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

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

This paper shares an Early-Career Scientist (ECS) perspective on potential themes for the upcoming International Association of Hydrological Sciences (IAHS) scientific decade (SD). Six discussion sessions were organised in four countries in western Europe in spring 2022. Early-career hydrologists were invited to join the sessions to formulate potential SD themes, to provide feedback on themes proposed in earlier sessions, and to further develop the proposed themes. This community paper summarizes the outcome of these discussion sessions, where three potential themes were identified that 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 can provide valuable input for future discussions on the theme for the next IAHS SD and they can also serve as a guidance for future research pathways.

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

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 (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 (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.

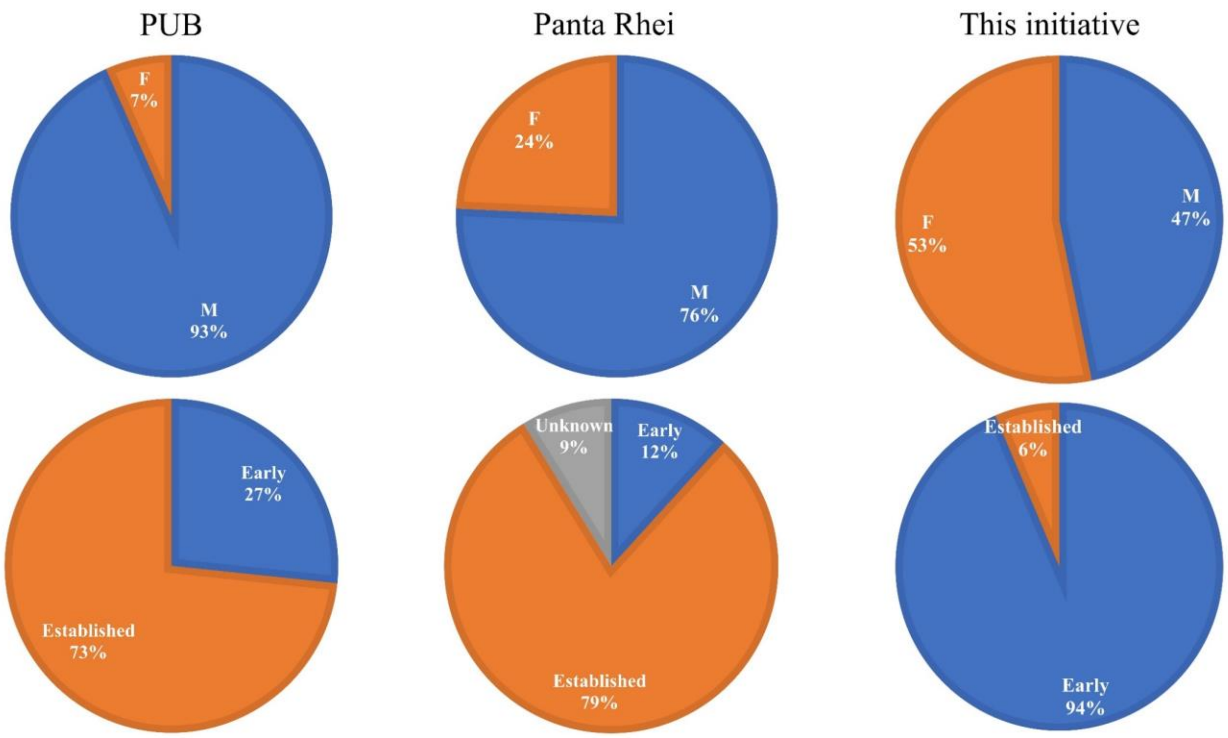

Figure 1: Gender (top, F=Female, M=Male) and career-stage (bottom) diversity in co-authors of initial publications of PUB (Sivapalan et al., 2003), Panta Rhei (Montanari et al., 2013), and this initiative. Early career scientists in these charts are defined as having received their latest degree (BSc, MSc, PhD) less than five years before publication of the paper.

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. With this community paper, we aim to decrease the underrepresentation of ECS and women involved in published papers related to the SD by providing an ECS view with a gender-balanced group on potential themes for the next SD. We present three potential themes for the upcoming SD endorsed by ECS: “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. 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 Albert-Ludwigs 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. While these sessions have greatly improved the influence of ECS in such discussions (Fig. 1), the session's geographic locations have inevitably led to a bias towards high-income countries. 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 (Horton, 1945; Dunne and Black, 1970a; Dunne and Black, 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 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 & 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 & Nobre, 2018; Amigo, 2020). Another example is groundwater abstraction that jeopardizes groundwater-dependent vegetation (Barron et al., 2014).

