannis, 2020; Kundzewicz, 2008; Madakumbura et al., 2019; Peleg et al., 2018). Climate change intensifies the hydrological cycle increasing for instance the frequency and intensity of droughts and floods (Bertola et al., 2020; Gloor et al., 2013; Wasko et al., 2021). More hydrological extremes make securing fresh water by, for example, reservoir management increasingly difficult (Carvalho-Santos et al., 2017). Combined with decreasing freshwater storage due to shrinking glaciers (Beniston and Stoffel, 2014) and the depletion of high quality groundwater aquifers (Rotzoll and Fletcher, 2013), the intensification of the water cycle threatens water security.

Until now, studies have mainly focused on identifying drivers of the intensification (Huntington, 2006; Ziegler et al., 2003). However, less is known about the mitigation of the risks that the hydrological intensification poses for agricultural productivity, water availability, and water quality (Abram et al., 2021; Paprotny et al., 2018). We urgently need to explore this impact and potential mitigation strategies. In particular, we need to identify spatial and temporal trends of dry and wet extremes to enable adaptations that store water for drier periods and redistribute it to drier areas (e.g. Dai et al., 2018). We need interdisciplinary adaptations such as hydraulic structures that can prevent flash floods and a guaranteed minimum flow discharge to protect river ecosystems.

In the past, the intensification of the hydrological cycle was often described according to the “dry gets dryer, wet gets wetter” paradigm (Held and Soden, 2006; Kitoh et al., 2013). However, recent studies showed that this paradigm is too simple and not universally true (Allan, 2014; Christidis and Stott, 2021; Greve et al., 2014; Kumar et al., 2015). Hence, we need to understand local mechanisms and drivers to help mitigate the consequences of extreme events, thereby ensuring fresh water availability. This is especially important in the global south, where water insecurity is a substantial issue (Vörösmarty et al., 2010).

Increased drought occurrence and severity is a key component of the intensification of the hydrological cycle. Droughts are driven by a series of complex feedback mechanisms between, amongst others, precipitation, soil moisture and evaporation. Drought events manifest themselves in the environment (i.e. low discharge), but their impacts include immense social, environmental, and economic ramifications (e.g. Nilson, 2014). Monitoring drought events is complicated as they present themselves in different parts of the water cycle (i.e. soil moisture, groundwater, surface water) in different phases of the event (Buitink et al., 2021; van Loon, 2015). Remote sensing data with increasing accuracy and spatiotemporal resolution provide opportunities to monitor different parts of the hydrological cycle simultaneously (West et al., 2019). Regardless, challenges remain in accurately predicting droughts (Sutanto et al., 2020), as well as predicting the impact of climate change on drought occurrence and intensity (Vicente-Serrano et al., 2020). We must resolve these challenges and find solutions to prevent large scale drought impacts.

In addition to increasing the occurrence of dry extremes, the intensified water cycle increases the occurrence of wet extremes (Addo and Adeyemi, 2013; Ansah et al., 2020; De Luca et al., 2020; Pendergrass et al., 2017). In the last ten years, numerous extreme precipitation events have occurred with extensive impacts around the globe (e.g. Abram et al., 2021; Duan et al., 2014; Otto et al., 2018; Wasko et al., 2021). A recent example is the 2021 summer flood event that impacted a large part of north western Europe. Here, the connection with other disciplines was clearly visible as the impacts extended beyond hydrology: increased erosion led to large scour holes in the Meuse (Barneveld et al., 2022; Task Force Fact-finding hoogwater 2021, 2021). This extreme summer flood resulted from weather circumstances with a reoccurrence time of 400 years illustrating the extreme nature of the event (Kreienkamp et al., 2021). Yet, this was not an isolated event: the number of extreme rainfall events is increasing due to shifting global weather patterns and rising temperatures that enhance the atmospheric moisture-holding capacity (Held and Soden, 2006; Kennedy et al., 2016; Lenderink et al., 2017; Lenderink and van Meijgaard, 2008). More extreme rainfall events can result in floods with high socio-economic impacts, as well as increase the risk of flash floods

(Alfieri et al., 2015; Meyer et al., 2021; Piper et al., 2016). The risk of flash floods in urban areas is even higher due to their increasingly impervious surface (Cutter et al., 2018).

All in all, extreme events, both dry and wet, are expected to occur more frequently in the future (Wahl et al., 2015; Ward et al., 2018; Zscheischler et al., 2018). The same goes for compound events, where two extremes co-occur, such as a compound drought in which a precipitation deficit coincides with a heatwave (Buras et al., 2020; Seneviratne et al., 2010) and a compound flood in which precipitation excess coincides with a storm surge (Wahl et al., 2015). This requires improved early warning systems to limit the negative impacts of extreme events and long-term strategies to mitigate and cope with any remaining detrimental effects (Abram et al., 2021; Couasnon et al., 2020; Pappenberger et al., 2015; Ward et al., 2018; Wasko et al., 2021). However, assumptions of climate stationarity on which many of the statistical approaches are based are no longer valid (Milly et al., 2008). Predicting the risks of these types of events has therefore become more difficult. Improving hydrological forecasts thus requires improving the entire forecasting chain. The chain starts with weather forecasts that are the input for hydrological simulations (Emerton et al., 2016). These hydrological simulations provide the basis for impact forecasts (e.g. Sutanto et al., 2019). Finally, the risks are disseminated (Sorensen, 2000) together with suggested mitigation strategies.

To summarize, we propose that the focus of hydrological research should shift from identifying intensification to providing knowledge on how to mitigate its effects from local to global scales. Research questions that need answering are the following:

- What is the impact of an intensified hydrological cycle on the environment, ecosystem services and society?

- What areas are most at risk of the intensification of the hydrological cycle?
- How reliable are extreme event predictions that are based on extrapolating relatively short data series and how can this reliability be improved?
- How can early-warning systems be improved so that extreme events can be accurately predicted?
- Which mitigation strategies are suitable in the context of ongoing intensification of the hydrological cycle?

Water services under pressure

To raise awareness of the crucial role of water for nature and society, we advocate for a broader use of the “ecosystem services” framework in hydrology. More specifically, the water cycle could be seen as the ecosystem under study: “water services” (e.g. Lele, 2009; Ojea et al., 2012; Prasad, 2006). Following Daily's (1997) definition of ecosystem services, water services describe the conditions and processes through which the water cycle sustains and fulfils human life. We propose to extend this definition to include the vital role of water in the environment. By widely acknowledging and adopting water services as a concept in hydrology, scientific advances can help secure currently vulnerable water services in a dynamic natural and social environment.

Whereas water services indicate the services that water has for the environment and society, society also greatly influences the water system (Linton and Budds, 2014; Liu et al., 2014). This influence has been studied extensively during the *Panta Rhei* decade, leading to a push in the field of socio-hydrology (e.g. Di Baldassarre et al., 2018; McMillan et al., 2016; Pijl et al., 2018; Scott et al., 2014). Essential eco- and social systems heavily depend on limited water resources for services such as drinking water, irrigation water and hydropower. This dependence explains why the substantial population and economic growth over the last century caused a sharp increase in global domestic, industrial, and agricultural water demand (Oberle et al., 2019; Vörösmarty and Sahagian, 2000). The growing water demand threatens the sustainability of water systems and increases their vulnerability (Krol et al., 2003; McCluney et al., 2012). This vulnerability is exacerbated by unpredictable changes in the water cycle (e.g. hydrological intensification, salt intrusion) due to climate change (Oki and Kanae, 2006).

While society depends on water resources, anthropogenic activities have compromised the quality of these resources and related environmental systems. For instance, sea-level rise is threatening groundwater reservoirs (Rotzoll and Fletcher, 2013), and all parts of the water cycle are contaminated by pollutants such as plastic (Liu et al., 2020; van Emmerik and Schwarz, 2020), bilge water (Tiselius and Magnusson, 2017), nutrients (Lintern et al., 2020), pesticides (Payraudeau and Gregoire, 2012), road salt (Szklarek et al., 2022), and oil (Lucas and MacGregor, 2006). Next to affecting water quality, anthropogenic activities such as canalization also interrupt natural hydrological processes affecting water quantity (e.g. Owens et al., 2005). For example, ecosystem services such as flood protection and biodiversity are more likely to be lost from river deltas as a result of human activities upstream that interrupt natural sediment transport (Hoitink et al., 2020). Similarly, large-scaled drainage associated with land reclamation projects reduce the buffer function of wetlands and swamps (Nobis et al., 2020). Therefore, recent research has called to account for the dynamic impacts of anthropogenic activities in river transformation (Russell et al., 2021).

In the sustainable development goals, the United Nations (2015) recognize that sustainable water resource management is essential to ensure a sustainable future. Still, estimates suggest that water insecurity is threatening about 80% of the world’s population (Vörösmarty et al., 2010). Many of these people live in ecologically fragile, conflict-ridden, and violence-affected countries that suffer the most from poorly managed water resources (Anderson et al., 2021; World bank group, 2021). The water-peace-security nexus is further impacted by the COVID-19 pandemic (Mukhtarov et al., 2022) and recent intensifications of geopolitical rivalry (De Falco and Fiorentino, 2022). We believe scientific advances in hydrology could facilitate sustainable water resource management, especially for less resilient societies that are most threatened by water insecurity.

Hydrology has supported water resource management by generating and conveying understanding of water resources and hydrological extremes (Savenije and Van der Zaag, 2008). This traditional hydrological support should be broadened to incorporate human-water interactions, to include the spatiotemporal scales of water, and to tackle managerial challenges for transboundary water systems (Blöschl et al., 2019). This involves a holistic management approach, where the entire water cycle is seen as one system (Bakker, 2012; Cao and Warford, 2006; Giupponi and Gain, 2017). Implementation of this holistic approach can be supported by widely adopting the use of “water services” as a concept in hydrology. We suggest four key research questions for the theme “Water services under pressure” to advance the field of hydrology:

- How can we assess quantitative and qualitative water availability for sustainable water services?
- What hydrological knowledge is missing to provide solutions to support water services?
- How can the development of pressures on water services be identified, monitored and predicted?

- What are the scales and spatiotemporal distributions of pressures on water services?

