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

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

Abstract

The massive human impact on the hydrological cycle has led to the recognition that change in water resources modulated by humans and the feedback mechanisms between hydrology and society need to be better understood. As a consequence, the International Association of Hydrological Sciences initiated and conducted a decadal initiative entitled "Panta Rhei—Everything Flows: Change in hydrology and society" during 2013-2022. This review summarises the main scientific advances on change in hydrology and society, with a focus on the feedbacks between humans and water. Substantial progress has been made in leveraging new data sources, e.g., through social media harvesting. Much has been learned about detecting hydrological changes and attributing them to their drivers, e.g., climate effects on floods. Also, much headway has been made in understanding and modelling coupled socio-hydrological systems through combining methods from the social and natural sciences, such as system dynamics models. In terms of supporting water management and adaptation to change, progress has been made, although there is still much to be done. We recommend that the community takes a broader view of the hydrologic sciences, through 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 water problems of the world.

1. Introduction

The feedbacks between hydrology and society have accelerated in recent decades, so that the linkages, connections and interactions between these systems need to be better understood by the hydrological community (Montanari et al., 2013; Brondizio et al., 2016). Climate change, land-use and socio-economic changes including local human activities such as water management significantly alter the hydrological cycle, leading to changes in water availability, quality, 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). A lack of available freshwater 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 adapt to, or mitigate if not prevent, their adverse impacts 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. Therefore, it focuses on research on changes that involve a two-way coupling between human actions and water quantity and/or quality, i.e. on how aquatic environments and human societies coevolve in time and space.

1.1 The IAHS Scientific Decade: Panta Rhei—Everything Flows: Change in hydrology and society

After the IAHS scientific decade on Predictions in Ungauged Basins (PUB) in 2012 (Blöschl et al., 2013; Hrachowitz et al., 2013), the IAHS community started a global discussion to identify the most relevant societal challenges and shape the next IAHS scientific decade. The discussions through a blog that attracted thousands of visits and many comments converged to the understanding that "change" was the keyword for hydrological sciences in the XXIst century and that a broad perspective of global change is necessary. As climate change is affecting human societies mainly through changes in the water cycle, it was agreed that 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).

The IAHS decade 2013-2022 was presented at the IAHS Scientific Assembly in Göteborg, Sweden in July 2013. To emphasise the focus on change, this decade was called "Panta Rhei - Everything flows" after the aphorism that is attributed to Eraclitus from Ephesus, which means that nature and societies are continuously changing. The subtitle of the decade, "Change in

Hydrology and Society" was introduced to make the concept immediately clear. Supporting a community-based bottom-up organisation, 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. The overview of the Panta Rhei working groups and their cooperation with IAHS commissions (Fig. 1) emphasise the variety of scientific challenges that were considered and the diversity of approaches for their solutions, ranging from stochastic theories (e.g. Ceola et al., 2014) to socio-hydrological models based on partial differential equations (e.g. Di Baldassarre et al., 2013).

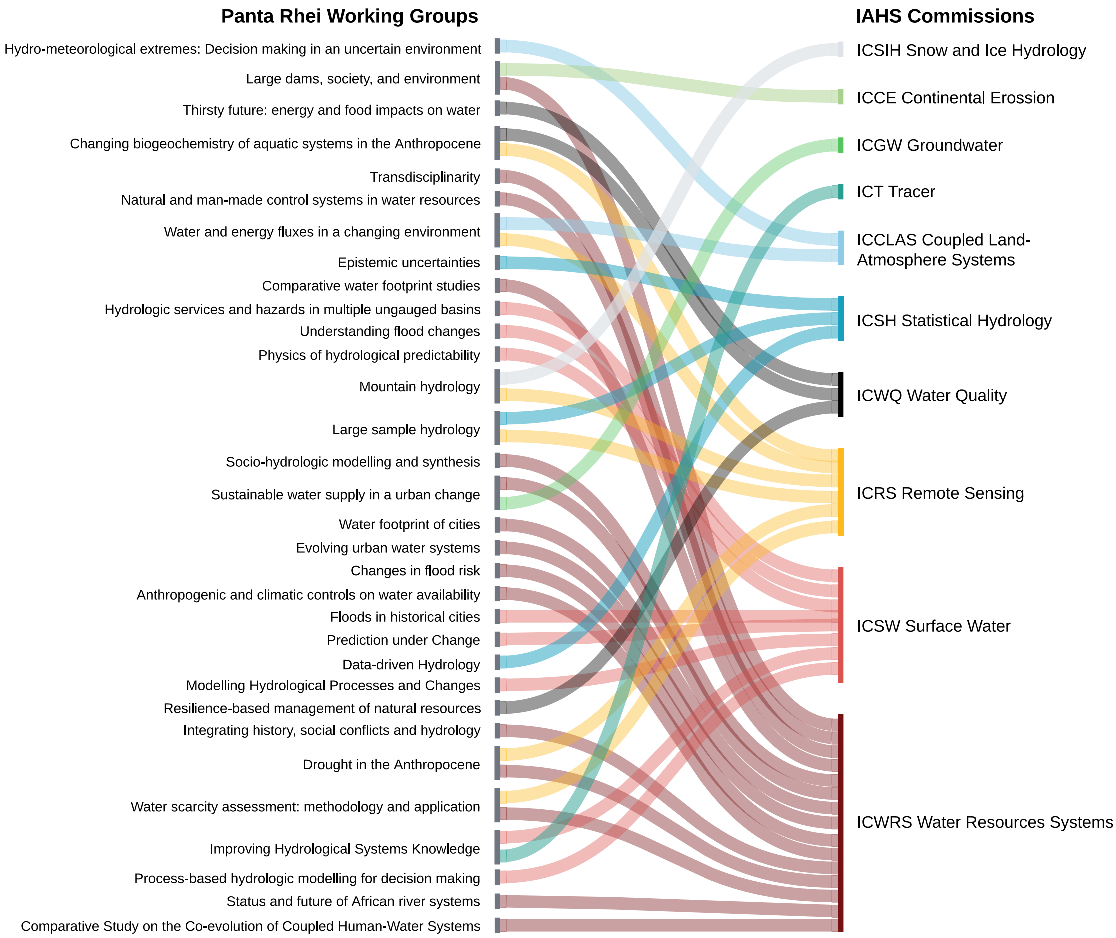

Figure 1. Links and cooperation between the Panta Rhei working groups and the IAHS commissions

During the decade, the substantial increase in the network of hydrologists and scientists in related disciplines, particularly social sciences, stimulated large-scale cooperation based on the exchange of knowledge and data, which was also part of the emergence of the Open Science paradigm (UNESCO, 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. 2022, 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 organisations. Furthermore, the long-term partnership of IAHS with several agencies of the United Nations and the UN Water coordination mechanism allowed strong synergies with, and scientific inputs to, multilateral efforts, including the implementation of SDG 6 "Clean Water and Sanitation" and interlinkages within Agenda 2030 (e.g. Young et al., 2015; Mahé et al., 2021; Cudennec et al., 2020, 2022a; Dixon et al., 2022; ISC, 2023). Given this plethora of initiatives, our review is not restricted to studies directly belonging to the Panta Rhei initiative, which we nevertheless see as very influential for driving global scientific engagement with the topic.

