Hydrological Sciences Journal

ISSN: 0262-6667 (Print) 2150-3435 (Online) Journal homepage: http://www.tandfonline.com/loi/thsj20

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To cite this article: Hilary McMillan, Alberto Montanari, Christophe Cudennec, Hubert Savenije, Heidi Kreibich, Tobias Krueger, Junguo Liu, Alfonso Mejia, Anne Van Loon, Hafzullah Aksoy, Giuliano Di Baldassarre, Yan Huang, Dominc Mazvimavi, Magdalena Rogger, Bellie Sivakumar, Tatiana Bibikova, Attilio Castellarin, Yangbo Chen, David Finger, Alexander Gelfan, David M. Hannah, Arjen Y. Hoekstra, Hongyi Li, Shreedhar Maskey, Thibault Mathevet, Ana Mijic, Adrián Pedrozo Acuña, María J. Polo, Victor Rosales, Paul Smith, Alberto Viglione, Veena Srinivasan, Elena Toth, Ronald van Nooyen & Jun Xia (2016) Panta Rhei 2013–2015: global perspectives on hydrology, society and change, Hydrological Sciences Journal, 61:7, 1174-1191, DOI: 10.1080/02626667.2016.1159308

To link to this article: http://dx.doi.org/10.1080/02626667.2016.1159308

Accepted author version posted online: 01 Mar 2016.
Published online: 12 Apr 2016.

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HYDROLOGICAL SCIENCES JOURNAL – JOURNAL DES SCIENCES HYDROLOGIQUES, 2016
VOL. 61, NO. 7, 1174–1191
http://dx.doi.org/10.1080/02626667.2016.1159308

Panta Rhei 2013–2015: global perspectives on hydrology, society and change

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ABSTRACT
In 2013, the International Association of Hydrological Sciences (IAHS) launched the hydrological decade 2013–2022 with the theme "Panta Rhei: Change in Hydrology and Society". The decade recognizes the urgency of hydrological research to understand and predict the interactions of society and water, to support sustainable water resource use under changing climatic and environmental conditions. This paper reports on the first Panta Rhei biennium 2013–2015, providing a comprehensive resource that describes the scope and direction of Panta Rhei. We bring together the knowledge of all the Panta Rhei working groups, to summarize the most pressing research questions and how the hydrological community is progressing towards those goals. We draw out interconnections between different strands of research, and reflect on the need to take a global view on hydrology in the current era of human impacts and environmental change. Finally, we look back to the six driving science questions identified at the outset of Panta Rhei, to quantify progress towards those aims.

ARTICLE HISTORY
Received 7 October 2015
Accepted 23 February 2016

EDITOR
D. Koutsoyiannis

ASSOCIATE EDITOR
not assigned

KEYWORDS
Panta Rhei; hydrological decade; socio-hydrology; climate change; human impacts; global hydrology; water resources; water security; society

1 Introduction

The hydrological cycle, from catchments to global scales, has for thousands of years been intimately linked with human activity. Humans have a direct impact on 83% of Earth's land area (Sanderson *et al.* 2002) and use 54% of available global freshwater runoff (Postel *et al.* 1996). Eighty percent of the world's population lives under high water security threat, and 65% of global river discharge is under moderate to high biodiversity threat (Vörösmarty *et al.* 2010). No wonder, then, that hydrology is now complemented by socio-hydrology (Sivapalan *et al.* 2012, Di Baldassarre *et al.* 2015, Sivapalan and Blöschl 2015), and the hydrological cycle by the hydro-social cycle (Linton and Budds 2014). In response to the imperative to include human impact as integral to hydrological research, the International Association of Hydrological Sciences (IAHS) launched the hydrological decade 2013–2022 with the theme "Panta Rhei: Change in Hydrology and

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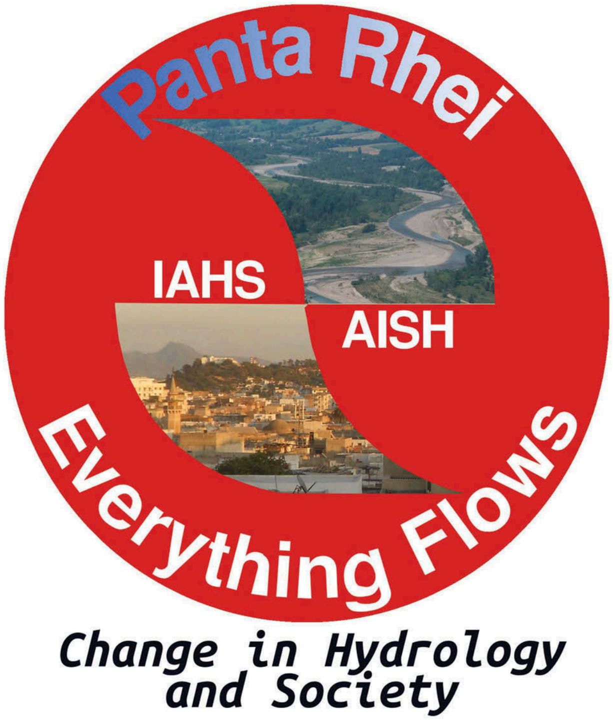

Figure 1. The Panta Rhei logo.

Society” (Montanari *et al.* 2013; Fig. 1). This paper reports on the first Panta Rhei biennium 2013–2015. We summarize the most pressing research questions and provide examples from around the globe, through the eyes of the working groups embarking on those challenges.