Current trends in hydrology

Next to the themes, we identified four important trends in hydrology. These trends are not included as a theme, since they concern the way of conducting research. We note that these trends have gained traction over the past years, and think that fully incorporating them in the hydrological sciences can help make research more efficient, more reproducible, and easier to apply in practice. That is why we think these trends should be incorporated in the design of the upcoming SD. The following four trends are discussed here:

- Big data
- Inter-and multidisciplinarity
- Bridging science and practice
- Open science

Big data

In the early days of hydrology, hydrological data were limited to those collected in the field. Automized sensors greatly improved the availability of in situ data, but they are still characterized by high costs and limited spatial coverage. New technologies such as remote sensing have provided us with better spatiotemporal data coverage, as well as measurements covering a larger part of the hydrological cycle, including for instance precipitation, evapotranspiration, snow, soil moisture, and water storage (Addor et al., 2017; Almagro et al., 2021; Arsenault et al., 2016; Cui et al., 2018; Klingler et al., 2021). Due to the size of these datasets, big data is a big topic in the environmental sciences including hydrology (Chen and Wang, 2018, Gaffoor, et al. 2020). We recognize the value of big data in improving data-driven science on water resources. With higher data availability, questions arise on how to use this data efficiently and how to extract knowledge from different data sources simultaneously.

Big data in hydrology does not only present new opportunities, but also challenges. First of all, data quality and uncertainty are pressing issues, as poor or inconsistent data quality can lead to inaccurate interpretations and unreliable conclusions (Lawton, 2021; McMillan et al., 2018). To create robust big data, they need to be validated against in situ data. Thus, in-situ data collection needs to be incentivized to sustain in-situ validation efforts (Allen and Berghuijs, 2020), while research should also focus on minimizing the spatial mismatch between the scales of in-situ and big data (Loew et al., 2017). Another challenge is that big data analyses, such as machine learning, are often complex. This complexity makes results difficult to interpret, validate and reproduce.

Secondly, despite the development of big data, data-sparse regions still exist (Wilby, 2019) and hydrology is often still considered a data-limited science. Data availability is not evenly distributed over the globe and over the layers of the hydrological systems. In particular, data are missing on subsurface variables. We should therefore continue to develop affordable data collection, which can help the growth of citizen-science products that have the potential to increase observations in data-sparse regions (Buytaert et al., 2014). We should also continue performing reanalyses to fill temporal gaps in historical data.

Lastly, storing large datasets is challenging due to limited and/or expensive storage. Historical data is already being rapidly lost (Benito et al., 2015; Talke and Jay, 2013), so besides ensuring that data we collect now will remain available for future generations, we should also focus on conserving the work of previous generations that have not (yet) been digitized.

While big data has the potential to advance our understanding of hydrology, there is a strong need to develop universal data collection protocols to improve the foundations of reproducible data analysis and predictions. We should aim to use the full potential of all available data together, without subjectively selecting and rejecting data sources. We suggest to increase the cooperation between hydrologists and data scientists to jointly tackle the raised challenges defined here.

Inter- and multidisciplinarity

Seventeen sustainable development goals were posed by the United Nations that all ascend beyond boundaries of separate scientific disciplines (United Nations, 2015). Thus, to attain the SDGs, scientists need to adopt a more inter- and multidisciplinary approach. They can focus on their own discipline and share knowledge (multidisciplinarity) or combine the disciplines into a coherent whole (interdisciplinarity, Annan-Diab and Molinari, 2017). Hydrology can be more intertwined with closely related fields of research, such as meteorology (Sene, 2010), sedimentology (Waldschläger et al., 2022), and plant sciences (Konkol et al., 2022).

The complex themes of past and future SDs require efforts to bridge the divide between the environmental and social sciences (transdisciplinarity). In line with hydrology’s collaborative history, the non-solitary research style was also recognized as a key pillar to the success of the *Panta Rhei* decade (Montanari et al., 2013) and is gaining traction in other scientific disciplines as well (Van Noorden, 2015). Thus, we should critically evaluate what and how scientific expertise outside of hydrology could be integrated in hydrology (Seidl and Barthel, 2017). However, practical difficulties arise when conducting multi-, inter-, or transdisciplinary research (e.g. Brown et al., 2015; Lang et al., 2012; Lélé and Norgaard, 2005; Strober, 2006). Such collaborations are often characterized by considerable differences in scientific culture, potentially impeding their success. For example, environmental researchers may experience social sciences as subjective, while it may frustrate social scientists if environmental researchers do not recognize social implications (Brown et al., 2015). Familiarizing oneself with such cultural differences facilitates effective multi-, inter-, and transdisciplinary research.

We argue that education on these collaborative approaches as well as on related disciplines will pave the way for more successful collaborations. Funding agencies, educators, institutions, publishers and researchers should continue to promote collaborations between disciplines to incentivize, streamline and disseminate multi-, inter-, and transdisciplinary research to drive global sustainable development.

Bridging science and practice

One of the research questions posed in *Panta Rhei* was: "How can we support societies to adapt to changing conditions by considering the uncertainties and feedbacks between natural and human-induced hydrological changes?" (Montanari et al., 2013). This question is part of the attention that has been given to close the gap between science and practice. We distinguish the gap between hydrology and water management and between science and the general public and will start to discuss the first. Stakeholders are increasingly incorporated in research through collaborations between scientists, companies and governments, often stimulated by funding agencies. For example, Cortes Arevalo et al. (2020) use visual storytelling to strengthen the science-practice interface. Additionally, working groups that stimulate the bridge between science and practice have also been set up, such as the IAHS CANDHY working group. They aim to "*stimulate discussion, sharing of knowledge, information, data, ideas* *fostering scientific and professional exchange of academic, institutional and citizen communities interested in the "Citizen AND HYdrology" topic*". We endorse these efforts and see them as the first part of the bridge, but we argue both gaps should be reduced even further.

In order to decrease the gap, we should overcome the difficulties that are encountered when aiming to bridge science and practice. For one, clear communication is impeded by different interpretation of water-related words such as river and dike (Venhuizen et al., 2019). On top of that, stakeholders may hesitate to implement scientific knowledge due to a lack of trust, contradictory findings, or high costs (Raška et al., 2022). Overcoming these challenges would enable the use of state-of-the-art knowledge in decision-making (McMillan et al., 2016) and requires clear and open communication between scientists, stakeholders and policy makers, as well as a reflection on governance strategies based on scientific output. We acknowledge the debate of the role of science in society (Higgins et al., 2006), but we believe science should benefit society. Therefore, stakeholders and policy makers need to address what knowledge is needed in practice, and scientists need to clearly address the limitations of their research.

Science and the general public are brought closer by science communication. Scientists communicate their findings, because they want to be transparent to the general public (Kirchner, 2017), to reduce scepticism (Hamilton et al., 2015), and to inform and educate (Dudo and Besley, 2016). However, science communication is not easy. Scientists sharing their results have to translate their research into intriguing stories with a clear narrative about potentially controversial topics. In doing so, they may run into miscommunication, misinterpretation, and exaggeration (Lutz et al., 2018).

We propose to empower the future generation of scientists by incorporating science communication in their curricula.

Open science

Publishing scientific work open access (OA) has become increasingly common, with many funding agencies requiring research to be published OA. However, open science (OS) does not end at publishing OA. OS includes opening all parts of the research process: ideation, data collection and analysis, and dissemination of the results to peers as well as the public. Science can be made more open and reproducible by sharing data on public repositories, using open software, by sharing preprints and negative results, and by having an open-peer review process. OS increases accessibility to fellow scientists and the public, improves reproducibility, transparency, and collaboration, and credits original ideas and work properly (Gil et al., 2016; Hall et al., 2022; van Emmerik et al., 2018). Moreover, OS can bridge the global North-South research divide leading to increased inclusivity in science practices (Adcock and Fottrell, 2008; Tennant et al., 2016).

Publishers and scientists already widely acknowledge the importance of OS. Some journals require both data and code to be Findable, Accessible, Interoperable, and Reusable (FAIR standards, (Stall et al., 2017; Wilkinson et al., 2016)). In turn, hydrological researchers are raising awareness by sharing guidelines like the "Open Hydrology Practical Guide" (Hall et al., 2022).

While science as a whole is becoming increasingly open, some challenges still need to be tackled. First, OS is financially and timewise more expensive for the researchers. Financially, OA involves fees, and storing research data is expensive. Timewise, publishing reproducible code and data is more labour-intensive than storing code and data for personal use (Hall et al., 2022). Moreover, not all observations are quantifiable and transferable (Blume et al., 2018). Publishing code and data requires experience with for example version control, which is often lacking (Hall et al., 2022). A second challenge is that publishing data is sometimes prevented due to privacy, commercial, political, and economic concerns (Zipper et al., 2020). Third, preprints are often criticized for their poor scientific quality due to lacking prior peer review.

A fully open and transparent way of doing science can lead to faster advances in hydrology and is therefore, in our opinion, the only way forward. We do believe that the discussed three challenges can and should be tackled to promote OS in hydrological research. On top of that, OS should be included in education and additional efforts to practice OS should be better rewarded in the academic system. Since these efforts cannot stand on their own, it is important that funding agencies also see the value of OS. Additional funding is required to fully incorporate OS in education and to support any additional efforts scientists make to publish their research OS.

Synthesis and outlook

Climate change and population growth give rise to hydrological threats. We see these threats as the central problem for hydrology in the coming decade. Hydrological research should thus be focused on alleviating these threats. This can be done from different perspectives. Therefore, we are convinced that the theme of the upcoming decade should offer a perspective to tackle hydrological threats. We identified three perspectives that could be the theme for the upcoming IAHS SD: “Tipping points and thresholds in hydrology”, “Intensification of the water cycle”, and “Water services under pressure” (Figure 2). We also identified four trends that concern the way in which hydrological research is conducted: big data, bridging science and practice, open science, and inter- and multidisciplinarity. If future research is executed according to these guidelines, it could more efficiently benefit the entire hydrological community and more effectively alleviate the hydrological threats.

