Panta Rhei

a decade of progress in research on change in hydrology and society

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REVIEW

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ABSTRACT

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

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1 Introduction

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

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

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

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

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

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

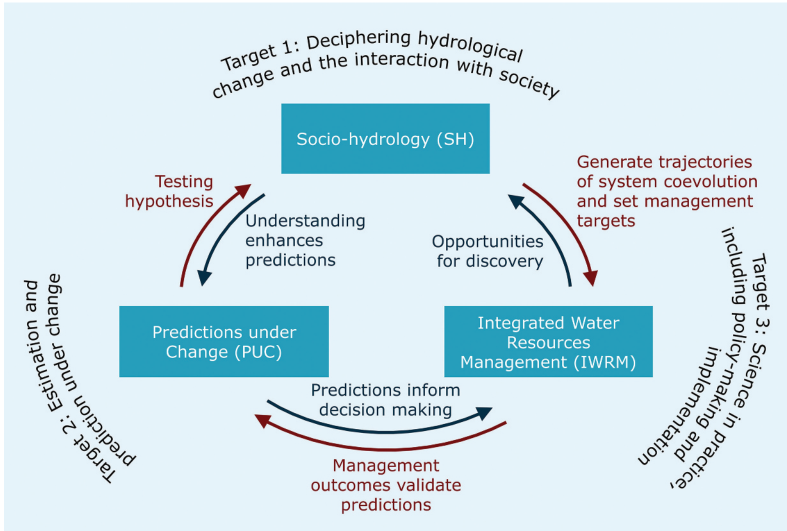

Figure 2. Panta Rhei research encompasses three domains – socio-hydrology (SH), predictions under change (PUC), and integrated water resources management (IWRM) – to achieve its three targets (figure adapted from Montanari *et al.* 2013, Thompson *et al.* 2013).

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

1.2 The three domains of Panta Rhei research

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

The domain of socio-hydrology attempts to understand the complex interactions and feedbacks between human and water systems (Sivapalan *et al.* 2012). It contributes to deciphering hydrological change and its interaction with societies (Target 1 in Montanari *et al.* 2013). The innovation of socio-hydrological research is to model the co-evolution of human–water systems with an integrated approach to better understand the above-mentioned feedbacks and unintended consequences of human interventions over long periods of time. Along with empirical research across scales and places, stylized models based on differential equations are promising tools that can help explore socio-hydrological dynamics and contribute to theory development (Di Baldassarre *et al.* 2015). In addition, socio-hydrology draws on tools developed in research on socio-ecological and complex systems to expand socio-hydrological knowledge (Troy *et al.* 2015). With these tools, however, predictability is debatable in view of the contingent nature of some environmental and societal processes, as well as the importance of retroactive loops and the possible presence of tipping points (Sivapalan and Blöschl 2015, Bai *et al.* 2016). The goal is, rather, the projection of alternative, plausible and co-evolving trajectories of the socio-hydrological system, which may help stakeholders identify safe or desirable operating spaces (Srinivasan *et al.* 2017a). As such, socio-hydrology aims to be a use-inspired science to inform the complex water sustainability challenges faced in the Anthropocene (Sivapalan *et al.* 2014, Sivapalan and Blöschl 2015, Di Baldassarre *et al.* 2019) and be applied to policy-making (Troy *et al.* 2015).

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

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

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

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

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

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

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

2 Scientific progress on monitoring and data analysis

Improving our understanding of the long-term co-evolution of hydrological systems has required associating geophysical and anthropogenic processes that have historically been observed at disparate temporal, spatial, and social scales. Improving data interoperability and accessibility to enable interdisciplinary research was therefore an essential component of the Panta Rhei scientific decade. Many initiatives and approaches have improved data accessibility, discovered new, unconventional data, developed innovative approaches to data integration and analyses, and used citizen science, thus contributing to answering the science question "How can we advance our monitoring and data analysis capabilities to predict and manage hydrological change?" The Panta Rhei collection of key scientific papers contains 58 papers (17%) that contribute to answering this question (see Supplementary material).