1.2 The three domains of Panta Rhei research

The Science Plan of Panta Rhei organised 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) Prediction under Change (Target 2), and (3) Integrated Water Resources Management (Target 3), as Panta Rhei aimed to bridge past developments with new opportunities (Figure 2).

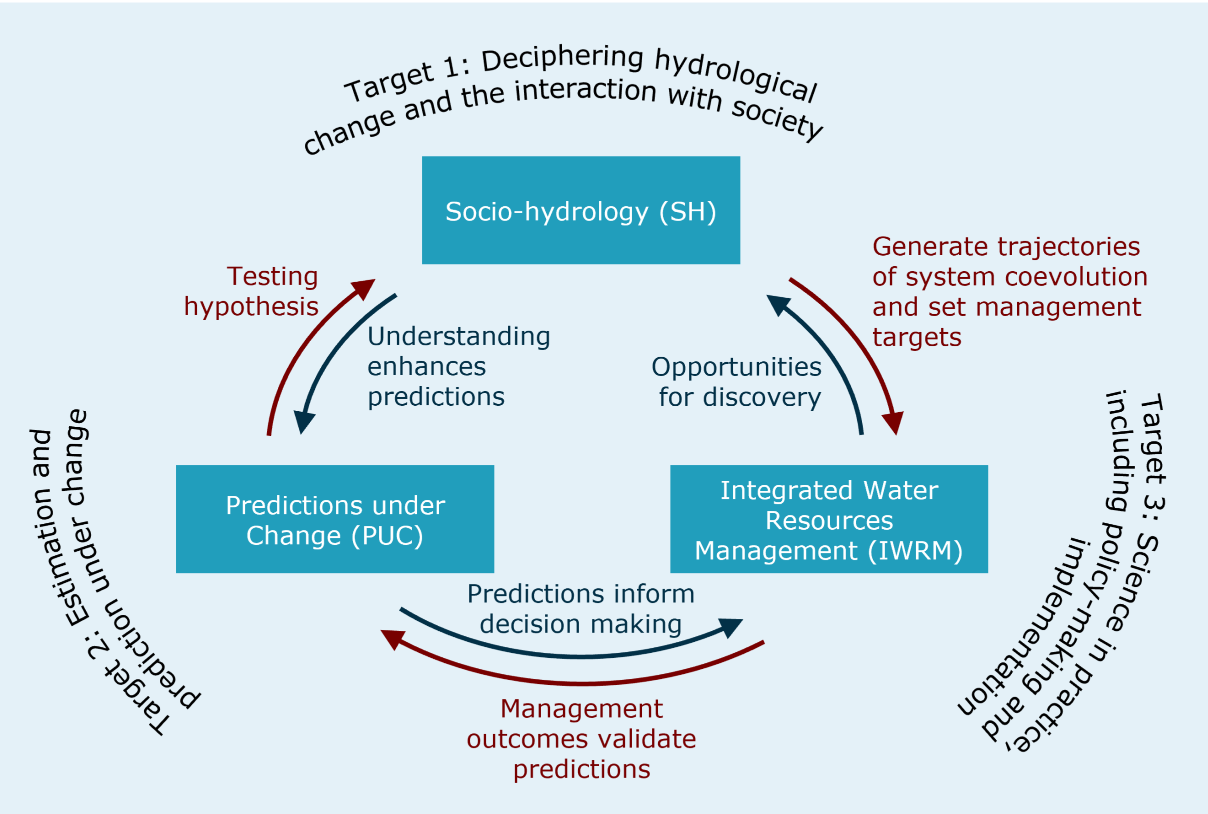

Figure 2 Panta Rhei research encompasses three domains: Socio-hydrology (SH), Prediction under Change (PUC), and Integrated Water Resources Management (IWRM) to achieve its three targets (Figure adapted from Montanari et al. 2013, Thompson et al. 2013).

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 the 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 Bloeschl, 2015; Bai et al., 2016). However, a 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. 2017). As such, socio-hydrology aims to be a use-inspired science to inform the complex water sustainability challenges faced in the Anthropocene (Sivapalan and Blöschl 2015; Sivapalan et al., 2014; Di Baldassarre et al., 2019) and be applied for policy making (Troy et al. 2015).

The domain of **Prediction 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 that it 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 in order to serve as a basis for 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 et al., 2004). It has high societal relevance and, therefore, aims for iterative exchange between science, technology and societies. It brings science into practice, including policy making 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-level planning, stakeholder participation, the integration of water management across different sectors, and the consideration of social, economic, and environmental factors. The approach also emphasises 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 organised 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 a number of specific research findings from the scientific decade 2013-2022.

Table 1: Organisation 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 use
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	4. Understanding socio-hydrological systems

hydrological processes? What are the boundaries of coupled hydrological and societal 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

As a basis for this review, the Panta Rhei community has compiled a collection of 351 key scientific papers that contribute to answer these science questions (see Supplement). For each paper, the most important results and scientific advances are briefly described and it is indicated which of the scientific questions of Panta Rhei the paper contributes to answering. 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. Some studies were directly initiated by a Panta Rhei working groups, while some were inspired by the IAHS Panta Rhei scientific decade, and others worked independently of these activities. This review aims to cover scientific advancements from all these studies on change in hydrology and society, but with a specific focus on changes that involve a two-way coupling between human actions and water quantity and quality.

1. Scientific progress on monitoring and data use

Many initiatives and approaches have improved data accessibility, discovered new data, and developed innovative data integration and analyses, as well as used citizen science and have as such contributed to answer 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 Supplement).