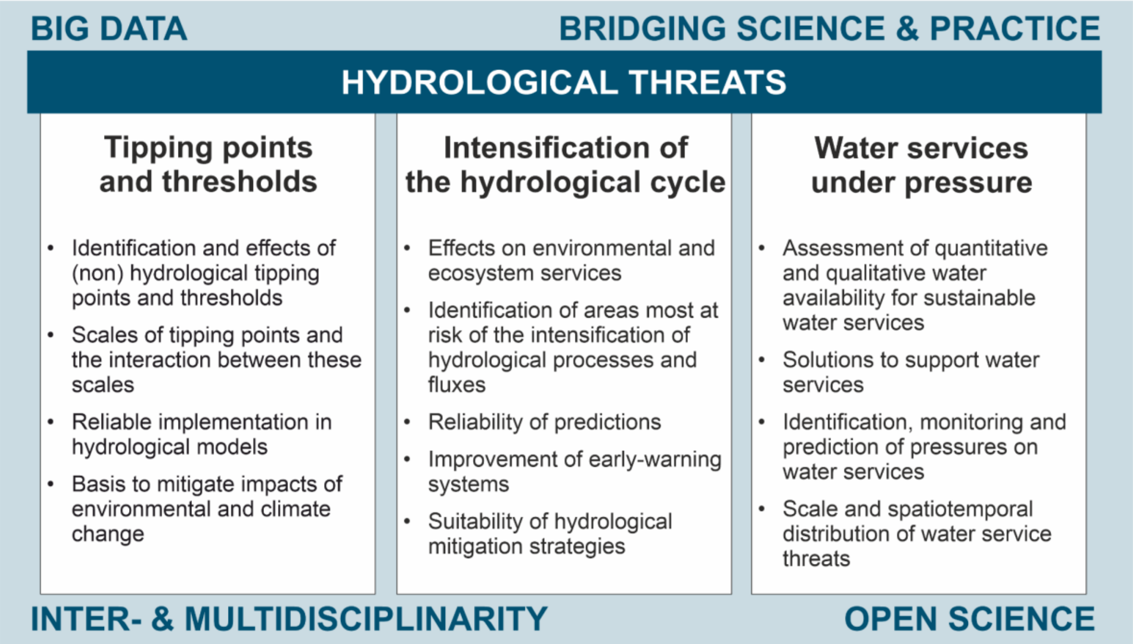

Figure 2: Overview of the themes and trends presented in this paper.

The three themes and four trends are presented separately in this paper, but it should be noted that they are highly connected. The themes outline possible pathways of future hydrological research and the trends have the potential to improve the speed, applicability and reproducibility of hydrological research. The connectivity between themes is seen by for instance the co-occurrence of tipping points with the intensification of the hydrological cycle. Impact identification, mitigation strategies and reliable implementation in hydrological models are overlapping focal points in the themes. Connectivity between trends is visible in for instance using big data in combination with open science could lead to quicker advances in the field, as well as a more inclusive research community. If this is further combined with effective science communication, the knowledge can be directly applied by policy makers and the public to alleviate some of the threats we are currently facing as a society.

We offered an ECS perspective in the discussion on the theme of the new IAHS scientific decade. We synthesized the outcome of six discussion sessions in western

Europe in the spring of 2022. Along with the themes, we highlighted a number of research questions that, in our view, should be addressed in the next scientific decade. We acknowledge that the logistical limitations of our initiative have led to a spatial bias. To overcome the limitations posed by this bias, we encourage ECS across the world to share their opinion, get involved in the IAHS SD discussions, and organize their own ECS discussion sessions. These sessions could be organized according to the guidelines provided in the supporting information, which are also available online with the possibility to post comments (https://github.com/tvhat/ECSdiscussion-IAHSSD). By targeting currently underrepresented groups with this type of sessions, inclusivity is actively pursued, which we deem necessary as a passive open invitation will not automatically lead to diversity. We hope to see a lively discussion as a result of this opinion paper and are confident that the presented themes, research questions, and trends will feed into the larger debate on the next IAHS SD.

Acknowledgements

This project was funded by the Hydrology and Quantitative Water management group, the Wageningen Institute for Environment and Climate Research and the LEB Foundation. We want to thank all participants of the discussion sessions for their input. We also want to thank Danyka Byrnes, Moctar Dembélé, Nilay Dogulu, Pankaj Kumar, Daniel Myers, Albert Nkwasa, Bertil Nlend, Lina Stein, Anatoly Tsyplenkov and Florentine Weber for their feedback that helped improve this manuscript and our vision on the continuation of including more diversity.

References

Abram, N.J., Henley, B.J., Sen Gupta, A., Lippmann, T.J.R., Clarke, H., Dowdy, A.J., Sharples, J.J., Nolan, R.H., Zhang, T., Wooster, M.J., Wurtzel, J.B., Meissner, K.J., Pitman, A.J., Ukkola, A.M., Murphy, B.P., Tapper, N.J., Boer, M.M.,

2021. Connections of climate change and variability to large and extreme forest fires in southeast Australia. Commun. Earth Environ. 2, 1–17. https://doi.org/10.1038/s43247-020-00065-8

Adcock, J., Fottrell, E., 2008. The North-South information highway: case studies of publication access among health researchers in resource-poor countries. Glob. Health Action 1, 10.3402/gha.v1i0.1865. https://doi.org/10.3402/gha.v1i0.1865

Addo, K.A., Adeyemi, M., 2013. Assessing the impact of sea-level rise on a vulnerable coastal community in Accra, Ghana. Jàmbá J. Disaster Risk Stud. 5, 8. https://doi.org/10.4102/jamba.v5i1.60

Addor, N., Newman, A.J., Mizukami, N., Clark, M.P., 2017. The CAMELS data set: catchment attributes and meteorology for large-sample studies. Hydrol. Earth Syst. Sci. 21, 5293–5313. https://doi.org/10.5194/hess-21-5293-2017

Alfieri, L., Burek, P., Feyen, L., Forzieri, G., 2015. Global warming increases the frequency of river floods in Europe. Hydrol. Earth Syst. Sci. 19, 2247–2260. https://doi.org/10.5194/hess-19-2247-2015

Allan, R.P., 2014. Dichotomy of drought and deluge. Nat. Geosci. 7, 700–701. https://doi.org/10.1038/ngeo2243

Allen, S.T., Berghuijs, W.R., 2020. A need for incentivizing field hydrology, especially in an era of open data: discussion of “The role of experimental work in hydrological sciences – insights from a community survey”*. Hydrol. Sci. J. 65, 1262–1265. https://doi.org/10.1080/02626667.2018.1495837

Almagro, A., Oliveira, P.T.S., Meira Neto, A.A., Roy, T., Troch, P., 2021. CABra: a novel large-sample dataset for Brazilian catchments. Hydrol. Earth Syst. Sci. 25, 3105–3135. https://doi.org/10.5194/hess-25-3105-2021

Amigo, I., 2020. When will the Amazon hit a tipping point? Nature 578, 505–507. https://doi.org/10.1038/d41586-020-00508-4

Anderson, W., Taylor, C., McDermid, S., Ilboudo-Nébié, E., Seager, R., Schlenker, W., Cottier, F., de Sherbinin, A., Mendeloff, D., Markey, K., 2021. Violent conflict exacerbated drought-related food insecurity between 2009 and 2019 in sub-Saharan Africa. Nat. Food 2, 603–615. https://doi.org/10.1038/s43016-021-00327-4

Annan-Diab, F., Molinari, C., 2017. Interdisciplinarity: Practical approach to advancing education for sustainability and for the Sustainable Development Goals. Int. J.

Manag. Educ., Principles for Responsible Management Education 15, 73–83. https://doi.org/10.1016/j.ijme.2017.03.006

Ansah, S.O., Ahiataku, M.A., Yorke, C.K., Otu-Larbi, F., Yahaya, B., Lamptey, P.N.L., Tanu, M., 2020. Meteorological Analysis of Floods in Ghana. Adv. Meteorol. 2020, e4230627. https://doi.org/10.1155/2020/4230627

Arsenault, R., Bazile, R., Ouellet Dallaire, C., Brissette, F., 2016. CANOPEX: A Canadian hydrometeorological watershed database. Hydrol. Process. 30, 2734–2736. https://doi.org/10.1002/hyp.10880

Bailey, R.M., 2011. Spatial and temporal signatures of fragility and threshold proximity in modelled semi-arid vegetation. Proc. R. Soc. B Biol. Sci. 278, 1064–1071. https://doi.org/10.1098/rspb.2010.1750

Bakker, K., 2012. Water Security: Research Challenges and Opportunities. Science 337, 914–915. https://doi.org/10.1126/science.1226337

Barneveld, H., Frings, R., Hoitink, T., 2022. Massive morphological changes during the 2021 summer flood in the River Meuse (No. EGU22-11253). Presented at the EGU22, Copernicus Meetings. https://doi.org/10.5194/egusphere-egu22-11253

Barron, O., Froend, R., Hodgson, G., Ali, R., Dawes, W., Davies, P., MacFarlane, D., 2013. Projected risks to groundwater-dependent terrestrial vegetation caused by changing climate and groundwater abstraction in the Central Perth Basin, Western Australia. Res. Outputs 2013. https://doi.org/10.1002/hyp.10014

Beniston, M., Stoffel, M., 2014. Assessing the impacts of climatic change on mountain water resources. Sci. Total Environ. 493, 1129–1137. https://doi.org/10.1016/j.scitotenv.2013.11.122

Benito, G., Brázdil, R., Herget, J., Machado, M.J., 2015. Quantitative historical hydrology in Europe. Hydrol. Earth Syst. Sci. 19, 3517–3539. https://doi.org/10.5194/hess-19-3517-2015

Bernardino, P.N., De Keersmaecker, W., Fensholt, R., Verbesselt, J., Somers, B., Horion, S., 2020. Global-scale characterization of turning points in arid and semi-arid ecosystem functioning. Glob. Ecol. Biogeogr. 29, 1230–1245. https://doi.org/10.1111/geb.13099

Bertola, M., Viglione, A., Lun, D., Hall, J., Blöschl, G., 2020. Flood trends in Europe: are changes in small and big floods different? Hydrol. Earth Syst. Sci. 24, 1805–1822. https://doi.org/10.5194/hess-24-1805-2020