2.1 Improved data accessibility

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

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

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

2.2 New, unconventional data

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

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

2.3 Data integration and machine learning

The combination of datasets with both process-based modelling and machine learning (ML) approaches can be integrated in tools that decision makers can use to investigate the long-term effects of their management decisions (Xia *et al.* 2021). Furthermore, alongside large-scale or large-sample efforts, there are bespoke small-scale efforts to harness local hydrological understanding for improved social outcomes. For example, Hund *et al.* (2018) developed a data-based drought early warning system for communities dependent on an aquifer in Costa Rica, with predictions based on the local understanding of what climatic conditions typically lead to drought-induced hardship.

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

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

2.4 Citizen science

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

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

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

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

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

3 Scientific progress on drivers of change

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

3.1 Climate change

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

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

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

3.2 Land use and socio-economic change

Land use changes such as deforestation and urbanization have often caused increased surface runoff and a decreased baseflow (Levy *et al.* 2018, Müller *et al.* 2021). This effect, along with the regulation of river flows, e.g. for hydropower production, industrial use or flood protection, has substantially affected discharge regimes in many parts of the world (Vorogushyn and Merz 2013, Wang *et al.* 2017, Arheimer and Lindström 2019, Shrestha *et al.* 2022).

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

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

3.3 Changes in water quality

Climate change in terms of rising temperatures, changes in precipitation patterns, and extreme weather events have affected the water cycle, also leading to changes in water quality (e.g. Meier *et al.* 2014, Bartosova *et al.* 2019). In coastal areas, sea level rise, storm surges, drought, land subsidence and erosion were reported to affect salinity and water quality in soils, estuaries and aquifers (Dasgupta *et al.* 2015, Jasechko *et al.* 2020, Phlips *et al.* 2020). Water scarcity also impacts water quality, as pollution is more concentrated, so that recent scientific advances have been in the direction of quality-related and ecological water scarcity (Liu *et al.* 2016, 2022). Integrated assessments of water quality, quantity, and environmental flows have been widely applied at global, national, and local levels (Liu *et al.* 2017b, van Vliet *et al.* 2017, Ma *et al.* 2020).

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

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

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

3.4 Methodological advancements in the attribution of change

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

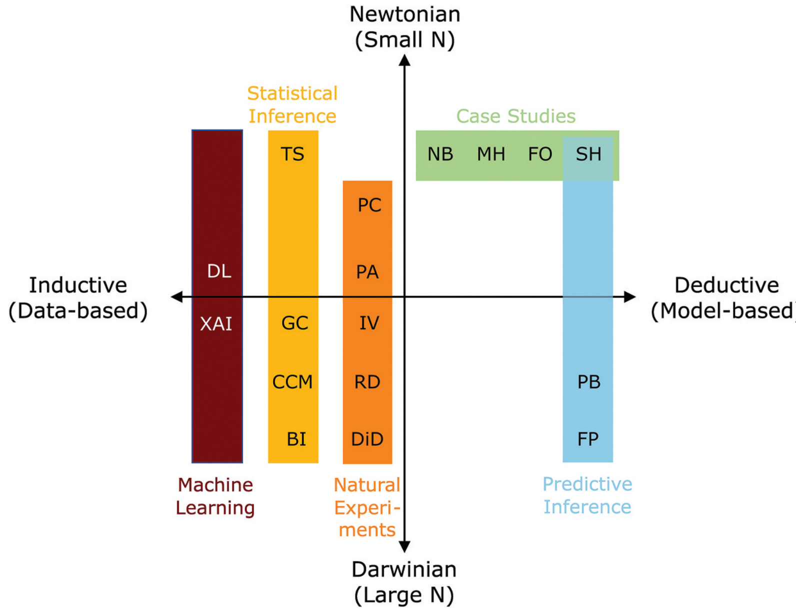

Figure 3. Approximative typology of attribution approaches: DL (diagnostic learning), XAI (explainable artificial intelligence), TS (time series analysis), GC (Granger causality analysis), CCM (convergent cross-mapping), BI (Bayesian inference), PC (paired catchments), PA (panel analysis), IV (instrumental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