2.1. Improved data accessibility

Over the past decade, innovations in traditional gauging networks, the combination of disparate data into easy-to-use large-sample datasets, and data sharing and open access initiatives have greatly improved the accessibility of hydrological and other data. A survey answered by over 300 hydrologists (Blume et al., 2017) highlights the importance of experimental work and of the continued operation and expansion of traditional monitoring networks to understand and predict changes in the hydrological system. For instance, flow monitoring at thousands of stations over decades has been the basis for identifying changes in high flows and seasonality as a result of climate change across Europe (Hall et al., 2014; Blöschl et al., 2019) and globally (Wang et al., 2024). New data have enabled advances in detecting human influence on river flow, for instance, showing that water abstractions aggravate droughts (Van Loon et al., 2022) and are to be taken into account to successfully predict the baseflow index (Bloomfield, 2021). Locally, human impacts can be measured with target inflow-outflow monitoring campaigns around water management infrastructure (Rangecroft et al., 2019), and targeted selection and analysis of pair-wise events can increase understanding of changes in both floods and droughts (Kreibich et al., 2019; 2022). Globally, newly released datasets enabled Huggins et al. (2022) to identify hotspots for social and ecological impacts.

Considerable effort has been spent on making data more accessible and intuitive to use, often via collation across locations and sources. This led to the production of the CAMELS (Catchment Attributes and Meteorology for Large-sample Studies) datasets, which combine daily hydrometeorological time series (atmospheric forcing and river flow), attributes characterising the landscape and anthropogenic impacts (e.g. reservoir capacity, human consumption) for hundreds of catchments (Newman et al., 2015; Addor et al., 2017; Alvarez-Garreton, 2018; Coxon et al., 2019; Chagas et al., 2020; Fowler et al., 2021; Höge et al., 2023). Addor et al. (2020) highlight progress made in sharing catchment data, yet, they also stress that substantial challenges remain. To address them, they propose the creation of a cloud-based community project, which led to the Caravan initiative (Kratzert et al., 2023). Other examples target more specific environments, 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 U.S (Turner et al., 2021). Multiple studies extend to larger even global spatial scales, focussing on, for example, gap-filling of globally available meteorological station data (Tang et al., 2021), meteorological reanalysis (Berg et al., 2018;

Hersbach et al., 2020), streamflow hindcasts (Ghiggi et al., 2019), global soil maps (Poggio et al., 2021), global ensemble meteorological data fields (Tang et al., 2022), global flood and drought data (Lindersson et al., 2020), and global catchment modelling including parameter estimations for ungauged basins worldwide (Arheimer et al., 2020; Santos et al., 2022).

There is increasing recognition that the collation of impact data is also highly valuable. For example, Papagiannaki et al. (2022) collated flood fatality data across 12 territories in Europe and its surrounds. The drought impact database of Stahl et al. (2016) harmonises nearly 5000 impact reports across governmental, media and academic sources. The Flood Damage Database HOWAS 21 provides object-specific flood damage data resulting from fluvial, pluvial and groundwater flooding mainly in Germany (Kellermann et al. 2020). From a broader socio-hydrological perspective, Alexander et al. (2020) stress that qualitative data are under-shared when compared to quantitative data and represent a largely untapped resource.

In addition to FAIR data (Wilkinson et al., 2016), referring to Findability, Accessibility, Interoperability and Reusability, data need to be relevant towards Supporting QUality Action and REsearch, an approach known as SQUARE (Cudennec et al., 2020). These qualities support the organisation of data into effective and value-adding data-knowledge-services (Cudennec et al., 2022a), while acknowledging the rights of related stakeholders (see e.g. CARE principles; Carroll et al., 2020). Despite the promising progress on open data accessibility during the decade, there are also signs of decline in river-flow monitoring and need for quality assurance when using open sources (Crochemore et al., 2020).

2.2 New data

The increasing availability and volume of digital data have also opened up new opportunities for hydrology research to include unstructured and qualitative data types in their research design. Examples of these qualitative data include texts such as newspaper articles, minutes of meetings or institutional documents: Wei et al. (2015) traced the evolution of societal value of water in Australia using news articles from 1843 to 2012; Carvalho et al. (2024) monitored how water allocation decisions have been made in Northeast Brazil from 1997 to 2021 using the minutes of water board committee meetings and Genova et al. (2022) traced the evolution of water environmental regulations in Chile during 1900-2016. News media coverage of extreme drought and precipitation events, measured by the number of articles published, has also proved useful for measuring issue salience (Quesnel and Ajami, 2017; Treuer et al., 2017; Roby et al., 2018). Newspaper articles have also been shown to be instrumental in collecting data on the socio-economic impacts of droughts and floods (de Brito et al., 2020; Sodoge et al. 2023).

Researchers can “scrape” the web and obtain large amounts of data from websites, social media, and other platforms. For instance, web-scraping and text analysis 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 (Scotti et al., 2020, Fohringer et al. 2015), and monitoring the occurrence of disasters (Kryvasheyeu et al., 2016). Data collected through car navigation apps such as Waze or Mapbox have 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).

To complement in-situ data, earth observation products (EO) have become common when 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), and the Surface Water and Ocean Topography SWOT mission, aimed at monitoring river hydraulic properties (Frasson et al., 2019). Based on satellites and open data Yamazaki et al. (2019) provided a global high-resolution map of river networks with flow accumulation, direction and river width, which was fundamental for a wide range of geoscience applications including flood risk assessment, aquatic carbon emissions, and climate modelling. In addition, several satellite constellations have been employed for monitoring key anthropogenic variables such as land-use and land-cover. Satellite products, combined with additional data, were found to provide valuable proxies of key human-water interactions, also beyond their original purpose (e.g., country-specific increasing trends in nighttime light correspond well with the increase in flood damage, Ceola et al., 2014).

Local-scale monitoring of environmental and human variables has been recently fostered by low-cost innovative wireless sensor networks (WSN) employed e.g., in the meteorological, agricultural and water services sectors (Ojha et al., 2015; Marais et al., 2016). These sensors are managed by either environmental agencies or private people, who could also support data collection (Bárdossy et al., 2021). Local sensors could be placed on-ground, on uncrewed aerial vehicles (UAVs) or on waterborne uncrewed surface vehicles (USVs) to easily monitor e.g., high-resolution elevation, agriculture, water quality, bathymetry and river discharge data (Tauro et al., 2018), and also serve as ground-truth datasets for EO products or new algorithms (Pimentel et al., 2017).