The title of this paper “Global perspectives on hydrology, society and change” draws from several motivations. The success of Panta Rhei, as with its predecessor, “Predictions in Ungauged Basins, PUB” (Sivapalan *et al.* 2003, Blöschl *et al.* 2013, Hrachowitz *et al.* 2013), is founded on collaborations between diverse research groups, nationally and internationally, from the developed and developing world. Panta Rhei benefits from interaction with other major worldwide hydrological cooperation frameworks, from intergovernmental and scientific spheres. In particular, these include the UNESCO International Hydrology Programme and the World Meteorological Organization Commission for Hydrology (Young *et al.* 2015, Wehn *et al.* 2016), the International Council for Science and the Intergovernmental Panel on Climate Change (Bai *et al.* 2016, Brondizio *et al.* in press). Panta Rhei has the explicit aim of superseding case studies, to derive general and transferable results. We believe that this can only be achieved through study and comparison of hydrological and socio-hydrological systems on a global scale.

A global perspective is essential due to the increasingly interconnected nature of human society, water and other resource use and human impacts on climate, land and water (Bierkens 2015, Vörösmarty *et al.* 2015). All these interconnections are emerging with an unprecedented intensity in the Anthropocene era, which we use to describe the period during which human activities have had a significant global impact on Earth’s ecosystems, including hydrology (Crutzen 2002, Steffen *et al.* 2011). Water exchanges include direct international water exchanges, transboundary river flows and global virtual water trade, with water quantity and quality both inherent to these transfers (Hoekstra 2011). International human impacts on water systems include climate change effects, as well as international land purchase and management and the effects of international policies. We hope that Panta Rhei will match these international exchanges of water with exchanges of water information, water governance knowledge and advances in the science of “hydrology, society and change”. In its latest global risk report, the World Economic Forum (2015) listed water crises as the most important risk to the global economy in terms of potential impact. We believe that Panta Rhei will provide a coherent and timely contribution of the hydrological community to the multiple challenges of water security (Vörösmarty *et al.* 2010, UN-Water 2013, Cudennec *et al.* 2015), planetary boundaries (Rockström *et al.* 2009) and capability building in these areas.

The remainder of this paper is organized as follows: in Section 2 we connect the Panta Rhei working groups to the driving science questions. In Section 3 we consider advances and challenges in monitoring, describing and predicting our changing world and in Section 4 we consider interactions of society and water in a global context, including descriptions of the socio-hydrological system, human and urban controls and water footprints. The governance of water, decision making and uncertainty are investigated in Section 5 and in Section 6 we focus on hydrological challenges in the Anthropocene, particularly water scarcity, water quality and flooding. Finally, in Section 7 we discuss the next steps of the Panta Rhei initiative.

2 Science questions and working groups of Panta Rhei

Six driving science questions were set out at the beginning of the Panta Rhei initiative (Table 1). These questions summarize the discussions, at meetings and online, that led to the formation of Panta Rhei. The questions provide a guiding framework for the working groups formed by the community, which lie at the heart of Panta Rhei, and drive the resulting collaborations and research. The working groups are listed in Table 2, showing a diverse range of themes identified by the community as important components of the shift towards research that embraces the interconnected nature of the physical, ecological, biogeochemical and human subsystems of the overarching hydrological system (Wagener *et al.* 2010). This section provides a brief summary of how the working groups’ research links to the science questions, to quantify progress towards these goals.

In many cases, Science questions 1, *What are the key gaps in our understanding of hydrological change*? and 5, *How can we advance our monitoring and data analysis capabilities to predict and manage hydrological change?* have been approached together, as groups working in remote areas such as the Tibetan Plateau look to new technologies such as remote sensing to improve our hydrological understanding (Section 3.1). However, to predict the behaviour of such systems under societal and climate changes remains an open challenge. Initiatives in crowd-sourcing and open data offer opportunities to make better use of existing data, and to

Table 1. The science questions of Panta Rhei, with examples, and a list of working groups addressing each question (working group numbers refer to Table 2).

Science question	Examples	Working groups
1 What are the key gaps in our understanding of hydrological change?	Complex geographic systems, such as mountain areas, urban areas, alluvial fans, deltas, intensive agricultural areas. Inter- and transdisciplinary understanding	4, 7, 8, 11, 12, 15, 16, 17, 18, 20, 26, 27, 30, 31
2 How do changes in hydrological systems interact with, and feedback to, natural and social systems driven by hydrological processes?	Study of history of these coupled systems Hydrology–society as tightly-coupled not loosely-coupled models. Interaction of natural variability with human effects.	2, 6, 7, 9, 12, 15, 16, 17, 18, 19, 20, 21, 24, 26, 27, 28, 30, 31
3 What are the boundaries of coupled hydrological and societal systems?	External drivers and internal system properties of change. Estimation of future boundary conditions.	2, 5, 7, 12, 15, 17, 18, 19, 20, 26, 27, 28, 30, 31
4 How can we use improved knowledge of coupled hydrological–social systems to improve model predictions, including estimation of predictive uncertainty and assessment of predictability?	Estimation of design variables under change, including scientific and societal uncertainty. Ability to make predictions in changing systems, including feedback effects that change the equilibrium behaviour	1, 2, 4, 7, 8, 10, 11, 12, 17, 18, 20, 21, 27, 30, 31
5 How can we advance our monitoring and data analysis capabilities to predict and manage hydrological change?	Opportunities for remote sensing in areas without dense hydrological networks Open data initiatives	1, 4, 7, 9, 10, 17, 18, 20, 21, 23, 24, 27, 30
6 How can we support societies to adapt to changing conditions by considering the uncertainties and feedbacks between natural and human-induced hydrological changes?	Impact on policy making and prediction Education strategies Interdisciplinary activity Science–society knowledge co-production	1, 2, 4, 5, 6, 7, 8, 9, 11, 16, 17, 18, 19, 20, 21, 24, 28, 30

Table 2. The working groups of Panta Rhei.