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

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

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

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

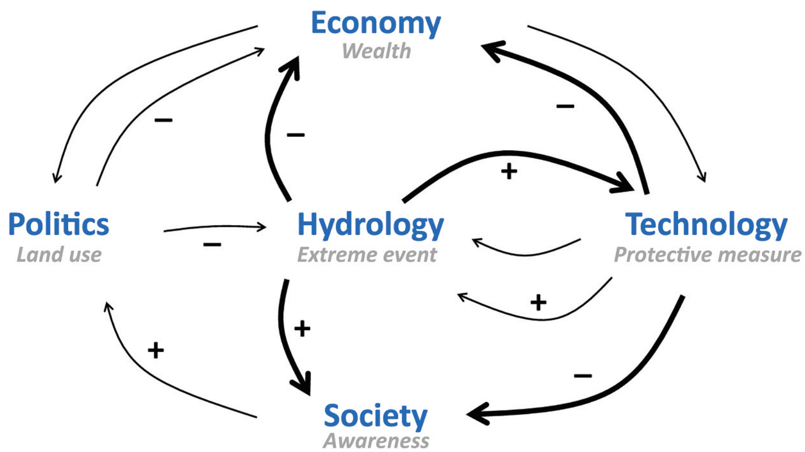

Figure 4. Causal loop diagram showing how hydrological, economic, political, technological, and social processes are all interlinked and gradually coevolve (continuous thin arrows), while being abruptly altered (continuous thick arrows) by the sudden occurrence of an extreme event. Depending on the choice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

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

4 Scientific progress on socio-hydrological systems

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

4.1 Concepts for socio-hydrological systems

It is well known that human societies increasingly influence the hydrological regime, deliberately or otherwise, by: (a) building dams and reservoirs to store water for different purposes; (b) diverting water flows for urban, industrial or agricultural use; (c) changing the characteristics of watersheds via land use change, including deforestation, urbanization, or drainage of wetlands; and (d) altering the regional or global climate via greenhouse gas emissions (Savenije *et al.* 2014).

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

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

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

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

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

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

4.2 Approaches for assessing human–water systems

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

Models for large-scale studies primarily focus on the water–energy–food nexus or other aspects within the framework of the SDGs and have been adopted by institutional investors such as the World Bank (Liu *et al.* 2017a, Payet-Burin *et al.* 2019). Recently we have seen the development of models with very fine resolutions based on agent-based modelling (Wens *et al.* 2020, Ghoreishi *et al.* 2021) or various applications of statistical or ML methods to study interactions on the micro-scale. The purpose of modelling has shifted, to some degree, from finding universal modelling paradigms to finding suitable boundaries that ensure a simplicity that enables decision making while having the complexity that allows for robust assessment of the main impacts (Arnbjerg-Nielsen *et al.* 2022). Approaches have been developed to integrate quantitative and qualitative information in order to better understand the hydrological, socio-political, economic, and cultural contexts in different locations (Rangecroft *et al.* 2018, Vanelli *et al.* 2022), supported by socio-hydrology (Sivapalan and Blöschl 2015).

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

The Panta Rhei community has progressed our understanding of drought through the lens of human influences and coupled system co-evolution (Park *et al.* 2018, Cavus and Aksoy 2020, Wens *et al.* 2020). Such studies have revealed a strong linkage between human behaviour and drought effects across increasing time scales, which help to form a foundation for understanding and communicating such complexities within operational drought management (Cavus *et al.* 2022). Similarly, the conceptual basis for connecting social processes (adaptation, management) with flood events has been strengthened by incorporating, for instance, bounded rationality and prospect theories (Di Baldassarre *et al.* 2015, Kreibich *et al.* 2017, Michaelis *et al.* 2020). Progress has continuously been made in predicting basin-scale socio-hydrological dynamics of water use for agricultural and environmental purposes and its effects on societal conditions such as migration into agricultural basins and flood plains (Di Baldassarre *et al.* 2017, Roobavannan *et al.* 2018). There has also been progress in simulating the interplay between multiple hazards, water management, and societies. For example, Mazzoleni *et al.* (2021) showed that changes in flood and drought awareness can help contribute to the emergence of multiple human–water phenomena (e.g. sequence effect, reservoir effect, supply–demand cycle, and levee effect).

