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OPINION PAPER

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Theresa C. van Hateren[a,b*], Harro J. Jongen[a,c*], Hadeel Al-Zawaidah[a], Joris G.W. 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 O.E. Remmers[a], Jessica Ruijsch[i], Steven R. Rusli[a,j], Roeland C. van de Vijsel[a], Jerom P.M. Aerts[d], Sehouevi M.D. Agoungbome[d], Markus Anys[e], Sara Blanco Ramírez[g], Tim van Emmerik[a], Luca Gallitelli[k], Gabriela Chiquito Gesualdo[l], Wendy Gonzalez Otero[f], Sarah Hanus[g], Zixiao He[a,m], Svenja Hoffmeister[f], Ruben O. Imhoff[a,n], Tim Kerlin[f], Sumit M. Meshram[d], Judith Meyer[b,o], Aline Meyer Oliveira[g], Andreas C.T. 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[p], Kryss Waldschläger[a], Bas Walraven[d], Chanoknun Wannasin[a], Jan Wienhöfer[f], Mar J. Zander[a,q], Shulin Zhang[a,r], Jingwei Zhou[a], Judith Y. Zomer[a] and Bob W. Zwartendijk[a,s]

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ABSTRACT

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 multi-disciplinarity. 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 discussion sessions and commenting on this paper to make this initiative grow from a regional initiative to a global movement.

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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 United Nations Educational, Scientific and Cultural Organization (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. The last two SDs especially have shown that well-organized community efforts can shape the field of hydrology (Hrachowitz *et al.* 2013, McMillan *et al.* 2016, Kreibich *et al.* 2017). The two most recent decades focused on prediction in ungauged basins (PUB, 2002–2012; Sivapalan

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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. McMillan *et al.* 2016, Kreibich *et al.* 2017).

Because of increased cooperation between hydrologists, the 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 in specific sessions at IAHS conferences (Sivapalan *et al.* 2003, Montanari *et al.* 2013). 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 (ECSs) are important drivers of many research projects. Although they were invited and encouraged to participate in the discussion sessions, ECSs were rarely part of the author list of the resulting opinion papers (Fig. 1). Since the gender balance in hydrology differs between established researchers and ECSs (Popp *et al.* 2019), the diversity of the authors was also skewed (Fig. 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.

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 not necessarily different but at the very least 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 ECSs. This resulted in a gender-balanced group of co-authors consisting of mostly ECSs (Fig. 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 ECSs 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 has come to an end, change in hydrology and society is as important as it was 10 years ago (Blöschl *et al.* 2019). However, a new theme will boost hydrology and provide an 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 ECSs, in the discussion on the new SD theme, for which we adopted a different approach than was applied for previous SDs. For this initiative, ECSs were not strictly defined by years since their last graduation; rather, we welcomed anyone identifying as an 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, six discussion sessions took place over the course of five weeks at