Working group	Chair
1 Hydro-meteorological extremes: decision making in an uncertain environment	Adrián Pedrozo Acuña
2 Large dams, society, and environment	Bellie Sivakumar
3 Thirsty future: energy and food impacts on water	Ana Mijic
4 Changing biogeochemistry of aquatic systems in the Anthropocene	Hong-Yi Li
5 Transdisciplinarity	Tobias Krueger
6 Natural and man-made control systems in water resources	Ronald van Nooijen
7 Water and energy fluxes in a changing environment	Maria J. Polo
8 Epistemic uncertainties	Paul Smith
9 Comparative water footprint studies	Arjen Y. Hoekstra
10 Hydrologic services and hazards in multiple ungauged basins	Hilary McMillan
11 Understanding flood changes	Alberto Viglione
12 Physics of hydrological predictability	Alexander Gelfan
13 Mountain hydrology	Shreedhar Maskey
14 Large sample hydrology	Vazkén Andreassian
15 Socio-hydrologic modelling and synthesis	Veena Srinivasan
16 Sustainable water supply in urban change	Tatiana Bibikova
17 Water footprint of cities	Alfonso Mejia
18 Evolving urban water systems	Alfonso Mejia
19 Changes in flood risk	Heidi Kreibich
20 Anthropogenic and climatic controls on water availability (ACCuRAcY)	Attilio Castellarin
21 Floods in historical cities	Alberto Montanari
22 Prediction under change (PUC)	Hafzullah Aksoy
23 Data-driven hydrology	Elena Toth
24 Modelling hydrological processes and changes	Yangbo Chen
25 Resilience-based management of natural resources: the fundamental role of water and soil in functional ecosystems	David Finger
26 Integrating history, social conflicts and hydrology: from semi-pristine to highly modified hydrological systems	Victor Rosales Sierra
27 Drought in the Anthropocene	Anne van Loon
28 Water scarcity assessment: method and application	Junguo Liu
29 Improving hydrological systems knowledge	Jun Xia
30 Process-based hydrological modelling for decision-making	Chaopeng Shen
31 Status and future of African river systems	Jörg Helmschrot

enable communities to contribute towards the understanding of the hydrological systems that they interact with.

Many Panta Rhei members are contributing towards the quickly growing body of research in hydro-social systems (Section 3.2). This young area uses new terminology such as "socio-hydrology", "*the science of people and water, a new science that is aimed at understanding the dynamics and co-evolution of coupled human–water systems*" (Sivapalan *et al.* 2012), and the related concept of the "hydro-social cycle" that refers to the inseparable social, political and physical dimensions of water (Linton and Budds 2014). The area offers opportunities to ask fundamental questions regarding how to describe these coupled systems, approaching Science Question 2, *How do changes in hydrological systems interact with, and feedback to, natural and social systems driven by hydrological processes?* Strategies include using data-driven methods to understand the properties of these systems, and using case studies to understand interactions and feedbacks in situations, such as competition for water by industry and communities in Mexico. In a similar area, Science Question 3, *What are the boundaries of coupled hydrological and societal systems*? has encouraged working groups to consider how to treat linked drivers, such as energy, and linked systems, such as ecology (Section 4.1).

Panta Rhei deals with practical and pressing issues in prediction and governance of water resources. Many different types of models are used in water management, and therefore the responses to Science Question 4, *How can we use improved knowledge of coupled hydrological–social systems to improve model predictions, including estimation of predictive uncertainty and assessment of predictability?* are equally broad. They range from water scarcity models and metrics, predictions of flood or drought impacts, to prediction of downstream impacts from changes in mountain areas (Section 6). All these models seek to include the impacts and feedbacks of humans on hydrological systems. Groups are questioning how uncertain societal futures and epistemic uncertainties affect our ability to predict (Section 5.2). Panta Rhei seeks to empower societies to understand the coupled human–water system in Science Question 6, *How can we support societies to adapt to changing conditions by considering the uncertainties and feedbacks between natural and human-induced hydrological changes?* This question underlies Panta Rhei research to compare and contrast water governance strategies between countries, to understand cultural impacts of hydrological hazard, and to take a transdisciplinary approach to understanding that harnesses the multiple sources of water knowledge (Section 5.3). The research of all working groups is discussed in detail in the following sections 3–6.