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

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

5 Scientific progress on modelling and prediction

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

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

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

5.2 Quantitative and qualitative human–water systems modelling

Traditional hydrological models are best suited for simulation and prediction in natural catchments, assuming that conditions have not been influenced by societal interaction. Human influences were often only included as management scenarios during the simulation, frequently at a specific point in time (Montanari *et al.* 2013). The predictive capabilities of traditional hydrological models are based on empirical observations, with which the models are calibrated and validated (Aguilar *et al.* 2017). However, complex human–water system models must reflect human and social dynamics such as changing water institutions. The data needed to calibrate such models often include observations of choices made by humans or the evolution of institutions (Sarmento-Buarque *et al.* 2020). Further, modelling concepts have gone beyond the physics-based principles to include the governing principles behind human actions such as rules based on behavioural theories and evolutions of water institutions and governance that are a result of long-term slow-moving processes of values, norms and culture (Sivapalan and Blöschl 2015, Wesselink *et al.* 2017, Bartosova *et al.* 2021, Schrieks *et al.* 2021). For instance, a system-of-systems regional flood model was used to quantify the effect of changes in various risk components, including changes in land use, assets, and vulnerability, on flood risk (Metin *et al.* 2018). Recent models of human–water decision making have benefited from the novel application of concepts that exist in the social sciences domain, such as game theoretic concepts, agent-based models, and behavioural models (Bartosova *et al.* 2021, Schrieks *et al.* 2021). For example, heterogeneous decision making of farmers has been extensively modelled using agent-based models (Tamburino *et al.* 2020, Wens *et al.* 2020, 2022). Yu *et al.* (2017) used game theoretic concepts to incorporate collective action in a stylized human–water system model of flood resilience. The model rules which describe how humans interact with their water environment were also inspired by behavioural theories such as the theory of planned behaviour, so that the models provided realistic predictions of societal inequities and unintended consequences of agricultural water interventions (Pouladi *et al.* 2020, Alam *et al.* 2022). Integrating empirical data, e.g. from recorded events, into socio-hydrological models supports the simulation of real, long-term processes in human–flood systems, including future projections (Schoppa *et al.* 2024). Using Bayesian inference allows models to be calibrated with qualitative and quantitative data and even to include expert knowledge as a prior (Barendrecht *et al.* 2019).

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

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

It is increasingly acknowledged that human–water models developed to capture extremely long-term phenomena should be explicit about their uncertainty when applied to short-term decision making (Srinivasan *et al.* 2017a). Merz *et al.* (2015) argue that surprise is particularly important in attempting to overcome potential cognitive biases within coupled human–water management. Techniques such as behavioural experiments and surveys have been proposed to test hypotheses about human behaviour and biases in decision making (Tian *et al.* 2019, Yu *et al.* 2022). As such, the concept of scale, and how human–water processes may shift according to the lens through which they are studied and by whom, are of importance in bridging the gap between understanding human–water co-evolution and utilizing such insights for prediction. In this light, a means for defining, capturing, and communicating human–water model uncertainty, especially in narratives or qualitative causal loop diagrams developed for diverse decision makers, is essential (e.g. Höllermann and Evers 2019). Formal Bayesian and other methods have been proposed to analyse uncertainty in such models. Barendrecht *et al.* (2019) incorporated survey data in a human–flood systems model and provided quantitative uncertainty information based on Bayesian statistics.

5.3 Approaches to predict future trajectories

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

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

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

6 Scientific progress on water management and adaptation to change

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

6.1 Scenarios and possibility spaces

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

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

6.2 Adaptive water management

Adaptive water management is a planning process that is decidedly adaptive, aims to keep multiple pathways to the future open, and incorporates the knowledge and perspectives of stakeholders (Versteeg *et al.* 2021). In this way, it aims to avoid the following three problems that often lead to the failure of planning processes in water management: (1) traditional planning processes often emphasize the technical aspects of water management while ignoring the practices and knowledge of water users and other stakeholders; (2) they are based on an overly rational and linear ideal of the controllability of hydrology and infrastructure, which is untenable in a time of environmental change, non-stationarity and uncertainty; and (3) the planning processes are often not suitable for balancing the competing interests of stakeholders while keeping an eye on the feasibility and economic viability of the measures now and in the future (Butsch *et al.* 2022b, Conallin *et al.* 2022, Pham *et al.* 2022, Ward *et al.* 2020).