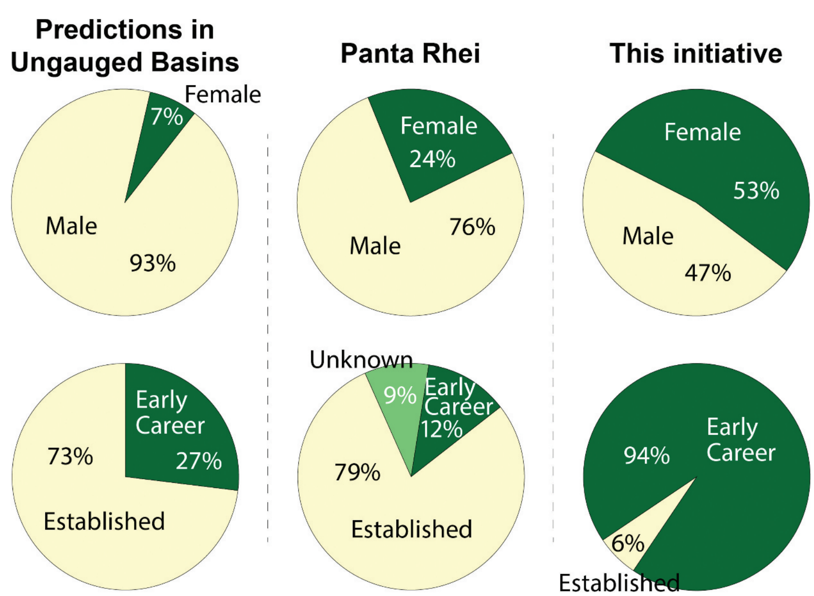

Figure 1. Gender (top) and career-stage (bottom) diversity in co-authors of initial publications of predictions in ungauged basins (15 co-authors, Sivapalan *et al.* 2003), Panta Rhei (34 co-authors, Montanari *et al.* 2013), and this initiative (49 co-authors). For the publications of Sivapalan *et 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.

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. Each session was attended by 10–30 participants. PhD candidates made up the majority of the participants, complemented by postdoctoral researchers and assistant professors. No master's students joined the discussions. The participants were all either scientists or engineers focusing on sub-topics of hydrology and environmental hydraulics. In total, around 75 people attended at least one of the sessions, and 49 of those (65%) decided to stay involved in the project by co-authoring this paper.

While these sessions have greatly improved the influence of ECSs in such discussions (Fig. 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 (Fig. 2), future efforts should aim to further broaden the diversity by including a larger geographical region.

All discussion sessions lasted an hour and 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 sub-disciplines 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 in the later sessions (i.e. "What would be the research questions tackled in the proposed themes?"). All questions can be found in the Supplementary material. Finally, each group summarized their answers to the questions at the plenary discussion that followed. ECSs were encouraged to voice their opinion on the theme of the next SD in small groups of peers without their voices being unintentionally overshadowed by the presence of senior scientists.

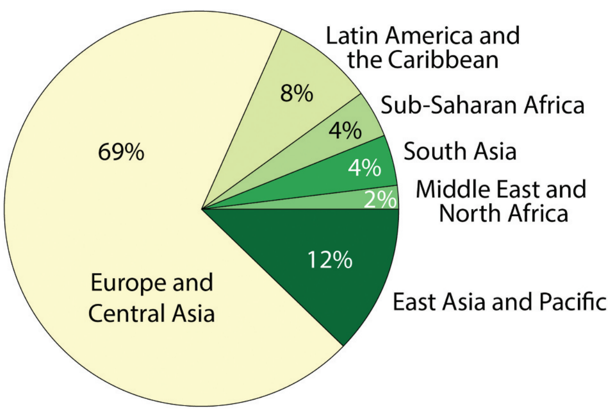

Figure 2. Regions of origin of the co-authors of this paper, according to the regions defined by the World Bank (Serajuddin *et al.* 2017).