3 Understanding the hydrology of our changing world

3.1 Hydrological data for the Anthropocene

3.1.1 Thinking big: benefits of large-scale hydrology

The aim of Panta Rhei to go beyond case studies, to find generalized but locally-relevant descriptions of changes in the global water cycle, requires a perspective that encompasses many different hydrological environments. This challenge is taken up by the Working Group on Large Sample Hydrology (Gupta *et al.* 2014). Large samples improve understanding by enabling more rigorous testing and comparison of competing model hypotheses and structures; and improve the robustness of generalizations, by allowing statistical analyses of model performances and downweighting outliers. Large samples also facilitate classification, regionalization and model transfer, by testing them in a wide diversity of hydro-meteorological contexts. Uncertainty estimates are improved when using large samples, by establishing the predictive capabilities and performance of hydrological models in a variety of hydro-meteorological contexts.

An enabling technology for large sample hydrology must be the availability of large, open datasets of hydrological variables. The Large Sample Hydrology group aims to gather, manage and share datasets, provide protocols to assess data quality on large samples of watersheds and share common standards for model assessment, comparison and communication of results. The Panta Rhei organization as a whole is investigating methods to share hydrological data specifically about human impacts and changes. The Working Group on Hydrologic Services and Hazards in Multiple Ungauged Basins is investigating data requirements and methods for hydrological modelling on a continental scale, and contributing to the debate on how diverse water science communities, such as catchment modellers, land surface modellers, operational hydrologists and the water management community, can come together to speed progress towards large-scale models of water systems (Archfield *et al.* 2015).

The same group are testing whether physically- and statistically-based methods can be combined for optimal estimates of hydrological variables. This meshes with the ACCuRAcY (Anthropogenic and Climate Controls on Water Availability) Group, who analysed large-scale and continental variability of precipitation and streamflows (see e.g. Niranjan Kumar and Ouarda 2014, Ouarda *et al.* 2014, Salinas *et al.* 2014) and the potential of geostatistical interpolation for continental prediction of surface water availability in ungauged basins (Pugliese *et al.* 2014). Both groups are interacting with the European open water data initiative SWITCH-ON (http://www.project.water-switch-on.eu/). These efforts all help to answer Science Question 5, *How can we advance our monitoring and data analysis capabilities to predict and manage hydrological change?* Future analyses will combine deterministic and geostatistical approaches to quantify changes in surface water availability associated with global and societal change.

3.1.2 Data needs and solutions

Data-hungry hydrological methods are hampered by the declining streamgauging networks in some developed countries, and their scarcity in developing and emerging countries (Hannah *et al.* 2011). The ACCuRAcY group suggests several responses to this challenge, including unconventional information sources, such as short data series from deployable monitoring equipment and historical/geomorphological information, and the possibilities for blending observed data with output from large-scale hydrological models. Advances in remote sensing technologies for monitoring inland water and land surface hydrological fluxes will play an important role (see e.g. Domeneghetti *et al.* 2014, 2015).

Other nonconventional data, such as crowd-sourcing, qualitative, soft and proxy data from social analyses, will also be relevant (Buytaert *et al.* 2014). Creative data-analysis techniques that maximize information retrieval may elicit understanding of integrated systems that include human or institutional agents. Data-driven methods, investigated by the Data-Driven Hydrology Working Group, will play a large role in understanding the complex interaction of natural and human dynamics, due to our current limited understanding of the system. We do not even know, yet, which variables or drivers are the most significant to describe the behaviour of the coupled systems and we do not know the exact form of the relationships governing the most important feedbacks (Troy *et al.* 2015b).

In the absence of well-established hypotheses that inform the model building process, development of socio-hydrological models must come from the application of data-driven methodologies (Sivapalan 2015) that may be applied first for the adaptive selection and processing (for example using dimension-reduction approaches recently applied in Big Data analysis) of the most relevant data and then in the set-up and refinement of the modelling framework.

3.2 Physics and predictability of the water cycle

Many demands on hydrologists involve simulations and predictions of a physical hydrological system response, from short-term flow forecasting to long-term analysis of water management scenarios. In our world with highly uncertain future climate, but with strong opportunities for large-scale water governance, understanding of the abilities and limits of hydrological predictability is critical (Blöschl 2006). In terrestrial hydrology, the term “predictability” is associated with "forecastability" or "effective predictability" (Douville 2010), i.e. a system with an opportunity for a skillful hydrological forecast. Recently however, predictability has been analysed as an intrinsic property of the hydrological system, unrelated to subjective factors (e.g. Shukla *et al.* 2013, Lavers *et al.* 2014). These new conceptual foundations of predictability link to system dynamics research, and lead us to question the system behaviour under changes.

The Working Group on Physics of Hydrological Predictability is tackling the questions of how predictability will change in the future, by understanding the interconnection, patterns and sources of predictability in hydrological, weather and climate components of the Earth system. Study of hydrological uncertainty caused by atmospheric variability showed that a considerable portion of the observed long-term trend in river runoff characteristics was driven by factors external to the atmosphere, i.e. sea surface temperature and sea ice concentration (Gelfan *et al.* 2015a, 2015b), and therefore indirect links between climate and terrestrial hydrology via oceans must be taken into account (e.g. Kingston *et al.* 2013). Such studies are essential for quantifying the robustness of hydrological models used in climate impact studies, under challenging conditions of changing hydrological regime (Thirel *et al.* 2015).