Blöschl, G., Bierkens, M.F.P., Chambel, A., Cudennec, C., Destouni, G., Fiori, A., Kirchner, J.W., McDonnell, J.J., Savenije, H.H.G., Sivapalan, M., Stumpp, C., Toth, E., Volpi, E., Carr, G., Lupton, C., Salinas, J., Széles, B., Viglione, A., Aksoy, H., Allen, S.T., Amin, A., Andréassian, V., Arheimer, B., Aryal, S.K., Baker, V., Bardsley, E., Barendrecht, M.H., Bartosova, A., Batelaan, O., Berghuijs, W.R., Beven, K., Blume, T., Bogaard, T., Borges de Amorim, P., Böttcher, M.E., Boulet, G., Breinl, K., Brilly, M., Brocca, L., Buytaert, W., Castellarin, A., Castelletti, A., Chen, X., Chen, Yangbo, Chen, Yuanfang, Chifflard, P., Claps, P., Clark, M.P., Collins, A.L., Croke, B., Dathe, A., David, P.C., de Barros, F.P.J., de Rooij, G., Di Baldassarre, G., Driscoll, J.M., Duethmann, D., Dwivedi, R., Eris, E., Farmer, W.H., Feiccabrino, J., Ferguson, G., Ferrari, E., Ferraris, S., Fersch, B., Finger, D., Foglia, L., Fowler, K., Gartsman, B., Gascoin, S., Gaume, E., Gelfan, A., Geris, J., Gharari, S., Gleeson, T., Glendell, M., Gonzalez Bevacqua, A., González-Dugo, M.P., Grimaldi, S., Gupta, A.B., Guse, B., Han, D., Hannah, D., Harpold, A., Haun, S., Heal, K., Helfricht, K., Herrnegger, M., Hipsey, M., Hlaváčiková, H., Hohmann, C., Holko, L., Hopkinson, C., Hrachowitz, M., Illangasekare, T.H., Inam, A., Innocente, C., Istanbulluoglu, E., Jarihani, B., Kalantari, Z., Kalvans, A., Khanal, S., Khatami, S., Kiesel, J., Kirkby, M., Knoben, W., Kochanek, K., Kohnová, S., Kolechkina, A., Krause, S., Kreamer, D., Kreibich, H., Kunstmann, H., Lange, H., Liberato, M.L.R., Lindquist, E., Link, T., Liu, J., Loucks, D.P., Luce, C., Mahé, G., Makarieva, O., Malard, J., Mashtayeva, S., Maskey, S., Mas-Pla, J., Mavrova-Guirguinova, M., Mazzoleni, M., Mernild, S., Misstear, B.D., Montanari, A., Müller-Thomy, H., Nabizadeh, A., Nardi, F., Neale, C., Nesterova, N., Nurtaev, B., Odongo, V.O., Panda, S., Pande, S., Pang, Z., Papacharalampous, G., Perrin, C., Pfister, L., Pimentel, R., Polo, M.J., Post, D., Prieto Sierra, C., Ramos, M.-H., Renner, M., Reynolds, J.E., Ridolfi, E., Rigon, R., Riva, M., Robertson, D.E., Rosso, R., Roy, T., Sá, J.H.M., Salvadori, G., Sandells, M., Schaefli, B., Schumann, A., Scolobig, A., Seibert, J., Servat, E., Shafiei, M., Sharma, A., Sidibe, M., Sidle, R.C., Skaugen, T., Smith, H., Spiessl, S.M., Stein, L., Steinsland, I., Strasser, U., Su, B., Szolgay, J., Tarboton, D., Tauro, F., Thirel, G., Tian, F., Tong, R., Tussupova, K., Tyralis, H., Uijlenhoet, R., van Beek, R., van der Ent, R.J., van der Ploeg, M., Van Loon, A.F., van Meerveld, I., van Nooijen, R., van Oel, P.R., Vidal, J.-P., von Freyberg, J., Vorogushyn, S., Wachniew, P., Wade, A.J., Ward, P., Westerberg, I.K., White, C., Wood, E.F., Woods, R., Xu, Z., Yilmaz, K.K., Zhang, Y., 2019. Twenty-three unsolved problems in hydrology (UPH) – a community perspective. Hydrol. Sci. J. 64, 1141–1158. https://doi.org/10.1080/02626667.2019.1620507

Blume, T., van Meerveld, I., Weiler, M., 2018. Incentives for field hydrology and data sharing: collaboration and compensation: reply to “A need for incentivizing field hydrology, especially in an era of open data”*. Hydrol. Sci. J. 63, 1266–1268. https://doi.org/10.1080/02626667.2018.1495839

Brown, R.R., Deletic, A., Wong, T.H.F., 2015. Interdisciplinarity: How to catalyse collaboration. Nature 525, 315–317. https://doi.org/10.1038/525315a

Buitink, J., Swank, A.M., van der Ploeg, M., Smith, N.E., Benninga, H.-J.F., van der Bolt, F., Carranza, C.D.U., Koren, G., van der Velde, R., Teuling, A.J., 2020. Anatomy of the 2018 agricultural drought in The Netherlands using in situ soil moisture and satellite vegetation indices. Hydrol. Earth Syst. Sci. Discuss. 1–17. https://doi.org/10.5194/hess-2020-358

Buitink, J., van Hateren, T.C., Teuling, A.J., 2021. Hydrological System Complexity Induces a Drought Frequency Paradox. Front. Water 3. https://doi.org/10.3389/frwa.2021.640976

Buras, A., Rammig, A., Zang, C.S., 2020. Quantifying impacts of the 2018 drought on European ecosystems in comparison to 2003. Biogeosciences 17, 1655–1672. https://doi.org/10.5194/bg-17-1655-2020

Buytaert, W., Zulkafli, Z., Grainger, S., Acosta, L., Alemie, T.C., Bastiaensen, J., De Bièvre, B., Bhusal, J., Clark, J., Dewulf, A., Foggin, M., Hannah, D.M., Hergarten, C., Isaeva, A., Karpouzoglou, T., Pandeya, B., Paudel, D., Sharma, K., Steenhuis, T., Tilahun, S., Van Hecken, G., Zhumanova, M., 2014. Citizen science in hydrology and water resources: opportunities for knowledge generation, ecosystem service management, and sustainable development. Front. Earth Sci. 2.

Cao, Y.S., Warford, J., 2006. Evolution of integrated approaches to water resource management in Europe and the United States: some lessons from experience.

Carvalho-Santos, C., Monteiro, A.T., Azevedo, J.C., Honrado, J.P., Nunes, J.P., 2017. Climate Change Impacts on Water Resources and Reservoir Management: Uncertainty and Adaptation for a Mountain Catchment in Northeast Portugal. Water Resour. Manag. 31, 3355–3370. https://doi.org/10.1007/s11269-017-1672-z

Christidis, N., Stott, P.A., 2021. The influence of anthropogenic climate change on wet and dry summers in Europe. Sci. Bull. 66, 813–823. https://doi.org/10.1016/j.scib.2021.01.020

Cortes Arevalo, V.J., Verbrugge, L.N.H., Sools, A., Brugnach, M., Wolterink, R., van Denderen, R.P., Candel, J.H.J., Hulscher, S.J.M.H., 2020. Storylines for practice: a visual storytelling approach to strengthen the science-practice interface. Sustain. Sci. 15, 1013–1032. https://doi.org/10.1007/s11625-020-00793-y

Couasnon, A., Eilander, D., Muis, S., Veldkamp, T.I.E., Haigh, I.D., Wahl, T., Winsemius, H.C., Ward, P.J., 2020. Measuring compound flood potential from river discharge and storm surge extremes at the global scale. Nat. Hazards Earth Syst. Sci. 20, 489–504. https://doi.org/10.5194/nhess-20-489-2020

Cui, Y., Chen, X., Gao, J., Yan, B., Tang, G., Hong, Y., 2018. Global water cycle and remote sensing big data: overview, challenge, and opportunities. Big Earth Data 2, 282–297. https://doi.org/10.1080/20964471.2018.1548052

Cutter, S.L., Emrich, C.T., Gall, M., Reeves, R., 2018. Flash Flood Risk and the Paradox of Urban Development. Nat. Hazards Rev. 19. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000268

Dai, L., Wörner, R., van Rijswick, H.F.M.W., 2018. Rainproof cities in the Netherlands: approaches in Dutch water governance to climate-adaptive urban planning. Int. J. Water Resour. Dev. 34, 652–674. https://doi.org/10.1080/07900627.2017.1372273

Daily, G.C., 1997. Introduction: What are ecosystem services?, in: Nature’s Services: Societal Dependence on Natural Ecosystems. Island Press.

Dakos, V., Matthews, B., Hendry, A.P., Levine, J., Loeuille, N., Norberg, J., Nosil, P., Scheffer, M., De Meester, L., 2019. Ecosystem tipping points in an evolving world. Nat. Ecol. Evol. 3, 355–362. https://doi.org/10.1038/s41559-019-0797-2

De Falco, S., Fiorentino, G., 2022. The GERD dam in the water dispute between Ethiopia, Sudan and Egypt. A scenario analysis in an ecosystem approach between physical and geopolitical geography. AIMS Geosci. 8, 233–253. https://doi.org/10.3934/geosci.2022014

De Luca, P., Messori, G., Wilby, R.L., Mazzoleni, M., Di Baldassarre, G., 2020. Concurrent wet and dry hydrological extremes at the global scale. Earth Syst. Dyn. 11, 251–266. https://doi.org/10.5194/esd-11-251-2020

Denissen, J.M.C., Teuling, A.J., Reichstein, M., Orth, R., 2020. Critical Soil Moisture Derived From Satellite Observations Over Europe. J. Geophys. Res. Atmospheres 125. https://doi.org/10.1029/2019JD031672

Devoie, É.G., Craig, J.R., Connon, R.F., Quinton, W.L., 2019. Taliks: A Tipping Point in Discontinuous Permafrost Degradation in Peatlands. Water Resour. Res. 55, 9838–9857. https://doi.org/10.1029/2018WR024488

Di Baldassarre, G., Wanders, N., AghaKouchak, A., Kuil, L., Rangecroft, S., Veldkamp, T.I.E., Garcia, M., van Oel, P.R., Breinl, K., Van Loon, A.F., 2018. Water shortages worsened by reservoir effects. Nat. Sustain. 1, 617–622. https://doi.org/10.1038/s41893-018-0159-0

Dijkstra, Y.M., Schuttelaars, Henk.M., Schramkowski, G.P., 2019. A Regime Shift From Low to High Sediment Concentrations in a Tide-Dominated Estuary. Geophys. Res. Lett. 46, 4338–4345. https://doi.org/10.1029/2019GL082302

Drijfhout, S., Bathiany, S., Beaulieu, C., Brovkin, V., Claussen, M., Huntingford, C., Scheffer, M., Sgubin, G., Swingedouw, D., 2015. Catalogue of abrupt shifts in Intergovernmental Panel on Climate Change climate models. Proc. Natl. Acad. Sci. 112, E5777–E5786. https://doi.org/10.1073/pnas.1511451112

Duan, W., He, B., Takara, K., Luo, P., Nover, D., Yamashiki, Y., Huang, W., 2014. Anomalous atmospheric events leading to Kyushu’s flash floods, July 11–14, 2012. Nat. Hazards 73, 1255–1267. https://doi.org/10.1007/s11069-014-1134-3

Dudo, A., Besley, J.C., 2016. Scientists’ Prioritization of Communication Objectives for Public Engagement. PLOS ONE 11, e0148867. https://doi.org/10.1371/journal.pone.0148867

Dunne, T., Black, R.D., 1970a. An Experimental Investigation of Runoff Production in Permeable Soils. Water Resour. Res. 6, 478–490. https://doi.org/10.1029/WR006i002p00478

Dunne, T., Black, R.D., 1970b. Partial Area Contributions to Storm Runoff in a Small New England Watershed. Water Resour. Res. 6, 1296–1311. https://doi.org/10.1029/WR006i005p01296