2.3 Data integration and machine learning

Leveraging these data developments, various new analyses approaches have been developed. The combination of datasets with both process-based modelling and machine-learning approaches can be integrated in tools that managers can use to investigate the impact of potential 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 (Vanelli et al., 2022). This is required as some human–water interactions cannot be addressed solely from a quantitative or qualitative perspective (Di Baldassarre et al., 2021; Rangecroft et al., 2021). While quantitative data allow researchers to identify generalizable patterns and dynamics, qualitative data inform about the underlying reasons for these relationships, using detailed descriptions and adding context (Riedlinger and Berkes, 2001; Alexander et al., 2020). As such, quantitative and qualitative data must be considered complementary and equally valuable to investigate interwoven social and physical processes. Even though bringing qualitative and quantitative data together meaningfully is a challenging task (Treuer et al., 2017), in particular in nexus approaches (Liu et al., 2017a; Cudennec et al., 2018; Heal et al., 2022), an 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 quantitative analysis by modelling 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 machine learning (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 build-up areas based on nighttime lights or buildings and map roads using aerial or satellite imagery (Alshehhi et al., 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 (Paprotny et a. 2021; Schoppa et al. 2020, Carisi et al., 2018). 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, thereby promoting the goal of 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 become increasingly popular in hydrology to satisfy the need for more dispersed and diverse observations of multiple water-related variables (Nardi et al., 2022). The benefits of citizen science go beyond merely expanding the scope of available scientific observation (Gura, 2013). It enables accounting for difficult-to-capture social, economic, educational, and behavioural dynamics and improves the acceptability of citizens on the recommended water management actions (Jollymore et al., 2017). As a result, scientists are increasingly realising the potential of citizen science to collect large amounts of data over wider areas and at a higher time-frequency (Buytaert et al., 2014; Walker et al., 2021).

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; Seibert 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 Njue et al. (2019), Kelly-Quinn et al. (2022), Buytaert et al. (2014), Hicks et al. (2019), See (2019), Nath and Kirschke (2023).

3. Scientific progress on drivers of change

Climate, land-use and socio-economic changes affecting freshwater quantity and quality were frequently assessed, attributed to their most likely drivers 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 supplement).

3.1 Climate change

Climate change is expected to significantly influence the water cycle, through a change in the global atmospheric circulation and a larger water-holding capacity of a warmer atmosphere. By 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. (2019) have shown 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, pointing to the joint action of climate change and anthropogenic alteration. Globally long-term annual streamflow appears to be increasing, but with strong local disparities as changes in rain patterns and water management strategies vary substantially across regions (Donat et al., 2016).

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 of local and regional studies, Merz et al. (2021) found that in more than half the catchments worldwide, floods have increased in the recent decades. In the last decades, floods have generally decreased in magnitude in Africa and Australia, have generally increased in the Amazon area, and trends are spatially variable in other continents (IPCC, 2022). River floods in Europe have increased in magnitude in the north-west and decreased in the south and east in the last 60 years (Blöschl et al., 2019; Bertola et al., 2020). Kemter et al. (2020) find that joint and correlated trends in the magnitudes and spatial extent of flooding exist in Europe. Changing seasonality of floods has been detected, more clearly than for their magnitudes (Blöschl et al., 2017 for Europe, Collins, 2018 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 different levels of confidence depending on the drought types (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). Hydrological droughts have been detected as increasing, based on streamflow and groundwater data, in fewer regions of the world (e.g., in the Mediterranean area, IPCC, 2022). Similar to floods, drought seasonality is also more strongly changing, especially in snow-dominated catchments. Brunner et al. (2023) find that high-elevation catchments in the Alps have a stronger change in drought type (from rainfall-driven to temperature-driven) and drought severity (shorter and higher deficit) than low-elevation catchments. In another study, Brunner and Tallaksen (2019) studied multi-year droughts in Europe and found that four regions, i.e. SE England, SE France, central Norway, and the Pre-Alpine area may become more affected by multi-year droughts in the future. As part of an increasing trend in drought severity (Montanari et al., 2023), the Po river basin (Italy) experienced its worst drought on record in 2022 (almost 600-year return period). The type and seasonality of precipitation, rather than its total amount, and the expansion of irrigated areas were found to be the main drivers of this change.

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 regulation of river flows for e.g., 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 combination of anthropogenic alterations of natural water streams and changing climate drivers has resulted in a new framework of droughts, that defines anthropogenic drought as a compound multidimensional and multiscale phenomenon. Anthropogenic droughts are governed by the combination of natural water variability, climate change, human decisions and activities, and altered micro-climate 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 have 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. Increasing water demand and decreasing surface water availability are frequent causes of groundwater overexploitation (Niend et al., 2018). Declining groundwater resources are exacerbated by misaligned incentives associated with the common-pool nature of the resource (Mullen et al., 2022).

Next to atmospheric drivers, flood impacts are also strongly influenced by changes in land use and socio-economic processes (Merz et al., 2021). Globally, in recent decades economic flood impacts strongly increased (Formetta and Feyen, 2019). Shifts in socio-economic systems foster human encroachment into floodplains and increase exposure to floods. Thus, increasing exposure was the main driver of the increase in flood losses during recent decades, in Europe (Paprotny et al., 2018; Stevens et al., 2016) and elsewhere (Tanoue et al., 2016; McAneney et al., 2019).

It is expected that future flood impacts will continue to increase significantly due to climatic and socio-economic changes (Rojas et al., 2013; Dottori et al., 2018). Projections of future flood risk in Europe indicated that hazard, exposure and vulnerability play together an important role in determining changes in the impact magnitude (Rojas et al., 2013; Vousdoukas et al., 2018; Steinhausen et al., 2022; Schoppa et al., 2024). For example, 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 hydrological cycle, leading also to changes in water quality, which has been frequently studied and modelled during the Panta Rhei decade (e.g. Meier et al., 2014, Bartosova et al., 2019). In coastal areas, sea level rise, storm surges, drought, land subsidence and erosion was reported to affect salinity and water quality in soils, estuaries and aquifers (Dasgupta et al. 2015; Philips et al., 2020; Jasechko et al., 2020). Water quality was also found to be crucial for the water-energy-food nexus (Heal et al., 2021), which is severely affected by climate change.