Detection and attribution of abrupt or gradual changes in environmental measurements is essential if we are to understand current system behaviour. For example, changes in land use, land cover and climate intertwine to create changes in runoff coefficients and water stress (Ayeni *et al.* 2015). A trend can result from gradual or disruptive, natural or human changes in the environment, whereas a jump may result from sudden catastrophic natural events. The Working Group on Predictions Under Change seeks to develop strategies to detect and model inhomogeneities or inconsistencies in time series data (see the review by Peterson *et al.* 1998). Through analysis of time series variability and structural characteristics (jump, trend, randomness, intermittency, probability distribution function, etc.), future projections or other uses of these data can incorporate our knowledge of environmental changes (e.g. Aksoy *et al.* 2008b, Efstratiadis *et al.* 2015, the review by Kundzewicz and Robson 2004). For example, streamflow characteristics can help in understanding possible effects of anthropogenic or natural short- or long-term changes. Any change in the physical conditions of the gauging system causes shifts in the time series. A major flood can cause erosion or sedimentation at the gauging station, and hence change the stage–discharge relationship and the corresponding predicted discharge series (Tsakalias and Koutsoyiannis 1999). Such information can be extracted from the jump analysis of the streamflow record (Aksoy *et al.* 2008a, Gedikli *et al.* 2010).

3.2.1 Anthropogenic changes in mountain areas

Predictions of hydrological systems are particularly challenging in harsh or sparsely-populated environments where data collection can be difficult. Mountains are "water towers" that sustain Earth's freshwater through snow, ice and lake storages, permafrost and groundwater recharge, but hydrological processes in mountainous regions are complex and heterogeneous and our understanding of them is restricted due to limited data. In regions with extensive glacier and snow cover, the hydrological regime is highly susceptible to climate change, and accurate predictions are essential because the potential hydrological impacts extend well beyond the mountains themselves (Beniston and Stoffel 2014, Khamis *et al.* 2014). Mountainous regions must therefore be addressed under Science Question 1 of Panta Rhei: *What are the key gaps in our understanding of hydrological change?*

The Working Group on Mountain Hydrology has identified a series of targets to improve understanding and prediction, and to inform water management in mountain regions. Basic system knowledge is still missing in many areas, e.g. quantifying the role of rainfall, snowmelt, glacier melt, soil moisture and groundwater in the water balance, but there are opportunities to integrate remote sensing information, including gravity observations (e.g. Ragettli *et al.* 2015), with targeted ground observations including tracer studies to improve data quality and quantity in mountainous regions (e.g. Gordon *et al.* 2015). Mountain hydrological regimes are undergoing climate, land cover, environmental and socio-economic changes, and these are inextricably linked as, for example, changes in extreme events and water availability impact on communities, and conversely human management of water resources changes the alpine water balance. Hence, there is a pressing need for modelling tools to help us understand the changing human–water system in mountain regions and their downstream landscapes (e.g. Coppola *et al.* 2014).

The Tibetan Plateau is a mountain region that, with its huge buffering capacity, is the guardian of the Yangtze River basin, protecting it against climatic fluctuations. The Yangtze is the largest river in China and the third largest river in the world, with 0.44 billion people in its watershed, contributing to 35.5% of the GDP (gross domestic product) in China. However, its water security is under threat from headwater change in the Tibetan Plateau, including linked climate, cryosphere, ecosystem and water cycle change. The Working Group on Improving Hydrological Systems Knowledge has chosen to study this system where knowledge of the mountain water cycle is critical to modelling and predicting changes in the middle and lower reaches of the Yangtze, including hydropower schemes, operation of the Three Gorges Dam, water use in the Jianghan Plain agricultural area, and ecological protection and flood control of the Poyang and Dongting lakes. Complementing this study, the Working Group on Modelling Hydrological Processes and Changes will study the major Pearl River system in southern China, using physically-based hydrological modelling with the Liuxihe model to map hydrological processes and changes.

3.2.2 Drivers of hydrological systems

A different lens through which to study the evolution and predictability of hydrological regimes is as systems jointly controlled by water and energy fluxes. These fluxes condition the availability of water and the fluxes of sediment and nutrients/pollutants at multiple scales. Ground or remote monitoring of energy fluxes in addition to water provide another data source to trace past and current trends and estimate future regimes in environments such as snow regions (Pérez-Palazón 2015), arid environments (Odongo *et al.* 2015) or "dehesas" (mixed agricultural-forestry environment) (Andreu *et al.* 2013). Energy fluxes may be considered an example of an external driver on water systems, helping us to answer Science Question 3, *What are the boundaries of coupled hydrological and societal systems?* The Working Group on Water and Energy Fluxes in a Changing Environment aims to synthesize a wide variety of areas in which changes in water and energy fluxes influence their current and future regime. Their work includes snow modelling and monitoring in Mediterranean regions (Herrero and Polo 2012, Pimentel *et al.* 2015), flood risk assessment (Egüen *et al.* 2015), water consumption in cropped areas (Pardo *et al.* 2014, Romaguera *et al.* 2014), sediment transport in semi-arid watersheds (Millares *et al.* 2014), environmental sustainability (Wen *et al.* 2014), water resource management infrastructures (Gómez-Beas *et al.* 2012), and adaptive actions assessment (Polo *et al.* 2014).