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

6.3 Participatory water governance

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

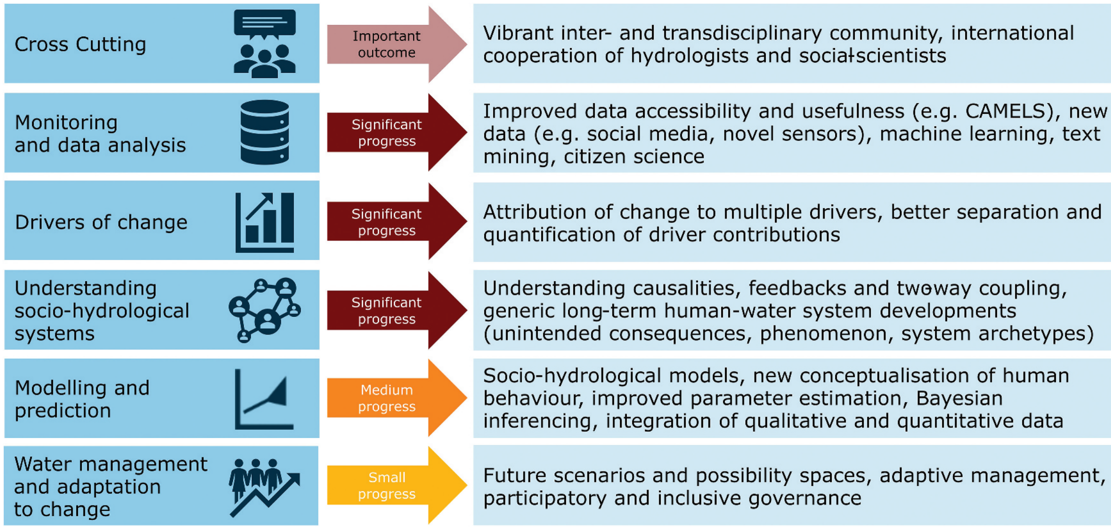

Figure 5. Summary of progress in research on change in hydrology and society in terms of hydrological science and practical water management.

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

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

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

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

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

7 Summary of scientific achievements

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

7.1 *Cross-cutting*

In addition to the creation of knowledge, an important outcome of the Panta Rhei initiative is non-tangible, namely the large and diverse community that formed during the decade, in line with the IAHS mandate. Cooperation of hydrologists, social scientists, and practitioners at local, regional, and international levels led to mutual benefits and new outcomes. Transdisciplinary project teams transformed our understanding of human–water systems, improving predictions and decision making. Close communication between scientists and stakeholders was essential, as new ideas and advancements are often generated by addressing changing societal needs with new approaches and technologies. The co-alignment of research with the UNESCO Intergovernmental Hydrological Programme (IHP) priorities for a water secure world in a changing environment, and with the efforts of the World Meteorological Organization (WMO) to support operational hydrology, enabled more stakeholders to participate in the creation of a new and sustainable water culture through co-creative knowledge and transformative education actions at several scales of governance.

7.2 Monitoring and data analysis

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

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

7.3 Drivers of change

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

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

7.4 Understanding socio-hydrological systems

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

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

7.5 Modelling and prediction

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

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

7.6 Water management and adaptation to change

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

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

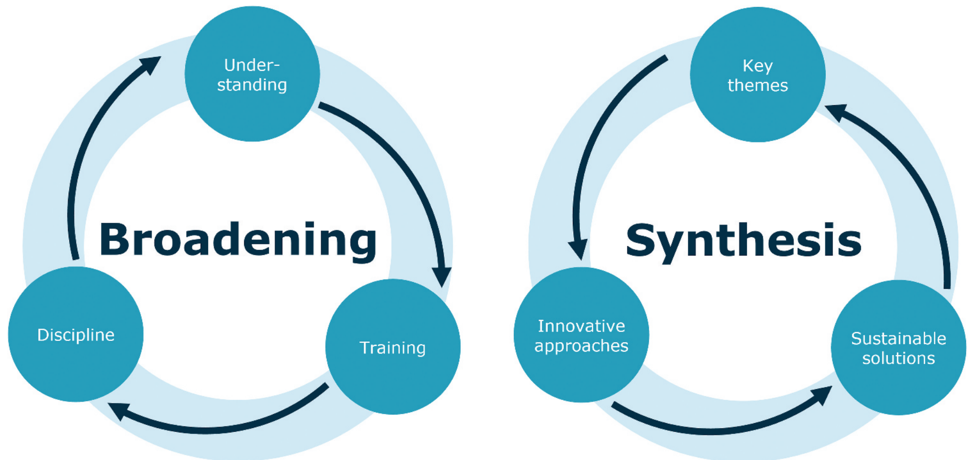

Figure 6. Recommendations to make progress by broadening understanding, discipline and training while synthesizing and focusing on key themes, the development of innovative approaches and sustainable solutions.

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

8 Recommendations

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

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

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

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

Broadening:

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

Synthesis:

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

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

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

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