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; 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, 1970; 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 (Dijkstra et al., 2019; Dakos 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 & 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 on 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 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. Kundzewics et al., 2008; Peleg et al., 2018; Madakumbura et al., 2019; Koutsoyiannis, 2020). 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 fresh water by, for example, reservoir management increasingly difficult (Carvalho-Santos et al., 2017). Combined with decreasing freshwater storage due to shrinking glaciers (Beniston & Stoffel, 2014) and the depletion of high quality groundwater aquifers (Rotzoll & 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 the 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 to enable adaptations that store water for drier periods and redistribute it to drier areas (i.e. 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 & Soden, 2006; Kitoh et al., 2013). However, recent studies showed that this paradigm is too simple and not universally true (Allen, 2014; Greve et al., 2014; Kumar et al., 2015; Christidis & Stott, 2021). 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 et al., 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., 2019). 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 & Adeyemi, 2013; Pendergrass et al., 2017; De Luca et al., 2020; Ansah et al., 2020). In the last ten 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 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 (TFFH-2021, 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 & Soden, 2006; Lenderink & van Meijgaard, 2008; Kennedy et al., 2016; Lenderink et al., 2017). More extreme rainfall events can result in floods with high socio-economic impacts, as well as increase the risk of flash floods (Schiermeier, 2011; 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) 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 (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 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. Prasad, 2006; Lele, 2009; Ojea et al., 2012). 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 (Liu et al., 2014; Linton & Budds, 2014). This influence has been 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 & 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 & 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 & Fletcher, 2013), and all parts of the water cycle are contaminated by pollutants such as plastic (van Emmerik & Schwarz, 2020; Liu et al., 2020), bilge water (Tiselius & Magnusson, 2017), nutrients (Lintern et al., 2020), pesticides (Payraudeau & Gregoire, 2011), road salt (Szklarek et al., 2022), and oil (Lucas & 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 (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 & Fiorentino 2022). We believe scientific advances, especially in hydrology, could facilitate assuring sustainable water resource management.

Hydrology has supported water resource management by generating and conveying understanding of water resources and hydrological extremes (Savenije & 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, 2006; Bakker, 2012; Giupponi & 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 presented 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 (Arsenault et al., 2016; Addor et al., 2017; Cui, et al. 2018; Klingler et al., 2021; Almagro 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 (McMillan, et al. 2019, Lawton, 2021). 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 & Berghuijs, 2018), 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 (Talke & 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 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 (UN, 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 & 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., 2021).

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. 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 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. 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 & 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; van Emmerik et al., 2018; Hall et al., 2022). Moreover, OS potentially improves the inclusivity of science for marginalized communities (Fox et al., 2021).

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 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., 2019). 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

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.

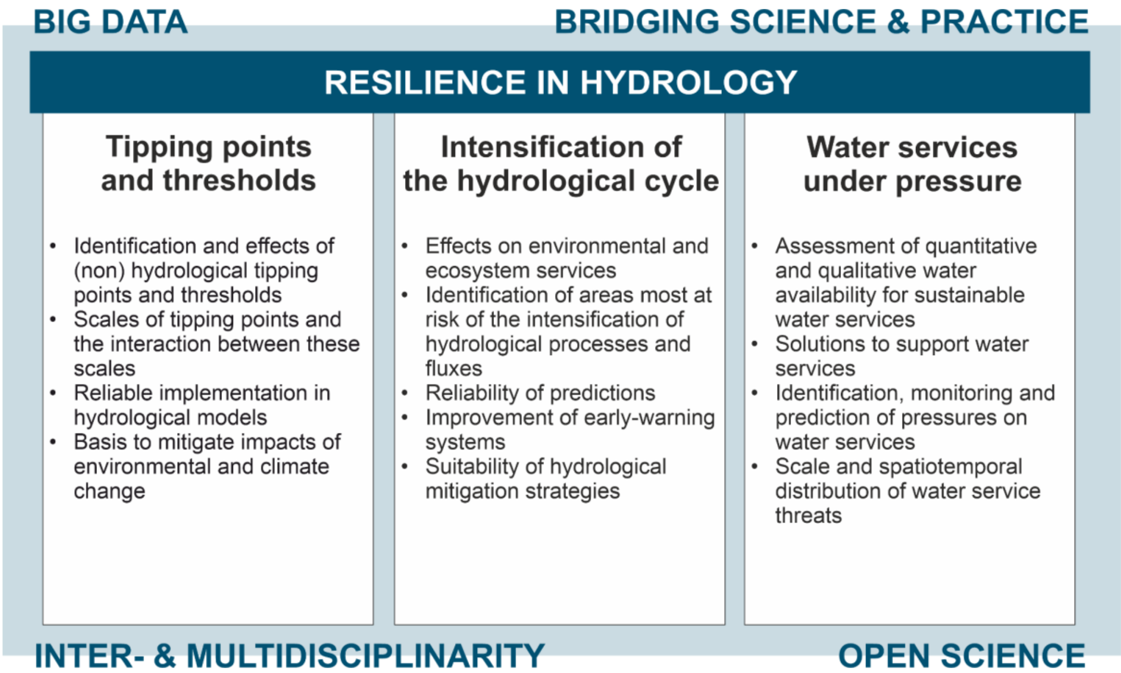

Figure 2: Overview of the themes and trends presented in this paper.

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.

With this community paper, we offer an ECS perspective in the discussion on the theme of the new IAHS scientific decade. We summarized 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. Together, these themes, questions, and trends could be valuable input for future discussions on the theme for the next scientific decade by both early career scientists and established scientists.

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Supporting information

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 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?