It is important to include water quality and biogeochemistry in our understanding of hydrological systems. Biogeochemistry in aquatic ecosystems is of critical importance to global freshwater sustainability, food and energy security and aquatic biodiversity. The aquatic systems of interest include receiving waters that serve human societies, such as rivers, lakes, reservoirs, estuaries and coastal seas. Humans directly alter the aquatic biogeochemical cycles by replacing native vegetation with agricultural crops, applying fertilizers and discharging untreated sewage, and indirectly by altering the water cycle (e.g. through dams and water withdrawals), impacting water quality, and through climate change. The Working Group on Changing Biogeochemistry of Aquatic Systems in the Anthropocene is studying the dynamics of coupled hydrological and biogeochemical processes under natural and human-induced changes, and developing improved models that can serve as tools for sustainable management of water quality and biodiversity in aquatic systems.

3.2.3 *Predictability in socio-hydrology*

It is increasingly recognized that water systems are not only impacted on by humans, but human societies also adapt in response to changes in water systems at different time scales (Sivapalan 2015). To achieve predictive insight into coupled human–water systems over a long period of time, these bi-directional feedbacks must be accounted for. Socio-hydrology is the study of dynamics and co-evolution of coupled human–water systems (Troy *et al.* 2015a). The Working Group on Socio-Hydrologic Modelling and Synthesis is addressing fundamental challenges in understanding socio-hydrological systems. These include understanding the organizing principles that characterize the behaviour of coupled human-water systems, and go beyond site-specific studies.

The Socio-Hydrology Working Group is addressing multiple challenges in understanding coupled human–water systems. Researchers have characterized and modelled the long-term dynamics and co-evolution in generalizable terms, such as social memory of floods or water scarcity and community sensitivity to the environment (Di Baldassarre *et al.* 2013a, 2013b, Zlinszky and Timár 2013, Elshafei *et al.* 2014, Liu *et al.* 2014). They have examined the role of human agency, norms and institutions in shaping societal responses (Ertsen *et al.* 2013, Wescoat 2013) and the inherent trade-offs between alternative trajectories (Scott *et al.* 2014). The working group has also addressed philosophical questions about the kinds of predictive insight achievable given the uncertainty of social futures and appropriate role of researchers studying such systems (Troy *et al.* 2015b, Lane 2014). They ask whether all socio-hydrological research must be embedded in stakeholder driven processes, and whether socio-hydrologists can truly be "impartial observers", or, whether by modelling the coupled system, they are also unwittingly "social engineers" who influence attitudes and social behaviours through their work.

4 Global interactions of society and water

4.1 *Hydrology, society and ecology*

As interactions of societies and hydrological systems change and intensify over time, it is important to understand their interactions in order to better predict the sustainability of both. Examples of a variety of human impacts on hydrology from New Zealand are shown in Fig. 2, where, despite low population densities, the hydrological cycle is significantly modified in many regions. The Working Group on Integrating History, Social Conflicts and Hydrology: From Semi-pristine to Highly Modified Hydrological Systems addresses the question of sustainability of hydrology–society

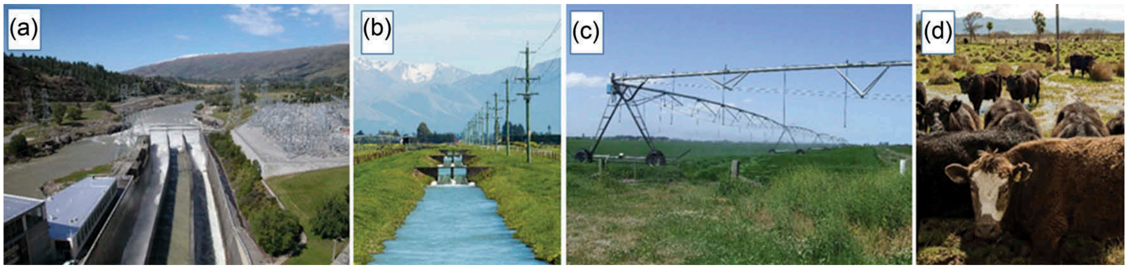

Figure 2. Human impacts on hydrology; examples from New Zealand: (a) water spilling over the Roxburgh Dam on the Clutha River; (b) irrigation channel near Methven, Canterbury; (c) centre-pivot irrigator on dairy pasture, Canterbury; and (d) cattle on wetland area, Wairarapa. Credit: NIWA Image Library, photographers Dave Allen, James Sukias.

interactions, initially using case studies of conflicting water-use scenarios in Mexico. Their first example is the Nejapa Valley in Oaxaca, a semi-pristine hydrological system where little industrial activity takes place and human settlements have been stable for centuries. Adding archaeological prints to hydrological simulations, they found that hydrology has been a controlling factor in human growth (Rosales-Sierra and Garcia-Govea 2014). Today the Nejapa Valley faces heavy mining exploitation with modern industrial technology. Research questions ask how mining water needs will be balanced against the needs of existing, stable human communities who are often opposed to the industrial activities (Aquino-Centeno 2012), and explores the role of legislation and corruption in this relationship (Rosales-Sierra 2007).