Ehret, U., Gupta, H.V., Sivapalan, M., Weijs, S.V., Schymanski, S.J., Blöschl, G., Gelfan, A.N., Harman, C., Kleidon, A., Bogaard, T.A., Wang, D., Wagener, T., Scherer, U., Zehe, E., Bierkens, M.F.P., Di Baldassarre, G., Parajka, J., van Beek, L.P.H., van Griensven, A., Westhoff, M.C., Winsemius, H.C., 2014. Advancing catchment hydrology to deal with predictions under change. Hydrol. Earth Syst. Sci. 18, 649–671. https://doi.org/10.5194/hess-18-649-2014

Emerton, R.E., Stephens, E.M., Pappenberger, F., Pagano, T.C., Weerts, A.H., Wood, A.W., Salamon, P., Brown, J.D., Hjerdt, N., Donnelly, C., Baugh, C.A., Cloke, H.L., 2016. Continental and global scale flood forecasting systems. WIREs Water 3, 391–418. https://doi.org/10.1002/wat2.1137

Figura, S., Livingstone, D.M., Hoehn, E., Kipfer, R., 2011. Regime shift in groundwater temperature triggered by the Arctic Oscillation. Geophys. Res. Lett. 38. https://doi.org/10.1029/2011GL049749

Gams, I., Gabrovec, M., 1999. Land use and human impact in the Dinaric karst. Int. J. Speleol. 28, 55–70. https://doi.org/10.5038/1827-806X.28.1.4

Gil, Y., David, C.H., Demir, I., Essawy, B.T., Fulweiler, R.W., Goodall, J.L., Karlstrom, L., Lee, H., Mills, H.J., Oh, J., Pierce, S.A., Pope, A., Tzeng, M.W., Villamizar, S.R., Yu, X., 2016. Toward the Geoscience Paper of the Future: Best practices for documenting and sharing research from data to software to provenance. Earth Space Sci. 3, 388–415. https://doi.org/10.1002/2015EA000136

Giupponi, C., Gain, A.K., 2017. Integrated water resources management (IWRM) for climate change adaptation. Reg. Environ. Change 17, 1865–1867. https://doi.org/10.1007/s10113-017-1173-x

Gloor, M., Brienen, R.J.W., Galbraith, D., Feldpausch, T.R., Schöngart, J., Guyot, J.-L., Espinoza, J.C., Lloyd, J., Phillips, O.L., 2013. Intensification of the Amazon hydrological cycle over the last two decades. Geophys. Res. Lett. 40, 1729–1733. https://doi.org/10.1002/grl.50377

Greve, P., Orlowsky, B., Mueller, B., Sheffield, J., Reichstein, M., Seneviratne, S.I., 2014. Global assessment of trends in wetting and drying over land. Nat. Geosci. 7, 716–721. https://doi.org/10.1038/ngeo2247

Hall, C.A., Saia, S.M., Popp, A.L., Dogulu, N., Schymanski, S.J., Drost, N., van Emmerik, T., Hut, R., 2022. A hydrologist’s guide to open science. Hydrol. Earth Syst. Sci. 26, 647–664. https://doi.org/10.5194/hess-26-647-2022

Hamilton, L.C., Hartter, J., Saito, K., 2015. Trust in Scientists on Climate Change and Vaccines. SAGE Open 5, 2158244015602752. https://doi.org/10.1177/2158244015602752

Held, I.M., Soden, B.J., 2006. Robust Responses of the Hydrological Cycle to Global Warming. J. Clim. 19, 5686–5699. https://doi.org/10.1175/JCLI3990.1

Higgins, P.A.T., Chan, K.M.A., Porder, S., 2006. Bridge over a philosophical divide. Evid. Policy 2, 249–255. https://doi.org/10.1332/174426406777068920

Hirota, M., Holmgren, M., Van Nes, E.H., Scheffer, M., 2011. Global Resilience of Tropical Forest and Savanna to Critical Transitions. Science 334, 232–235. https://doi.org/10.1126/science.1210657

Hoitink, A.J.F., Nittrouer, J.A., Passalacqua, P., Shaw, J.B., Langendoen, E.J., Huismans, Y., van Maren, D.S., 2020. Resilience of River Deltas in the Anthropocene. J. Geophys. Res. Earth Surf. 125, e2019JF005201. https://doi.org/10.1029/2019JF005201

Horton, R.E., 1945. Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology. Geol. Soc. Am. Bull. 56, 275. https://doi.org/10.1130/0016-7606(1945)56[275:EDOSAT]2.0.CO;2

Hrachowitz, M., Savenije, H.H.G., Blöschl, G., McDonnell, J.J., Sivapalan, M., Pomeroy, J.W., Arheimer, B., Blume, T., Clark, M.P., Ehret, U., Fenicia, F., Freer, J.E., Gelfan, A., Gupta, H.V., Hughes, D.A., Hut, R.W., Montanari, A., Pande, S., Tetzlaff, D., Troch, P.A., Uhlenbrook, S., Wagener, T., Winsemius, H.C., Woods, R.A., Zehe, E., Cudennec, C., 2013. A decade of Predictions in Ungauged Basins (PUB)—a review. Hydrol. Sci. J. 58, 1198–1255. https://doi.org/10.1080/02626667.2013.803183

Huntington, T.G., 2006. Evidence for intensification of the global water cycle: Review and synthesis. J. Hydrol. 319, 83–95. https://doi.org/10.1016/j.jhydrol.2005.07.003

IPCC, 2021. Climate change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Keefer, D.K., Wilson, R.C., Mark, R.K., Brabb, E.E., Brown, W.M., Ellen, S.D., Harp, E.L., Wieczorek, G.F., Alger, C.S., Zatkin, R.S., 1987. Real-time landslide warning during heavy rainfall. Science 238, 921–925. https://doi.org/10.1126/science.238.4829.921

Kennedy, D., Parker, T., Woollings, T., Harvey, B., Shaffrey, L., 2016. The response of high-impact blocking weather systems to climate change. Geophys. Res. Lett. 43, 7250–7258. https://doi.org/10.1002/2016GL069725

Kirchner, J.W., 2017. Science, politics, and rationality in a partisan era. Water Resour. Res. 53, 3545–3549. https://doi.org/10.1002/2017WR020882

Kirwan, M.L., Megonigal, J.P., 2013. Tidal wetland stability in the face of human impacts and sea-level rise. Nature 504, 53–60. https://doi.org/10.1038/nature12856

Kitoh, A., Endo, H., Krishna Kumar, K., Cavalcanti, I.F.A., Goswami, P., Zhou, T., 2013. Monsoons in a changing world: A regional perspective in a global context. J. Geophys. Res. Atmospheres 118, 3053–3065. https://doi.org/10.1002/jgrd.50258

Klingler, C., Schulz, K., Herrnegger, M., 2021. LamaH-CE: LArge-SaMple DAta for Hydrology and Environmental Sciences for Central Europe. Earth Syst. Sci. Data 13, 4529–4565. https://doi.org/10.5194/essd-13-4529-2021

Konkol, A., Schwenk, J., Katifori, E., Shaw, J.B., 2022. Interplay of River and Tidal Forcings Promotes Loops in Coastal Channel Networks. Geophys. Res. Lett. 49, e2022GL098284. https://doi.org/10.1029/2022GL098284

Koutsoyiannis, D., 2020. Revisiting the global hydrological cycle: is it intensifying? Hydrol. Earth Syst. Sci. 24, 3899–3932. https://doi.org/10.5194/hess-24-3899-2020

Kreibich, H., Krueger, T., Van Loon, A., Mejia, A., Liu, J., McMillan, H., Castellarin, A., 2017. Scientific debate of Panta Rhei research – how to advance our knowledge of changes in hydrology and society? Hydrol. Sci. J. 62, 331–333. https://doi.org/10.1080/02626667.2016.1209929

Kreienkamp, F., Philip, S.Y., Tradowsky, J.S., Kew, S.F., Lorenz, P., Arrighi, J., Belleflamme, A., Bettmann, T., Caluwaerts, S., Chan, S.C., Ciavarella, A., De Cruz, L., de Vries, H., Demuth, N., Ferrone, A., Fischer, E.M., Fowler, H.J., Goergen, K., Heinrich, D., Henrichs, Y., Lenderink, G., Kaspar, F., Nilson, E., Otto, F.E.L., Ragone, F., Seneviratne, S.I., Singh, R.K., Skalevag, A., Termonia, P., Thalheimer, L., van Aalst, M., Van den Bergh, J., Van de Vyver, H., Vannitsem, S., van Oldenborgh, G.J., Van Schaeybroeck, B., Vautard, R., Vonk, D., Wanders, N., 2021. Rapid attribution of heavy rainfall events leading to the severe flooding in Western Europe during July 2021. World Weather Attribution.

Krishnamurthy R, P.K., Fisher, J.B., Schimel, D.S., Kareiva, P.M., 2020. Applying Tipping Point Theory to Remote Sensing Science to Improve Early Warning Drought Signals for Food Security. Earths Future 8, e2019EF001456. https://doi.org/10.1029/2019EF001456

Krol, M.S., Jaeger, A.-K., Bronstert, A., 2003. Integrated Modeling of Climate Change Impacts in Northeastern Brazil, in: Gaiser, T., Krol, M., Frischkorn, H., de Araújo, J.C. (Eds.), Global Change and Regional Impacts: Water Availability and Vulnerability of Ecosystems and Society in the Semiarid Northeast of Brazil. Springer, Berlin, Heidelberg, pp. 43–56. https://doi.org/10.1007/978-3-642-55659-3_3

Kumar, S., Allan, R.P., Zwiers, F., Lawrence, D.M., Dirmeyer, P.A., 2015. Revisiting trends in wetness and dryness in the presence of internal climate variability and water limitations over land. Geophys. Res. Lett. 42, 10,867-10,875. https://doi.org/10.1002/2015GL066858

Kundzewicz, Z., 2008. Climate change impacts on the hydrological cycle. Ecohydrol. Hydrobiol. 8, 195–203. https://doi.org/10.2478/v10104-009-0015-y

Kupec, P., Deutscher, J., Futter, M., 2021. Longer Growing Seasons Cause Hydrological Regime Shifts in Central European Forests. Forests 12, 1656. https://doi.org/10.3390/f12121656

Lang, D., Wiek, A., Bergmann, M., Stauffacher, M., Martens, P., Moll, P., Swilling, M., Thomas, C., 2012. Lang DJ, Wiek A, Bergmann M, Stauffacher M, Martens P, Moll P, Swilling M, Thomas CJ. Transdisciplinary research in sustainability science: Practice, principles, and challenges. Sustainability Science. Sustain. Sci. 7. https://doi.org/10.1007/s11625-011-0149-x

Lawton, G., 2021. Data quality for big data: Why it's a must and how to improve it. URL https://www.techtarget.com/searchdatamanagement/feature/Data-quality-for-big-data-Why-its-a-must-and-how-to-improve-it (accessed 5.11.22).