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; this is referred to as a regime shift. These regime shifts can be either reversible or irreversible. A reversible tipping point indicates that the system can be restored under the same environmental circumstances, whereas an irreversible tipping point indicates that the system can only be restored 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 (Horton 1945, Dunne and Black 1970a, 1970b), 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 several 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. Lovejoy and Nobre 2018, Amigo 2020). 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 (Rockström *et al.* 2009, Steffen *et al.* 2015, IPCC 2021). 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 (Steffen *et al.* 2018, Lenton *et al.* 2019, Otto *et al.* 2020). 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 (Horton 1945, Dunne and Black 1970a, Dijkstra *et al.* 2019), groundwater (Bailey 2011, Figura *et al.* 2011), hydrometeorology (Buitink *et al.* 2020, Denissen *et al.* 2020, Krishnamurthy *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 (Scheffer *et al.* 2012, Nijp *et al.* 2019). In addition, modelled tipping points can only be verified after they occur (Denissen *et al.* 2020, Krishnamurthy *et al.* 2020). The impossibility of verifying unobserved tipping points is problematic since their occurrence comes with the drastic consequences of irreversible tipping behaviour for hydrological systems (e.g. Drijfhout *et al.* 2015, Dakos *et al.* 2019). 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 (Webster *et al.* 2016, van de Vijsel *et al.* 2021). 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 might greatly advance our scientific understanding of hydrological regime shifts and could 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. Kundzewicz 2008, Peleg *et al.* 2018, Madakumbura *et al.* 2019). Climate change intensifies the hydrological cycle, increasing (for instance) the frequency and intensity of droughts and floods (Gloor *et al.* 2013, Bertola *et al.* 2020, Wasko *et al.* 2021). More hydrological extremes make securing freshwater 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 (Ziegler *et al.* 2003, Huntington 2006). However, less is known about mitigation of the risks that the hydrological intensification poses for agricultural productivity, water availability, and water quality (Paprotny *et al.* 2018, Abram *et al.* 2021). 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 in the context of a rapidly changing climate to enable adaptations that store water for drier periods and redistribute it to drier areas (e.g. Dai *et al.* 2018). We need interdisciplinary collaborations that lead to 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, Greve *et al.* 2014, Kumar *et al.* 2015, Christidis and Stott 2021). Hence, we need to understand local mechanisms and drivers to help mitigate the consequences of extreme events, thereby ensuring freshwater 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 other things) 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 (van Loon 2015, Buitink *et al.* 2021). 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, Pendergrass *et al.* 2017, Ansah *et al.* 2020, De Luca *et al.* 2020). In the last 10 years, numerous extreme precipitation events have occurred with extensive impacts around the globe (e.g. Duan *et al.* 2014, Otto *et al.* 2018, Abram *et al.* 2021, Wasko *et al.* 2021). A recent example is the 2021 summer flood event that impacted a large part of northwestern 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 (Task Force Fact-finding hoogwater 2021, Barneveld *et al.* 2022). 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, Lenderink and van Meijgaard 2008, Kennedy *et al.* 2016, Lenderink *et al.* 2017). More extreme rainfall events can result in floods with high socio-economic impacts, and can increase the risk of flash floods (Alfieri *et al.* 2015, Piper *et al.* 2016, Meyer *et al.* 2021). 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 (Seneviratne *et al.* 2010, Buras *et al.* 2020), or 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 (Pappenberger *et al.* 2015, Ward *et al.* 2018, Couasnon *et al.* 2020, Abram *et al.* 2021, 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 from 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?
- What 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. Prasad 2006, Lele 2009, Ojea *et al.* 2012). Following Daily's (1997) definition of ecosystem services, water services, or hydrological services, describe the conditions and processes through which the water cycle sustains and fulfils human life (e.g. Underwood *et al.* 2018). 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 provides for the environment and society, society also greatly influences the water system (Linton and Budds 2014, Liu *et al.* 2014). This influence was studied extensively during the Panta Rhei decade, leading to a push in the field of socio-hydrology (e.g. Scott *et al.* 2014, McMillan *et al.* 2016, Di Baldassarre *et al.* 2018, Pijl *et al.* 2018). 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 (Vörösmarty and Sahagian 2000, Oberle *et al.* 2019). 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 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 reduces the buffer function of wetlands and swamps (Nobis *et al.* 2020). Therefore, there has been a call in recent research 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 (Cao and Warford 2006, Bakker 2012, 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 continuing and intensifying their application 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. Automated 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 (Arsenault *et al.* 2016, Addor *et al.* 2017, Cui *et al.* 2018, Almagro *et al.* 2021, 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 these data efficiently and how to extract knowledge from different data sources simultaneously.