Not all societal–hydrological interactions are exploitative. Since the start of human history, efforts have been made to manage and harvest water resources in a sustainable way to maintain ecosystem function (Antoniou *et al.* 2014, Mays 2014). With insights into ecosystem function, humans also became aware that their anthropogenic activities can have positive and negative impacts on ecosystem services (e.g. Malmqvist and Rundle 2002). A significant challenge for geoscience is to establish a socio-ecological system approach that brings in a holistic understanding of how these systems are interlinked and how their sustainability can be better maintained (Ostrom 2009). This can be illustrated by numerous current examples: e.g. sophisticated field investigations reveal that deep water mixing in Lake Issyk-Kul, Kirgizstan, is intensively distributing pollutants in the entire lake (Peeters *et al.* 2002). Although fishery is an important sector in the region, the local awareness of the importance of water quality is low. In another example, in Switzerland, strict water protection laws led to oligotrophication of alpine lakes, reducing fishing yields (Finger *et al.* 2007). While local fishermen argued that maintaining a local fishery is more ecologically sustainable than importing fish, their calls for artificial lake fertilization were rejected and were not accepted by the wider community.

Projected climate changes add a further layer of complexity to the socio-ecological system. Predictions of water availability in the European Alps reveal that water may become scarce during summer months as glaciers vanish (Beniston *et al.* 2011, Finger *et al.* 2012). Financially the hydropower sector is the most important water user. However, other stakeholders, including farmers and the tourism sectors will all be competing for the decreasing resources. Panta Rhei members are investigating how different environmental-flow policies may affect hydropower production potential and fluvial habitat suitability at the regional scale. In all the cases described, a socio-ecological system analysis could give added value to the geoscience results by identifying solutions that are both ecological and socially acceptable. Here, we directly tackle Science Question 3, *What are the boundaries of coupled hydrological and societal systems?*, as we seek to understand how ecology could be treated as a boundary condition to the socio-hydrological system, or as an integral component. The Working Group on Resilience-based Management of Natural Resources: The Fundamental Role of Water and Soil in Functional Ecosystems is using a representative case study in Iceland to investigate methods for embedding water resources research in socio-ecological systems.

4.2 Water resources infrastructure and control

Natural systems are often remarkably resilient thanks to their built-in feedback loops. Mankind's adaptation of those systems to the needs of society to a large extent relies on the same mechanism for the realization of desired behaviour. However, as society places more demands on resources, local systems are linked into composite systems that cover larger areas. One reservoir supplying water for local irrigation and household water can become part of a group of reservoirs and be called upon to take on additional roles in that context. Local measures to cope with low or high river discharges may have regional consequences and need to be integrated in a system along the entire river. In this way new feedback effects are created and systems become more complex and may acquire new equilibria and new behaviours. The Working Group on Natural and Man-made Control Systems in Water Resources is investigating the use of control theory concepts to study the composite system of the hydrological cycle interacting with global weather and human society. This point of view centres on the interaction of the dynamical system with natural and artificial control mechanisms.

One of the most conspicuous ways that societies control water resources is through construction of large dams. Large dams play a vital role in our socio-economic development, but there are also increasing concerns about their negative impacts on our environment and social fabric (Tortajada 2015). Intense pressures from high water consumption rates and multi-year drought can lead to severe declines in dam water storage, such as in the American Southwest (Fig. 3). Benefit-cost analysis of large dams is challenging, due to the absence of accurate models, lack of data, political factors and socio-cultural sensitivities, among others (Koutsoyiannis 2011). The Working Group on Large Dams, Society, and Environment is reviewing and collecting data on such hydrologic, ecologic and socio-economic factors, and analysing interactions within the dam–population–water–food–energy system (Chen *et al.* 2015). This work requires new approaches for analysis of water, ecologic and socio-economic data in combination, necessarily bringing together multiple experts. The long-term aim is to formulate scientifically sound, practically feasible and socially acceptable guidelines for dam construction and management.

4.3 Human impacts on global water use

4.3.1 Water and energy footprints

Human society is thirsty for both water and energy, and the two are intimately interlinked. Not only does energy have a water footprint, but water also has an energy footprint. Society faces dual demands to cope with water scarcity, and at the same time to reduce greenhouse gas emissions, posing a challenge for water resources management of how to integrate the embedded energy use (Rothausen and Conway 2011). While some work has been done on implications of energy use for irrigation agriculture, especially in South Asia

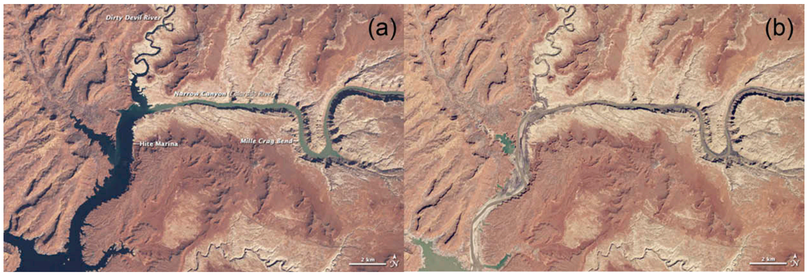

Figure 3. MODIS satellite images of Lake Powell, Colorado, USA, behind the Glen Canyon Dam, show severe declines in water level between (a) 1999 and (b) 2015 due to prolonged drought and high water withdrawals. Image credit: NASA.

(e.g. Malik 2002, Shah 2009), understanding and quantifying complex linkages between water and energy systems in cities is still in its infancy (Kenway *et al.* 2011, Nair *et al.* 2014). In particular, the end-use of water that is the most energy intensive water-sector process (Fidar *et al.* 2010, Perrone *et al.* 2011) is often neglected in water management and policy, and joint water–energy studies to address this issue are of high importance (De Stercke *et al.* 2015). The Working Group on Thirsty Future: Energy and Food Impacts on Water tackles this emerging issue.