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, degrading water quality (Dailey et al., 2014). Diffuse pollution that comes from multiple sources was found to remain in the environment for a very long time, making 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., 2022) and microplastics (Eerkes-Medrano et al., 2015) were raised during the scientific decade.

At the same time, traditional water-quality problems with agricultural activities and industries 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 increase 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 mobilisation of geogenic contaminants (e.g., arsenic) due to groundwater overuse (Erban et al., 2013).

Water scarcity also impacts water quality, as pollution is then more concentrated, so that recent scientific advances have been in the direction of quality-related water scarcity (Liu et al., 2016) and ecological water scarcity (Liu et al., 2022). Following an integrated framework of three-dimensional water scarcity (Liu et al. 2016), integrated assessments of water quality, quantity, and environmental flows have been widely applied at global, national, and local levels (Liu et al., 2017b; vanVliet et al., 2017; Ma et al., 2020).

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 (Capell et al., 2021). Nature-based solutions have proven to be efficient in addressing challenges in a holistic manner (Oral et al. 2021, Carvalho et al. 2022, Huang et al., 2020) although the impact at large-scale has been questioned, e.g. regarding wetland constructions for nutrient reduction (Arheimer and Pers, 2017). An integrated application of green and grey infrastructure is important for water security for now and in the future (Palmer et al., 2015). Technological advancements have contributed to both a significantly improved detection and treatment of water contaminants. Stricter environmental policies, regulations and standards are probably 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. For instance, detecting hydrological change implies distinguishing persistent changes in hydrological outcomes from the effects of stationary but long-memory climate variability and random observation errors. This first challenge has long been an area of focus in hydrology (Hall et al., 2014; Yang et al., 2019; Villarini and Wasko, 2021), as epitomised in Milly's obituary of stationarity (Milly, 2008) and associated debates (Koutsoyiannis and Montanari, 2014; Serinaldi and Kilsby, 2015; Milly et al., 2015). 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 hypothesised drivers (Merz et al. 2012). Elucidating such causal relationships is not only necessary to both improve predictions (Srinivasan et al., 2017) and develop theoretical insights (Muller and Levy, 2019) in today's rapidly changing human-impacted environments, it is also practically relevant in the process of developing and evaluating 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 (Figure 3).

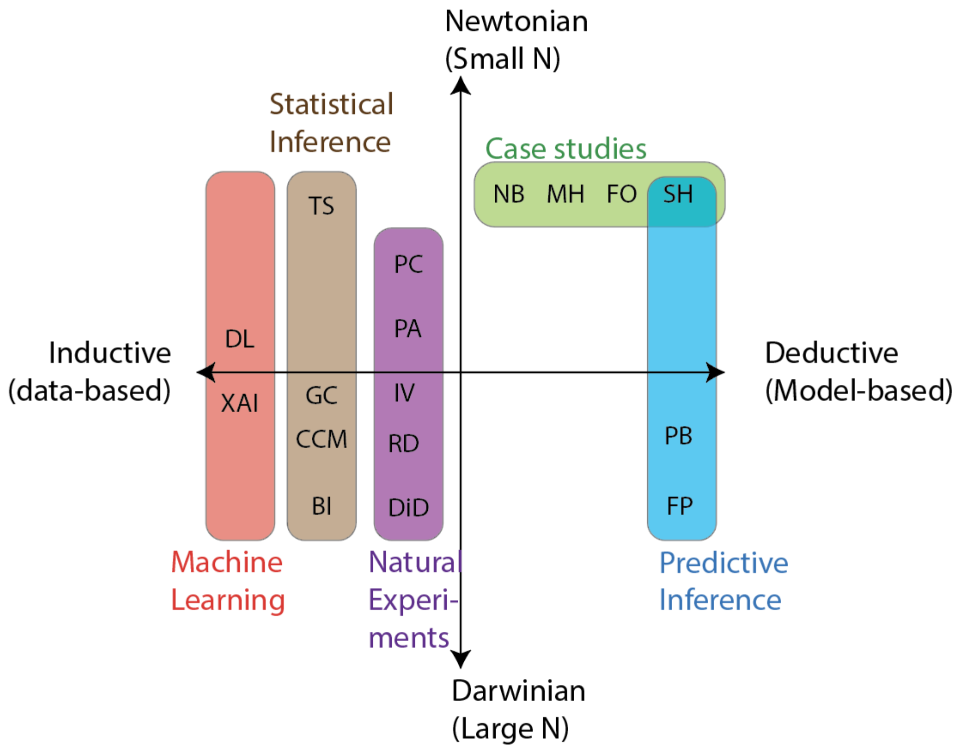

Figure 3. Approximative typology of attribution approaches: DL (Diagnostic Learning), XAI (Explainable Artificial Intelligence), TS (Time series analysis), GC (Granger causality analysis), CCM (Convergent Cross Mapping), BI (Bayesian Inference), PC (Paired catchments), RD (Regression Discontinuity), DiD (Difference-in-difference), PA (Panel analysis), IV (Instrumental Variable), NB (Narrative-based analysis), MH (Multiple Hypotheses), FO (Field Observation), SH (Socio-hydrologic Modelling), PB (Process-based or physical modelling), FP (Fingerprinting).

Hydrologists have long used deductive process-based models to address causal relationships through predictive inference (Ferrero et al., 2019). Therein, a parametric model is developed to capture the key physical processes assumed to govern hydrological dynamics in the considered region. The model is calibrated and validated against historical observations and then used to create counterfactual scenarios to test causal hypotheses. This approach is used to attribute hydroclimatic change (Chiang et al., 2021), changes in streamflow (Hundecha and Merz, 2012; Duethman et al., 2015; Badjana et al., 2017; Mao and Liu, 2019; Collar et al., 2022) and flood risk (Metin et al., 2018), among other characteristics. In a related approach, the hydrologic change is analysed by identifying a fingerprint: specific signatures of changes in the hypothesised drivers (Viglione et al., 2016; Arheimer and Lindstrom 2019; Bertola et al., 2019; Kemter et al., 2020; Bertola et al., 2021). 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. A key assumption of the above approaches is that all potential processes that give rise to the observed change are known a-priori and are controlled for, either through direct observation and incorporation into the model, or through proper randomization (Muller and Levy, 2019). In many cases, this assumption is not satisfied, for example due to the complexity of the systems, to data scarcity (Duethman et al, 2020) or because of dynamic feedbacks with social and ecological processes that can simultaneously serve as drivers and outcomes of hydrological change (Srinivasan et al., 2017).