Big data in hydrology presents not only 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 (McMillan *et al.* 2018, Lawton 2021). To make big data robust, 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 or 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 (Talke and Jay 2013, Benito *et al.* 2015), 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 increasing the cooperation between hydrologists and data scientists to jointly tackle the 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 these goals, 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 into hydrology (Seidl and Barthel 2017). However, practical difficulties arise when conducting multi-, inter-, or transdisciplinary research (e.g. Lélé and Norgaard 2005, Strober 2006, Lang *et al.* 2012, Brown *et al.* 2015). 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 closing 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 by discussing 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" (Montanari 2021, p. 1) 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 this, 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 policymakers, as well as a reflection on governance strategies based on scientific output. We acknowledge the debate on the role of science in society (Higgins *et al.* 2006), but we believe science should benefit society. Therefore, stakeholders and policymakers 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 in open access (OA) format 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, sharing preprints and negative results, and 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, van Emmerik *et al.* 2018, Hall *et al.* 2022). 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; Wilkinson *et al.* 2016, Stall *et al.* 2017). 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 more expensive for the researchers, both financially and timewise. 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 believe that the three challenges discussed here 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

During the past two IAHS SDs, strong advances in the field of hydrology were made. In the first, PUB (Sivapalan *et al.* 2003), work was done on reducing predictive uncertainty in hydrology. During the second, Panta Rhei (Montanari *et al.* 2013), the interaction between hydrology and society was studied. Thanks to these decades, hydrological models and predictions have improved, as has our understanding of vital hydrological processes. The gained knowledge and improved hydrological tools allow us to tackle different problems in hydrology that we previously could not. For the upcoming SD, we therefore propose to use this enhanced toolbox to tackle hydrological threats caused by climate change and population growth. This can be approached from different perspectives. We identified three perspectives that could be selected as the theme for the upcoming IAHS SD: "Tipping points and thresholds in hydrology," "Intensification of the water cycle," and "Water services under pressure" (Fig. 3). We also identified four trends that

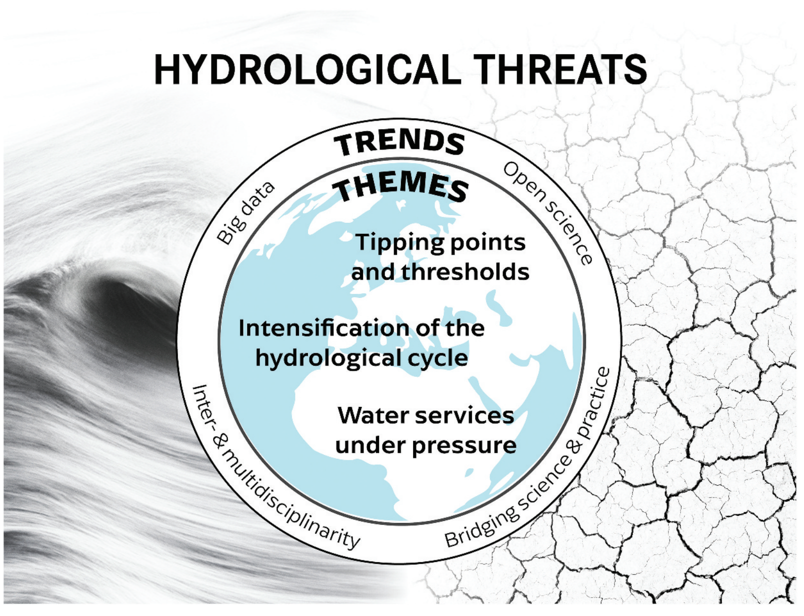

Figure 3. Overview of the themes and trends presented in this paper.

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.

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 in, 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, the fact that 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 policymakers 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 SD. 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 SD. We acknowledge that the logistical limitations of our initiative have led to a spatial bias. This may have caused certain topics that are vital to the future in hydrology, especially in regions not represented by the authors, to be overlooked. To overcome the limitations posed by this bias, we encourage ECSs around 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 Supplementary material, 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.

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