Lele, S., 2009. Watershed services of tropical forests: from hydrology to economic valuation to integrated analysis. Curr. Opin. Environ. Sustain. 1, 148–155. https://doi.org/10.1016/j.cosust.2009.10.007

Lélé, S., Norgaard, R.B., 2005. Practicing Interdisciplinarity. BioScience 55, 967–975. https://doi.org/10.1641/0006-3568(2005)055[0967:PI]2.0.CO;2

Lenderink, G., Barbero, R., Loriaux, J.M., Fowler, H.J., 2017. Super-Clausius–Clapeyron Scaling of Extreme Hourly Convective Precipitation and Its Relation to Large-Scale Atmospheric Conditions. J. Clim. 30, 6037–6052. https://doi.org/10.1175/JCLI-D-16-0808.1

Lenderink, G., van Meijgaard, E., 2008. Increase in hourly precipitation extremes beyond expectations from temperature changes. Nat. Geosci. 1, 511–514. https://doi.org/10.1038/ngeo262

Lenton, T.M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W., Schellnhuber, H.J., 2019. Climate tipping points — too risky to bet against. Nature 575, 592–595. https://doi.org/10.1038/d41586-019-03595-0

Lintern, A., McPhillips, L., Winfrey, B., Duncan, J., Grady, C., 2020. Best Management Practices for Diffuse Nutrient Pollution: Wicked Problems Across Urban and Agricultural Watersheds. Environ. Sci. Technol. 54, 9159–9174. https://doi.org/10.1021/acs.est.9b07511

Linton, J., Budds, J., 2014. The hydrosocial cycle: Defining and mobilizing a relational-dialectical approach to water. Geoforum 57, 170–180. https://doi.org/10.1016/j.geoforum.2013.10.008

Liu, K., Courtene-Jones, W., Wang, X., Song, Z., Wei, N., Li, D., 2020. Elucidating the vertical transport of microplastics in the water column: A review of sampling methodologies and distributions. Water Res. 186, 116403. https://doi.org/10.1016/j.watres.2020.116403

Liu, Y., Tian, F., Hu, H., Sivapalan, M., 2014. Socio-hydrologic perspectives of the co-evolution of humans and water in the Tarim River basin, Western China: the

Taiji–Tire model. Hydrol. Earth Syst. Sci. 18, 1289–1303. https://doi.org/10.5194/hess-18-1289-2014

Loew, A., Bell, W., Brocca, L., Bulgin, C.E., Burdanowitz, J., Calbet, X., Donner, R.V., Ghent, D., Gruber, A., Kaminski, T., Kinzel, J., Klepp, C., Lambert, J.-C., Schaepman-Strub, G., Schröder, M., Verhoelst, T., 2017. Validation practices for satellite-based Earth observation data across communities. Rev. Geophys. 55, 779–817. https://doi.org/10.1002/2017RG000562

Lovejoy, T.E., Nobre, C., 2018. Amazon Tipping Point. Sci. Adv. 4, eaat2340. https://doi.org/10.1126/sciadv.aat2340

Loverde-Oliveira, S.M., Huszar, V.L.M., Mazzeo, N., Scheffer, M., 2009. Hydrology-Driven Regime Shifts in a Shallow Tropical Lake. Ecosystems 12, 807.

Lucas, Z., MacGregor, C., 2006. Characterization and source of oil contamination on the beaches and seabird corpses, Sable Island, Nova Scotia, 1996–2005. Mar. Pollut. Bull. 52, 778–789. https://doi.org/10.1016/j.marpolbul.2005.11.023

Lutz, S.R., Popp, A., van Emmerik, T., Gleeson, T., Kalaugher, L., Möbius, K., Mudde, T., Walton, B., Hut, R., Savenije, H., Slater, L.J., Solcerova, A., Stoof, C.R., Zink, M., 2018. HESS Opinions: Science in today’s media landscape – challenges and lessons from hydrologists and journalists. Hydrol. Earth Syst. Sci. 22, 3589–3599. https://doi.org/10.5194/hess-22-3589-2018

Madakumbura, G.D., Kim, H., Utsumi, N., Shiogama, H., Fischer, E.M., Seland, Ø., Scinocca, J.F., Mitchell, D.M., Hirabayashi, Y., Oki, T., 2019. Event-to-event intensification of the hydrologic cycle from 1.5 °C to a 2 °C warmer world. Sci. Rep. 9, 3483. https://doi.org/10.1038/s41598-019-39936-2

Marty, C., 2008. Regime shift of snow days in Switzerland. Geophys. Res. Lett. 35. https://doi.org/10.1029/2008GL033998

Mayor, A.G., Bautista, S., Rodriguez, F., Kéfi, S., 2019. Connectivity-Mediated Ecohydrological Feedbacks and Regime Shifts in Drylands. Ecosystems 22, 1497–1511. https://doi.org/10.1007/s10021-019-00366-w

McCluney, K.E., Belnap, J., Collins, S.L., González, A.L., Hagen, E.M., Nathaniel Holland, J., Kotler, B.P., Maestre, F.T., Smith, S.D., Wolf, B.O., 2012. Shifting species interactions in terrestrial dryland ecosystems under altered water availability and climate change. Biol. Rev. 87, 563–582. https://doi.org/10.1111/j.1469-185X.2011.00209.x

McMillan, H., Montanari, A., Cudennec, C., Savenije, H., Kreibich, H., Krueger, T., Liu, J., Mejia, A., Van Loon, A., Aksoy, H., Di Baldassarre, G., Huang, Y., Mazvimavi, D., Rogger, M., Sivakumar, B., Bibikova, T., Castellarin, A., Chen, Y., Finger, D., Gelfan, A., Hannah, D.M., Hoekstra, A.Y., Li, H., Maskey, S., Mathevet, T., Mijic, A., Pedrozo Acuña, A., Polo, M.J., Rosales, V., Smith, P., Viglione, A., Srinivasan, V., Toth, E., van Nooyen, R., Xia, J., 2016. Panta Rhei 2013–2015: global perspectives on hydrology, society and change. Hydrol. Sci. J. 61, 1174–1191. https://doi.org/10.1080/02626667.2016.1159308

McMillan, H.K., Westerberg, I.K., Krueger, T., 2018. Hydrological data uncertainty and its implications. WIREs Water 5, e1319. https://doi.org/10.1002/wat2.1319

Meyer, J., Neuper, M., Mathias, L., Zehe, E., Pfister, L., 2021. More frequent flash flood events and extreme precipitation favouring atmospheric conditions in temperate regions of Europe. Hydrol. Earth Syst. Sci. Discuss. 1–28. https://doi.org/10.5194/hess-2021-628

Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P., Stouffer, R.J., 2008. Stationarity Is Dead: Whither Water Management? Science 319, 573–574. https://doi.org/10.1126/science.1151915

Montanari, A., Young, G., Savenije, H.H.G., Hughes, D., Wagener, T., Ren, L.L., Koutsoyiannis, D., Cudennec, C., Toth, E., Grimaldi, S., Blöschl, G., Sivapalan, M., Beven, K., Gupta, H., Hipsey, M., Schaefli, B., Arheimer, B., Boegh, E., Schymanski, S.J., Di Baldassarre, G., Yu, B., Hubert, P., Huang, Y., Schumann, A., Post, D.A., Srinivasan, V., Harman, C., Thompson, S., Rogger, M., Viglione, A., McMillan, H., Characklis, G., Pang, Z., Belyaev, V., 2013. "Panta Rhei—Everything Flows": Change in hydrology and society—The IAHS Scientific Decade 2013–2022. Hydrol. Sci. J. 58, 1256–1275. https://doi.org/10.1080/02626667.2013.809088

Mukhtarov, F., Papyrakis, E., Rieger, M., 2022. Covid-19 and WaterWater, in: Papyrakis, E. (Ed.), COVID-19 and International Development. Springer International Publishing, Cham, pp. 157–173. https://doi.org/10.1007/978-3-030-82339-9_12

Nace, R.L., 1965. Status of the International Hydrological Decade. J. AWWA 57, 819–823. https://doi.org/10.1002/j.1551-8833.1965.tb01468.x

Nijp, J.J., Temme, A.J.A.M., van Voorn, G.A.K., Kooistra, L., Hengeveld, G.M., Soons, M.B., Teuling, A.J., Wallinga, J., 2019. Spatial early warning signals for impending regime shifts: A practical framework for application in real-world landscapes. Glob. Change Biol. 25, 1905–1921. https://doi.org/10.1111/gcb.14591

Nilson, E., 2014. Auswirkungen des Klimawandels auf das Abflussgeschehen und die Binnenschifffahrt in Deutschland : Schlussbericht KLIWAS-Projekt 4.01, KLIWAS-Schriftenreihe / BfG – KLIWAS-43/2014. Bundesanstalt für Gewässerkunde, Koblenz. https://doi.org/10.5675/KLIWAS_43/2014_4.01

Nobis, K., Schumann, M., Lehmann, B., Linke, H.-J., 2020. Die Anwendung der ländlichen Bodenordnung bei der Renaturierung und naturnahen Entwicklung von Fließgewässern, 1. Aufl. 2020 edition. ed. Springer Spektrum, Wiesbaden Heidelberg.

Oberle, B., Bringezu, S., Hatfield-Dodds, S., Hellweg, S., Schandl, H., Clement, J., 2019. Global Resources Outlook: 2019. International Resource Panel, United Nations Envio, Paris, France.