Owing to the difficulty in incorporating all important couplings into process-based hydrological models, a data-based inductive approach to attribution is often used instead -- in the sense that no specific mechanism is assumed a priori. These models are generally statistical in nature and rely on the detection and interpretation of statistical relationships, either in time (Arheimer and Lindstrom 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; Muller et al., 2021). In terms of attribution, three alternative strategies are generally deployed to interpret the detected correlations as causal. First, the structure of the data themselves 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 (rather than the data themselves) can be leveraged by identifying so-called natural experiments (Muller and Levy, 2019), for instance through panel regression analysis (Blum et al., 2020; Davenport et al., 2020; Mondino et al., 2021), difference-in-difference (Muller et al., 2016; Levy et al., 2018; Penny et al., 2020), regression discontinuity (Sekhri, 2014; Perez-Valentin and Muller, 2020), instrumental variables (Dang and Konar, 2018; Deryugyina and Konar, 2017), exogenous shocks such as wildfires (Pimentel and Arheimer 2021) or covariate matching (Wagenaar et al., 2018; Brunner, 2021). Third, machine learning can be leveraged to explicitly control for (rather than randomise) all plausible sources of variations, for instance using so-called ‘diagnostic learning’ (Razavi et al., 2022), ‘explainable artificial intelligence’ (Althoff et al., 2021; Veigel et al., 2023) or autoencoders (Bassi et al., 2024). The past behaviour of a system is simulated to interpret the decision-making strategy of the machine learning algorithm (Davenport and Diffenbaugh, 2021).

The above approaches use variations and correlations across quantitative data observed for an extended number of sites to draw generalizable insights and infer causal relationships (external validity). A complementary set of approaches tackles attribution by seeking to reconstruct a plausible narrative to explain the observed phenomena for a limited number of cases (internal validity). The complementary nature of these so-called Darwinian (large sample) and Newtonian (small sample) approaches is discussed in Harman and Troch (2014). Approaches seeking to elucidate the internal mechanics of a small number of units, either through 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), field-based studies (Burt and McDonnel, 2015), multiple hypotheses approaches (Srinivasan et al., 2014; Penny et al., 2022b; Fowler et al., 2022b; Chan et al., 2022), socio-hydrological or agent-based models (Kandasammy 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). Therein, attribution is often based on corroboration across multiple sources of data (Nusser and Schmidt, 2017; Frota et al., 2021). For example, Srinivasan et al. (2014) combine quantitative observations with qualitative ethnographic information to evaluate multiple hypotheses on the drivers of changing streamflow in a heavily urbanised catchment.

4. Scientific progress on socio-hydrological systems

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 supplement).

4.1 Concepts for socio-hydrological systems

It is well-known that human societies increasingly influence the hydrological regime, deliberately or not 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, urbanisation, 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 the occurrence of 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, Figure 4 shows the interplay between human and water systems. 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 (Van Loon et al., 2016; AghaKouchak, et al., 2021).

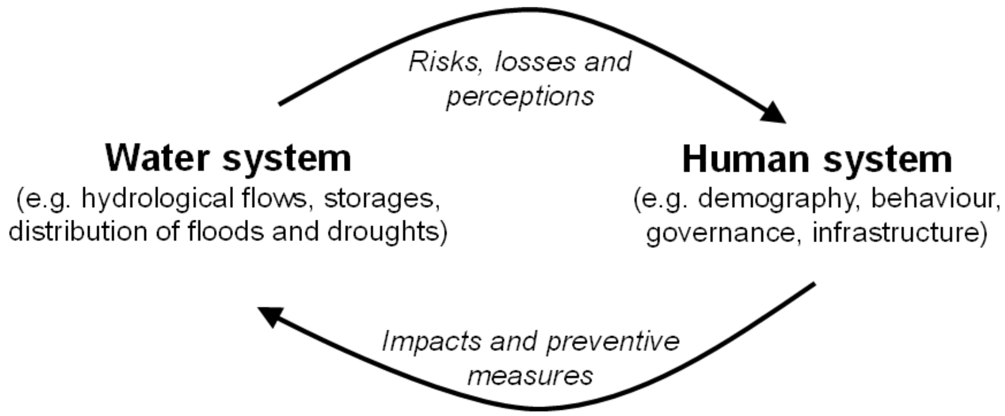

Figure 4. The interplay of human and water systems.

These complex interactions and feedbacks between human and water systems (Figure 4) can generate socio-hydrological phenomena, i.e. patterns across places or even across different 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).

Table 2. Overview of socio-hydrological phenomena (Source: Di Baldassarre et al., 2019)

General phenomenon	Main characteristics	Sub-phenomena	Implications for IWRM
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)	·Focus on reducing social vulnerability. ·Better communication of water-related risks. ·Proper quantification and pricing of risk by insurance companies. ·Enhanced integration of hard and soft path measures.
Supply-demand cycle (Kallis, 2010)	Increasing supply enables growth that in turn generates higher demands.	*Fixes that backfire* (Gohari et al., 2013)	·Focus on reducing demands rather than increasing supply. ·Price water accurately; scarcity value. ·Diversity water sources during drought; implement water conservation measures.
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)	·Focus on keeping adaptive capacities. ·Avoid maladaptive response to drought that might exacerbate future flood losses.
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)	·Need to consider supply chain water use since local reduction in water use that accompany wealth may be offset by non-local water use increases.
Rebound effect (Alcott, 2005)	Increasing efficiency leads to higher consumption .	*Irrigation efficiency paradoxes* (Dumont et al., 2013)	·Implement governance for cap and trade system of water. ·Installing water efficient technologies is not necessarily going to lead to less water use. ·Implement water basin use caps in addition to water efficient technologies.
Aggregation effect	Undesirable outcomes at the system scale from aggregated optimal decisions at the individual scale.	*Collective action* (Olson, 1965) (Ostrom, 1990)	·Implement systems level governance, e.g. property rights for potential tragedy-of-the-commons cases.

	Desirable outcomes at the system scale from aggregated inequalities at the individual scale.	*Water injustice* (Zwarteveen et al., 2017)	·Focus on the distribution of costs and benefits, not only average values. ·Consider vulnerable communities.
Institutional complexity	Trade-off between resilience and efficiency.	*Robustness-fragility trade-off* (Csete and Doyle, 2002)	·Operationalize multi-objective optimization, to e.g. make sure poor households do not get cutoff from water supply when pricing scheme is changed. ·Explicitly consider links between multiple systems.