Ojea, E., Martin-Ortega, J., Chiabai, A., 2012. Defining and classifying ecosystem services for economic valuation: the case of forest water services. Environ. Sci. Policy 19–20, 1–15. https://doi.org/10.1016/j.envsci.2012.02.002

Oki, T., Kanae, S., 2006. Global Hydrological Cycles and World Water Resources. Science 313, 1068–1072. https://doi.org/10.1126/science.1128845

Otto, F.E.L., Wolski, P., Lehner, F., Tebaldi, C., van Oldenborgh, G.J., Hogesteeger, S., Singh, R., Holden, P., Fučkar, N.S., Odoulami, R.C., New, M., 2018. Anthropogenic influence on the drivers of the Western Cape drought 2015–2017. Environ. Res. Lett. 13, 124010. https://doi.org/10.1088/1748-9326/aae9f9

Otto, I.M., Donges, J.F., Cremades, R., Bhowmik, A., Hewitt, R.J., Lucht, W., Rockström, J., Allerberger, F., McCaffrey, M., Doe, S.S.P., Lenferna, A., Morán, N., van Vuuren, D.P., Schellnhuber, H.J., 2020. Social tipping dynamics for stabilizing Earth’s climate by 2050. Proc. Natl. Acad. Sci. 117, 2354–2365. https://doi.org/10.1073/pnas.1900577117

Owens, P.N., Batalla, R.J., Collins, A.J., Gomez, B., Hicks, D.M., Horowitz, A.J., Kondolf, G.M., Marden, M., Page, M.J., Peacock, D.H., Petticrew, E.L., Salomons, W., Trustrum, N.A., 2005. Fine-grained sediment in river systems:

environmental significance and management issues. River Res. Appl. 21, 693–717. https://doi.org/10.1002/rra.878

Pappenberger, F., Cloke, H.L., Parker, D.J., Wetterhall, F., Richardson, D.S., Thielen, J., 2015. The monetary benefit of early flood warnings in Europe. Environ. Sci. Policy 51, 278–291. https://doi.org/10.1016/j.envsci.2015.04.016

Paprotny, D., Sebastian, A., Morales-Nápoles, O., Jonkman, S.N., 2018. Trends in flood losses in Europe over the past 150 years. Nat. Commun. 9, 1985. https://doi.org/10.1038/s41467-018-04253-1

Payraudeau, Gregoire, 2012. Modelling pesticides transfer to surface water at the catchment scale: a multi-criteria analysis. Agron. Sustain. Dev. 32, 479–500. https://doi.org/10.1007/s13593-011-0023-3

Peleg, N., Marra, F., Fatichi, S., Molnar, P., Morin, E., Sharma, A., Burlando, P., 2018. Intensification of Convective Rain Cells at Warmer Temperatures Observed from High-Resolution Weather Radar Data. J. Hydrometeorol. 19, 715–726. https://doi.org/10.1175/JHM-D-17-0158.1

Pendergrass, A.G., Knutti, R., Lehner, F., Deser, C., Sanderson, B.M., 2017. Precipitation variability increases in a warmer climate. Sci. Rep. 7, 17966. https://doi.org/10.1038/s41598-017-17966-y

Pijl, A., Brauer, C.C., Sofia, G., Teuling, A.J., Tarolli, P., 2018. Hydrologic impacts of changing land use and climate in the Veneto lowlands of Italy. Anthropocene 22, 20–30. https://doi.org/10.1016/j.ancene.2018.04.001

Piper, D., Kunz, M., Ehmele, F., Mohr, S., Mühr, B., Kron, A., Daniell, J., 2016. Exceptional sequence of severe thunderstorms and related flash floods in May and June 2016 in Germany – Part 1: Meteorological background. Nat. Hazards Earth Syst. Sci. 16, 2835–2850. https://doi.org/10.5194/nhess-16-2835-2016

Popp, A.L., Lutz, S.R., Khatami, S., van Emmerik, T.H.M., Knoben, W.J.M., 2019. A Global Survey on the Perceptions and Impacts of Gender Inequality in the Earth and Space Sciences. Earth Space Sci. 6, 1460–1468. https://doi.org/10.1029/2019EA000706

Prasad, N., 2006. Privatisation Results: Private Sector Participation in Water Services After 15 Years. Dev. Policy Rev. 24, 669–692. https://doi.org/10.1111/j.1467-7679.2006.00353.x

Raška, P., Bezak, N., Ferreira, C.S.S., Kalantari, Z., Banasik, K., Bertola, M., Bourke, M., Cerdà, A., Davids, P., Madruga de Brito, M., Evans, R., Finger, D.C., Halbac-Cotoara-Zamfir, R., Housh, M., Hysa, A., Jakubínský, J., Solomun, M.K., Kaufmann, M., Keesstra, S., Keles, E., Kohnová, S., Pezzagno, M., Potočki, K., Rufat, S., Seifollahi-Aghmiuni, S., Schindelegger, A., Šraj, M., Stankunavicius, G., Stolte, J., Stričević, R., Szolgay, J., Zupanc, V., Slavíková, L., Hartmann, T., 2022. Identifying barriers for nature-based solutions in flood risk management: An interdisciplinary overview using expert community approach. J. Environ. Manage. 310, 114725. https://doi.org/10.1016/j.jenvman.2022.114725

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S.I., Lambin, E., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J., 2009. Planetary Boundaries: Exploring the Safe Operating Space for Humanity. Ecol. Soc. 14, art32. https://doi.org/10.5751/ES-03180-140232

Rosier, S.H.R., Reese, R., Donges, J.F., De Rydt, J., Gudmundsson, G.H., Winkelmann, R., 2021. The tipping points and early warning indicators for Pine Island Glacier, West Antarctica. The Cryosphere 15, 1501–1516. https://doi.org/10.5194/tc-15-1501-2021

Rotzoll, K., Fletcher, C.H., 2013. Assessment of groundwater inundation as a consequence of sea-level rise. Nat. Clim. Change 3, 477–481. https://doi.org/10.1038/nclimate1725

Russell, C., Waters, C.N., Himson, S., Holmes, R., Burns, A., Zalasiewicz, J., Williams, M., 2021. Geological evolution of the Mississippi River into the Anthropocene. Anthr. Rev. 8, 115–140. https://doi.org/10.1177/20530196211045527

Savenije, H.H.G., Van der Zaag, P., 2008. Integrated water resources management: Concepts and issues. Phys. Chem. Earth Parts ABC, Integrated Water Resources Management in a Changing World 33, 290–297. https://doi.org/10.1016/j.pce.2008.02.003

Scheffer, M., Bascompte, J., Brock, W.A., Brovkin, V., Carpenter, S.R., Dakos, V., Held, H., van Nes, E.H., Rietkerk, M., Sugihara, G., 2009. Early-warning signals for critical transitions. Nature 461, 53–59. https://doi.org/10.1038/nature08227

Scheffer, M., Carpenter, S.R., Lenton, T.M., Bascompte, J., Brock, W., Dakos, V., van de Koppel, J., van de Leemput, I.A., Levin, S.A., van Nes, E.H., Pascual, M., Vandermeer, J., 2012. Anticipating critical transitions. Science 338, 344–348. https://doi.org/10.1126/science.1225244

Scott, C.A., Vicuña, S., Blanco-Gutiérrez, I., Meza, F., Varela-Ortega, C., 2014. Irrigation efficiency and water-policy implications for river basin resilience. Hydrol. Earth Syst. Sci. 18, 1339–1348. https://doi.org/10.5194/hess-18-1339-2014

Seidl, R., Barthel, R., 2017. Linking scientific disciplines: Hydrology and social sciences. J. Hydrol. 550, 441–452. https://doi.org/10.1016/j.jhydrol.2017.05.008

Sene, K., 2010. Hydrometeorology.

Seneviratne, S.I., Corti, T., Davin, E.L., Hirschi, M., Jaeger, E.B., Lehner, I., Orlowsky, B., Teuling, A.J., 2010. Investigating soil moisture–climate interactions in a changing climate: A review. Earth-Sci. Rev. 99, 125–161. https://doi.org/10.1016/j.earscirev.2010.02.004

Sivapalan, M., Takeuchi, K., Franks, S.W., Gupta, V.K., Karambiri, H., Lakshmi, V., Liang, X., McDonnell, J.J., Mendiondo, E.M., O’Connell, P.E., Oki, T., Pomeroy, J.W., Schertzer, D., Uhlenbrook, S., Zehe, E., 2003. IAHS Decade on Predictions in Ungauged Basins (PUB), 2003–2012: Shaping an exciting future for the hydrological sciences. Hydrol. Sci. J. 48, 857–880. https://doi.org/10.1623/hysj.48.6.857.51421

Sorensen, J.H., 2000. Hazard Warning Systems: Review of 20 Years of Progress. Nat. Hazards Rev. 1, 119–125. https://doi.org/10.1061/(ASCE)1527-6988(2000)1:2(119)

Stall, S., Robinson, E., Wyborn, L., Yarmey, L., Parsons, M., Lehnert, K., Cutcher-Gershenfeld, J., Nosek, B., Hanson, B., 2017. Enabling FAIR Data Across the Earth and Space Sciences. Eos. https://doi.org/10.1029/2017EO088425

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sörlin, S.,

2015. Planetary boundaries: Guiding human development on a changing planet. Science 347, 1259855. https://doi.org/10.1126/science.1259855

Steffen, W., Rockström, J., Richardson, K., Lenton, T.M., Folke, C., Liverman, D., Summerhayes, C.P., Barnosky, A.D., Cornell, S.E., Crucifix, M., Donges, J.F., Fetzer, I., Lade, S.J., Scheffer, M., Winkelmann, R., Schellnhuber, H.J., 2018. Trajectories of the Earth System in the Anthropocene. Proc. Natl. Acad. Sci. 115, 8252–8259. https://doi.org/10.1073/pnas.1810141115

Strober, M.H., 2006. Habits of the Mind: Challenges for Multidisciplinary Engagement. Soc. Epistemol. 20, 315–331. https://doi.org/10.1080/02691720600847324

Sutanto, S.J., van der Weert, M., Wanders, N., Blauhut, V., Van Lanen, H.A.J., 2019. Moving from drought hazard to impact forecasts. Nat. Commun. 10, 4945. https://doi.org/10.1038/s41467-019-12840-z

Sutanto, S.J., Wetterhall, F., Lanen, H.A.J.V., 2020. Hydrological drought forecasts outperform meteorological drought forecasts. Environ. Res. Lett. 15, 084010. https://doi.org/10.1088/1748-9326/ab8b13

Szklarek, S., Górecka, A., Wojtal-Frankiewicz, A., 2022. The effects of road salt on freshwater ecosystems and solutions for mitigating chloride pollution - A review. Sci. Total Environ. 805, 150289. https://doi.org/10.1016/j.scitotenv.2021.150289

Talke, S.A., Jay, D.A., 2013. Nineteenth Century North American and Pacific Tidal Data: Lost or Just Forgotten? J. Coast. Res. 29, 118–127. https://doi.org/10.2112/JCOASTRES-D-12-00181.1

Task Force Fact-finding hoogwater 2021, 2021. Hoogwater 2021; Feiten en Duiding. Expertisenetwerk waterveiligheid.

Tennant, J.P., Waldner, F., Jacques, D.C., Masuzzo, P., Collister, L.B., Hartgerink, Chris.H.J., 2016. The academic, economic and societal impacts of Open Access: an evidence-based review. F1000Research 5, 632. https://doi.org/10.12688/f1000research.8460.3

Tiselius, P., Magnusson, K., 2017. Toxicity of treated bilge water: The need for revised regulatory control. Mar. Pollut. Bull. 114, 860–866. https://doi.org/10.1016/j.marpolbul.2016.11.010

United Nations, 2015. Transforming our world: The 2030 agenda for sustainable development.

van de Vijsel, R.C., van Belzen, J., Bouma, T.J., van der Wal, D., van de Koppel, J., 2021. Algal-Induced Biogeomorphic Feedbacks Lay the Groundwork for Coastal Wetland Development. J. Geophys. Res. Biogeosciences 126, e2021JG006515. https://doi.org/10.1029/2021JG006515

van der Velde, Y., Temme, A.J.A.M., Nijp, J.J., Braakhekke, M.C., van Voorn, G.A.K., Dekker, S.C., Dolman, A.J., Wallinga, J., Devito, K.J., Kettridge, N., Mendoza, C.A., Kooistra, L., Soons, M.B., Teuling, A.J., 2021. Emerging forest-peatland bistability and resilience of European peatland carbon stores. Proc. Natl. Acad. Sci. U. S. A. 118, e2101742118. https://doi.org/10.1073/pnas.2101742118

van Emmerik, T., Popp, A., Solcerova, A., Müller, H., Hut, R., 2018. Reporting negative results to stimulate experimental hydrology: discussion of “The role of experimental work in hydrological sciences – insights from a community survey.” Hydrol. Sci. J. 63, 1269–1272. https://doi.org/10.1080/02626667.2018.1493203

van Emmerik, T., Schwarz, A., 2020. Plastic debris in rivers. WIREs Water 7, e1398. https://doi.org/10.1002/wat2.1398

van Loon, A.F., 2015. Hydrological drought explained. WIREs Water 2, 359–392. https://doi.org/10.1002/wat2.1085

Van Noorden, R., 2015. Interdisciplinary research by the numbers. Nat. News 525, 306. https://doi.org/10.1038/525306a

Venhuizen, G.J., Hut, R., Albers, C., Stoof, C.R., Smeets, I., 2019. Flooded by jargon: how the interpretation of water-related terms differs between hydrology experts and the general audience. Hydrol. Earth Syst. Sci. 23, 393–403. https://doi.org/10.5194/hess-23-393-2019

Verbesselt, J., Umlauf, N., Hirota, M., Holmgren, M., Nes, E.H. van, Herold, M., Zeileis, A., Scheffer, M., 2016. Remotely sensed resilience of tropical forests. Nat. Clim. Change 6, 1028–1031.

Vicente-Serrano, S.M., Domínguez-Castro, F., McVicar, T.R., Tomas-Burguera, M., Peña-Gallardo, M., Noguera, I., López-Moreno, J.I., Peña, D., El Kenawy, A., 2020. Global characterization of hydrological and meteorological droughts under future climate change: The importance of timescales, vegetation-CO2 feedbacks and changes to distribution functions. Int. J. Climatol. 40, 2557–2567. https://doi.org/10.1002/joc.6350

Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S.E., Sullivan, C.A., Liermann, C.R., Davies, P.M., 2010. Global threats to human water security and river biodiversity. Nature 467, 555–561. https://doi.org/10.1038/nature09440

Vörösmarty, C.J., Sahagian, D., 2000. Anthropogenic Disturbance of the Terrestrial Water Cycle. BioScience 50, 753–765. https://doi.org/10.1641/0006-3568(2000)050[0753:ADOTTW]2.0.CO;2

Wahl, T., Jain, S., Bender, J., Meyers, S.D., Luther, M.E., 2015. Increasing risk of compound flooding from storm surge and rainfall for major US cities. Nat. Clim. Change 5, 1093–1097. https://doi.org/10.1038/nclimate2736

Waldschläger, K., Brückner, M.Z.M., Carney Almroth, B., Hackney, C.R., Adyel, T.M., Alimi, O.S., Belontz, S.L., Cowger, W., Doyle, D., Gray, A., Kane, I., Kooi, M., Kramer, M., Lechthaler, S., Michie, L., Nordam, T., Pohl, F., Russell, C., Thit, A., Umar, W., Valero, D., Varrani, A., Warrier, A.K., Woodall, L.C., Wu, N., 2022. Learning from natural sediments to tackle microplastics challenges: A multidisciplinary perspective. Earth-Sci. Rev. 228, 104021. https://doi.org/10.1016/j.earscirev.2022.104021

Ward, P.J., Couasnon, A., Eilander, D., Haigh, I.D., Hendry, A., Muis, S., Veldkamp, T.I.E., Winsemius, H.C., Wahl, T., 2018. Dependence between high sea-level and high river discharge increases flood hazard in global deltas and estuaries. Environ. Res. Lett. 13, 084012. https://doi.org/10.1088/1748-9326/aad400

Wasko, C., Shao, Y., Vogel, E., Wilson, L., Wang, Q.J., Frost, A., Donnelly, C., 2021. Understanding trends in hydrologic extremes across Australia. J. Hydrol. 593, 125877. https://doi.org/10.1016/j.jhydrol.2020.125877

Webster, J.R., Knoepp, J., Swank, W., Miniat, C., 2016. Evidence for a regime shift in nitrogen export from a forested watershed. Ecosystems 19, 881–895. https://doi.org/10.1007/s10021-016-9974-1

West, H., Quinn, N., Horswell, M., 2019. Remote sensing for drought monitoring & impact assessment: Progress, past challenges and future opportunities. Remote Sens. Environ. 232, 111291. https://doi.org/10.1016/j.rse.2019.111291

Wilby, R.L., 2019. A global hydrology research agenda fit for the 2030s. Hydrol. Res. 50, 1464–1480. https://doi.org/10.2166/nh.2019.100

Wilkinson, M.D., Dumontier, M., Aalbersberg, Ij.J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., da Silva Santos, L.B., Bourne, P.E., Bouwman, J., Brookes, A.J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C.T., Finkers, R., Gonzalez-Beltran, A., Gray, A.J.G., Groth, P., Goble, C., Grethe, J.S., Heringa, J., 't Hoen, P.A.C., Hooft, R., Kuhn, T., Kok, R., Kok, J., Lusher, S.J., Martone, M.E., Mons, A., Packer, A.L., Persson, B., Rocca-Serra, P., Roos, M., van Schaik, R., Sansone, S.-A., Schultes, E., Sengstag, T., Slater, T., Strawn, G., Swertz, M.A., Thompson, M., van der Lei, J., van Mulligen, E., Velterop, J., Waagmeester, A., Wittenburg, P., Wolstencroft, K., Zhao, J., Mons, B., 2016. The FAIR Guiding Principles for scientific data management and stewardship. Sci. Data 3, 160018. https://doi.org/10.1038/sdata.2016.18

World bank group, 2021. Global Water Security and Sanitation Partnership Annual Report 2021.

Ziegler, A.D., Sheffield, J., Maurer, E.P., Nijssen, B., Wood, E.F., Lettenmaier, D.P., 2003. Detection of Intensification in Global- and Continental-Scale Hydrological Cycles: Temporal Scale of Evaluation. J. Clim. 16, 535–547. https://doi.org/10.1175/1520-0442(2003)016<0535:DOIIGA>2.0.CO;2

Zipper, S.C., Jaramillo, F., Wang-Erlandsson, L., Cornell, S.E., Gleeson, T., Porkka, M., Häyhä, T., Crépin, A.-S., Fetzer, I., Gerten, D., Hoff, H., Matthews, N., Ricaurte-Villota, C., Kummu, M., Wada, Y., Gordon, L., 2020. Integrating the Water Planetary Boundary With Water Management From Local to Global Scales. Earths Future 8, e2019EF001377. https://doi.org/10.1029/2019EF001377

Zscheischler, J., Westra, S., van den Hurk, B.J.J.M., Seneviratne, S.I., Ward, P.J., Pitman, A., AghaKouchak, A., Bresch, D.N., Leonard, M., Wahl, T., Zhang, X., 2018. Future climate risk from compound events. Nat. Clim. Change 8, 469–477. https://doi.org/10.1038/s41558-018-0156-3

Supporting information

We invite other ECS to continue the discussion on the IAHS SD. Here we provide a guideline based on the discussion sessions for this initiative. Depending on the session, we deviated slightly from the schedule below responding to the course of the discussion. The schedule describes a one-hour session with 20-40 people, which could be extended to accommodate for more interaction. After the schedule, we list the questions that served as input for the discussion. The questions evolved over the course of the six discussion sessions. To provide insight in this evolution, the questions are presented below per session. These questions were discussed in small groups, after which answers were shared in a plenary round and discussed together.

Session schedule

Introduction (5 min)

- History of the decades
- Aim of the initiative
- Planning of the session
- Questions

Break-out groups (25 min)

- Discussing the questions
- 4-5 people
- As diverse as possible (institute, sub-discipline)

Plenary explanation (10 min)

- Summarizing outcome of break-out groups

- 1-2 min per group

Plenary discussion (20 min)

- Reacting to other groups
- Answering the prepared questions

Questions per session

Session 1 to 3 (Wageningen University and Research, Technische Universiteit Delft, Luxembourg Institute of Science and Technology)

- What is a paper all members of your group could collaborate on?
- What is the bigger theme around this paper? Is this suitable as a theme for a hydrological decade?
- What do you expect to be key words for hydrology in the near future?
- What should be the focus of the next hydrological decade?

Session 4 (Karlsruhe Institute of Technology)

- What do you expect to be key words for hydrology in the near future?
- What should be the focus of the next hydrological decade?
- Which of these themes do you think are relevant for the next decade?

    1. Modelling for food security
    2. Adaptation to the intensification of the hydrological cycle
    3. Tipping points in hydrology
    4. Integration of diverse data into models
    5. Interdisciplinary solutions for deltas under stress

6. Multi/transdisciplinarity in hydrology: Enhancing the connection between science and engineering

- What do you think is missing from this list?

Session 5 (University of Zürich)

- Which themes could you form within these categories?
  1. Climate change – Extremes – Droughts – Floods – Intensified water cycle – Tipping points
  2. Machine learning – AI – Big data – Citizen science – Open science – Remote sensing
  3. Inter/multidisciplinarity – Science+engineering
  4. Impacts – Water-Food-Energy – Nature-based solutions
  5. Vulnerable areas – Scaling – Human impact
- Feel free to add or mix & match!

Session 6 (University of Freiburg)

- Themes
  1. Tipping points and thresholds in hydrology
  2. Intensification of the hydrological cycle
  3. Water, food, and energy security
- Trends
  1. Big data
  2. Bridging science and practice
  3. Open science
  4. Inter- and multidisciplinarity
- Do you agree with the themes and trends?

- What would be the research questions tackled in the proposed themes?