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; Di Baldassarre et al., 2015; Muller 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 resolution based on agent-based modelling (Wens et al., 2020; Ghoreishi et al., 2021) or various applications of statistical or machine learning 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, 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 and Anderies, 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 timescales, 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, 2022; 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.

5. Scientific progress on modelling and prediction

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 supplement).

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 hydrologic response (Montanari et al., 2013; McMillan et al., 2016; Ceola 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 (Grimaldi et al., 2011; Fowler et al., 2022) 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. For example, a model that incorporates biases induced by successive wet and dry years in reservoir operation decision making can be seen as modelling a stationary process (Mason et al., 2018). This has also opened possibilities to apply standard calibration and validation techniques that often require stationarity. For example, 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 impact on flow from human-induced change of catchment characteristics (Arheimer and Lindstrom, 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 Bloeschl, 2015; Wesselink et al., 2017; Bartassello et al., 2021; Schrieks et al., 2021). Recent models of human-water decision-making have benefited from the novel concepts that exist in the social sciences domain such as game theoretic concepts, agent-based models, and behavioural models (Bartassello et al., 2021; Schrieks et al., 2021). For example, heterogeneous decision making of farmers has been extensively modelled using agent-based models (Wens et al., 2020, 2022; Tamburino et al., 2020). Yu et al. (2017) used game theoretic concepts to incorporate collective action in coupled human water system models 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).

The application of hydrological models as well as human-water system models is not objective and models' subjectivity should be better recognised (Lane, 2014; Merz et al., 2015; Melsen et al., 2018; Addor and Melsen, 2019; Yu et al., 2022). It is now acknowledged that 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), lack of neutrality in political implications, and difficulties with transdisciplinary collaboration of diverse human agents (Melsen et al., 2018). Yu et al. (2022) have highlighted that the complexities of human-water systems such as decision making at various space, time 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, 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., 2017). Merz et al. (2015) argue that surprise is particularly important in attempting to overcome potential cognitive biases within coupled human-water management. Here techniques such as behavioural experiments and social surveys have been proposed to quantify biases (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 with which they are studied and by whom, are of importance in bridging the gap between understanding human-water co-evolution and utilising such insights for prediction. In this light, a means for defining, capturing, and communicating human-water model uncertainty, especially in narratives developed for diverse decision-makers is essential. 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

The Panta Rhei community has developed a spectrum of data and modelling methods, 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; Ward et al., 2020; Wens et al., 2021).

There have been several socio-hydrological studies, mostly in human-agricultural and human-flood systems, that 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's economy increases sustainability and is 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%.

6 Scientific progress on water management and adaptation to change

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 supplement).

6.1 Scenarios and possibility spaces

Prediction is central to water resources management and planning. Socio-hydrological models aim to show under which 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 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 the 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 emphasise 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., 2022; Conallin et al., 2022; Pham et al., 2022).

The Panta Rhei initiative has supported adaptive water management through inter- and transdisciplinary research and collaboration between hydrologists, social scientists and 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. The following examples emerged during Panta Rhei: 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, 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, 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).

As the following examples demonstrate, the Panta Rhei initiative's contributions to supporting participatory water governance range from novel approaches, theoretical frameworks, inclusion and quantification of social variables to 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. Hong et al. (2024) criticised the stakeholder participation in the implementation of the Murray-Darling Basin Plan by analysing the public submission data during 2007-2022. 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 marginalised 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 prioritise 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). There are many more examples that demonstrate how co-design with potential end-users from the public and private sector as well as civil society organisations 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 characterised 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 (Brelsford et al, 2020; Hayashi et al., 2021).

7 Summary of scientific achievements

Inter- and transdisciplinary collaboration on change in hydrology and society has generated concepts, methods, results and applications that have filled many key gaps in our understanding of hydrological and societal change and led to advances in science and practical water management, as presented in the different sections of this review, which we visualise in Figure 5 and summarise as follows.

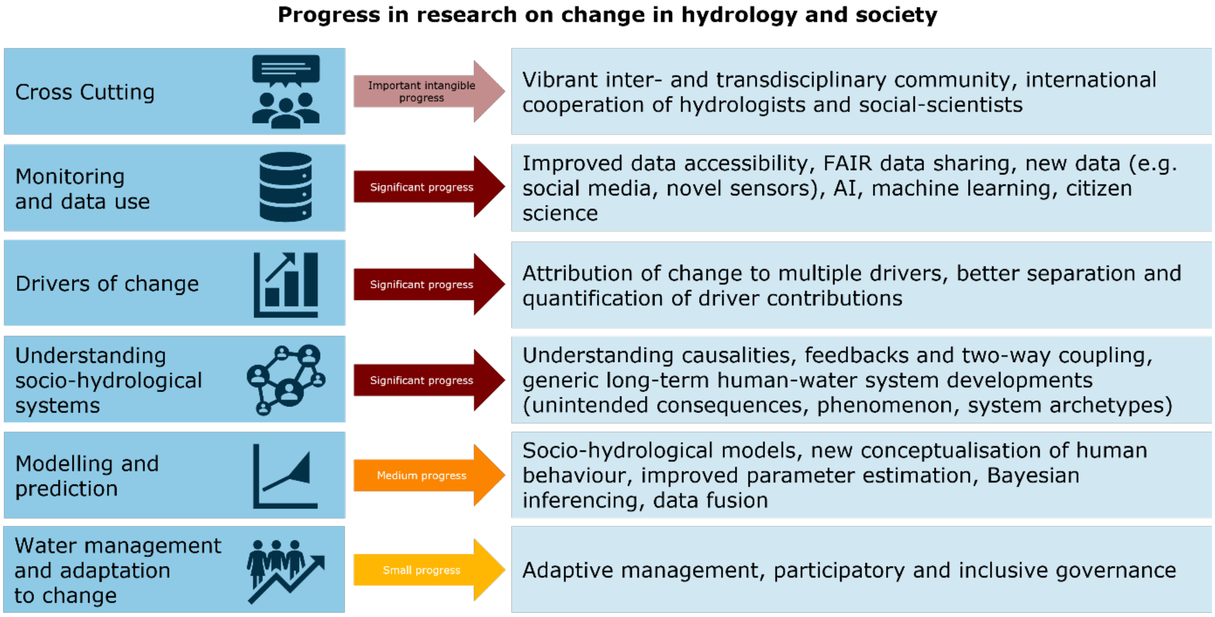

Figure 5 Summary of advances in research on change in hydrology and society in terms of hydrological science and practical water management

Cross Cutting

The main outcome of the Panta Rhei initiative seems to be non-tangible, that is the large diverse community that formed during the decade, in line with the IAHS mandate. Local to international cooperation of hydrologists, social scientists and practitioners lead to mutual benefits and new outcomes. Transdisciplinary project teams enabled a transformation of our understanding of human-water systems improving predictions and decision-making. The close communication between scientists and stakeholders was essential, as new ideas and advancements are often generated through addressing changing societal needs with new approaches and technologies. The co-alignment of research with the UNESCO-IHP's priorities for a water secure world in a changing environment, and with WMO's efforts 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.

Monitoring and data use

Accessibility of data has increased significantly, also due to increasing community data sharing initiatives. This is true for hydrological data, e.g. CAMELS initiatives, but also for socio-hydrological data, e.g. Panta Rhei benchmark data compilations, which match hydrological data with socio-economic and behavioural data. Open and equitable data sharing is supported by international principles such as the FAIR and CARE principles, as well as the ongoing multilateral consolidation of Open Science principles.

New methods of analysis (e.g. machine learning, AI), 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 sensitisation, educational aspects and knowledge generation through the involvement of multiple points of view, was further confirmed and consolidated.

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 the intensification of agriculture including irrigation, 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 the individual contributions of drivers to change. These comprehensive, mainly model-based, but occasionally also data-based analyses improved our understanding of the long-term developments of complex human-water systems, and stressed the importance of human decisions and actions e.g. for the mitigation of flood and drought risks.

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 including contrasting different places with modelling 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 organising the range of socio-hydrologic 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.

Modelling and prediction

Various powerful socio-hydrological model approaches have been developed which describe feedbacks, e.g. causal loops, and include new conceptualisations 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 hydrologic 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 inferencing 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 complex pathways, e.g. including tipping points and non-linear system dynamics.

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 of measures are not only determined by cost-benefit analyses but also flexibility and adaptability of measures are considered.

Participatory and inclusive governance is needed, involving all stakeholder groups (users, planners and policy-makers at all levels, in particular at the river basin scale, thus from different countries if relevant). 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.

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 10 years ago. However, we also realise that the more our knowledge of nature and humans increases, the larger is the number of relevant interactions and feedbacks that newly come to our attention and as such the larger the complexity and uncertainty in our understanding and predictions. We continue to endeavour to answer the question "What are the key gaps in our understanding of hydrological change" and to close 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 Decade and world-wide research efforts on change in hydrology and society have created a vibrant and productive community of natural, social and interdisciplinary scientists and practitioners (Pande et al. 2022), which is probably the most important and lasting outcome of the 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 by bringing together scientists and practitioners from various disciplines within the framework of IAHS and beyond (Kreibich et al. 2022). These are all recommendation 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 the future research on water and societies, which the new International Commission on Human-Water Feedbacks (ICHWF) is designed to spearhead. We also need to synthesise knowledge to see order and patterns in the apparent disorder and high complexity, not only through the normal scientific discourse but also through more specific efforts such as periodic meta-analyses. Finally, we need to contribute to a better world by a concerted effort of using our predictive capabilities to solve water problems in a way that accounts for the long-term feedbacks between humans and water.

We, therefore, recommend that the community take a broader view of the hydrologic sciences in three dimensions while, at the same time pursue synthesis, also in three dimensions (Figure 6):

- **Broadening the understanding** 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.
- **Focusing on key themes**, e.g., as proposed by the Unsolved Problems in Hydrology (UPH; Blöschl et al., 2019) initiative, 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 technological advance in order to advance the hydrological sciences even further in a coherent way.
- **Finding sustainable solutions** as proposed by the new IAHS Decade (2023-2032) on "Science for solutions: Hydrology Engaging Local People IN one Global world (HELPING)" (Arheimer et al., 2024).

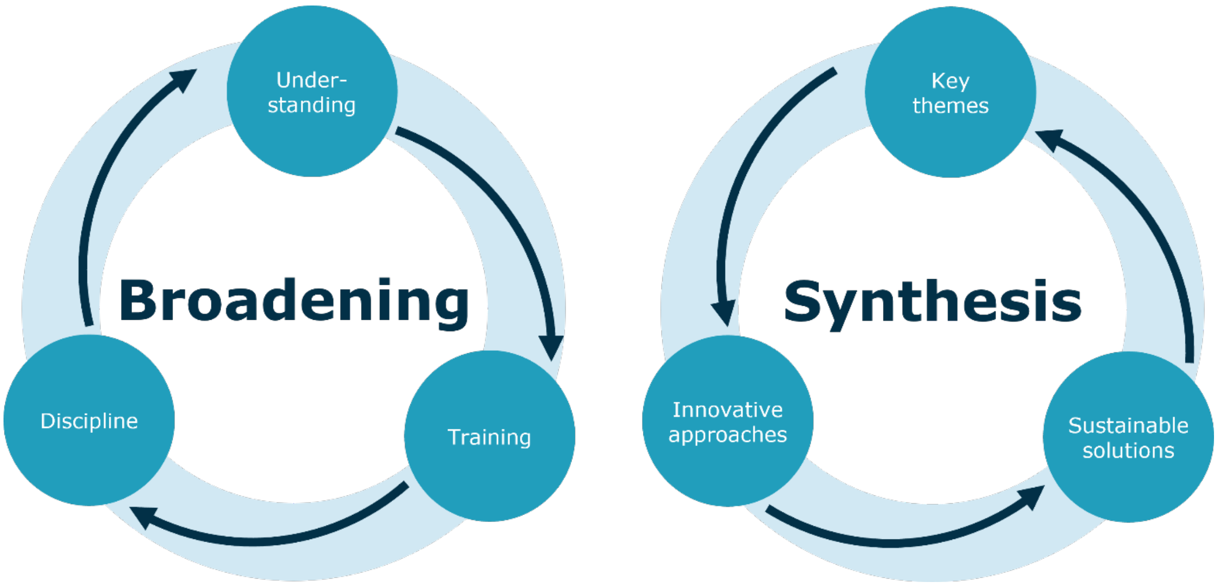

Figure 6 Recommendation to make progress by broadening the understanding, the discipline and the training while synthesising and focusing on key themes, the development of innovative approaches and sustainable solutions.

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