Conversely, human activities and energy use have a water footprint. Water not only plays a key role in serving societies and economies, but also constrains development, with important implications for best practice water governance (Savenije *et al.* 2014). These implications are being investigated by the Working Group on Comparative Water Footprint Studies. Integrating water considerations into energy policies is essential to ensure that water footprints do not increase as a result of policies to reduce humanity's carbon footprint (Mekonnen *et al.* 2015a). Demand for hydropower is increasing, yet the water footprints of reservoirs are poorly understood. Liu *et al.* (2016) calculated reservoir water footprints (freshwater that evaporates from reservoirs) in China based on 875 representative reservoirs. The footprint totalled 27.9 x 10^9 m^3 per year, or 22% of China's total annual water consumption. Ignoring the reservoir water footprint seriously underestimates human water appropriation. The reservoir water footprint associated with industrial, domestic and agricultural water footprints caused water scarcity in six of the 10 major Chinese river basins for 2 to 12 months annually.

The development of international trade will strongly influence future spatial patterns of water consumption and pollution, as shown for example by Flachsbarth *et al.* (2015) in a case study for Latin America and the Caribbean. Mekonnen *et al.* (2015b) show, for the same region, how substantial use of land and water resources for producing export crops like soy bean goes hand in hand with significant levels of domestic undernourishment. Semi-arid countries, such as in North Africa and the Middle East, increasingly externalize their water footprint of consumption, thus increasing their dependency on foreign water resources (Schyns and Hoekstra 2014, Antonelli and Tamea 2015). Feeding all people on the planet under existing water constraints will require better water supply and demand management, but in the end also the adoption of diets that are less water-intensive (Vanham *et al.* 2013). Research shows a significant overlap between countries that receive food aid and those that face practices of land and water grabbing (Jackson *et al.* 2015). Problems of water scarcity and pollution intricately relate to energy, agriculture, trade, aid and consumption patterns, requiring governments to integrate water concerns into agriculture and trade policy domains, and companies and investors to integrate water into their business model. Even though companies increasingly adopt strategies of water stewardship (Hoekstra 2014a), recent research shows that overall transparency over water use and pollution, particularly with respect to supply chains, is still poor (Linneman *et al.* 2015).

4.3.2 *Water redistribution in space and time*

Spatial resolution is known to affect the assessment of water footprints and impacts related to crop production. However, the temporal aspects of crop cultivation and the related impacts have been neglected in global analyses. Such aspects are important because different crops can shift irrigation water consumption within a year, increasing or decreasing the related water stress. Consequently, an annual assessment might be misleading regarding crop choices within and among different regions. Hoekstra *et al.* (2012) calculated monthly water scarcity for the world's major river basins, showing that half of the basins, inhabited by 2.7 billion people, are facing severe water scarcity during at least one month of the year. Similarly, Pfister and Bayer (2014) developed a monthly water stress index for more than 11 000 watersheds globally. Irrigation water consumption for 160 crop groups was calculated on a monthly basis and on a high spatial resolution (10 km), estimating global irrigation water consumption in the year 2000 at 1210 × 10^9 m^3. Regional water stress changed considerably when using a monthly, rather than annual or longer, time scale. Similarly, hydroclimatic variability has been shown to affect "green" and "blue" water availability and demand in global agriculture, and, therefore, the ability of a region to produce sufficient calories (Kummu *et al.* 2014). Their analysis showed that more than half of the 2.6 billion people living under water scarcity would have to rely on international trade to reach the reference diet.

Water can be spatially redistributed, in physical terms through water transfer projects and virtually through embodied water, for the production of traded products. Zhao *et al.* (2015) explored whether such water redistributions can help mitigate water stress in China by integrating an economic model with water-use data. The results show that physical water flows in major water transfer projects amounted to 4.5% of national water supply, whereas virtual water flows accounted for 35% in 2007. The analysis shows that physical and virtual water flows do not play a major role in mitigating water stress in the water-receiving regions but do exacerbate water stress for the water-exporting regions.

4.3.3 Urban water flows

Cities drive water use through their economic power and connections with other regions, and create both virtual and physical water flows through their consumption and production of goods and services. The Working Group on Water Footprint of Cities is attempting to quantify and identify the potential role played by urban virtual water flows, which should be considered in urban water planning and management, and must by its nature be attempted alongside the multitude of urban stakeholders. Paterson *et al.* (2015) compared different methods to assess virtual water flows. They identified research needs to develop new methods for urban water footprint analysis (Rushforth and Ruddell 2015), and to implement Embedded Resource Accounting in cities (Ruddell *et al.* 2014). New concepts such as urban metabolism studies may help to account for direct water uses in cities. Urban areas include many different types of boundaries, which exert a control on both virtual and physical flows. Understanding the influence of different boundaries on urban flows represents an important area of research.

Physical urban-water systems comprise three main subsystems: water supply, wastewater treatment and stormwater management; the last of which is being studied by the Evolving Urban Water Systems Working Group. Their emphasis is on stormwater management as a coupled natural–human system, extending the traditional narrower focus on impact reduction, and dealing with critical societal issues such as protection against floods and the preservation of water quality and biodiversity. In this context, Woodward *et al.* (2014) examined the concentration of oestrogens in soils affected by treated wastewater irrigation. They found that time of sampling, land cover and irrigation can affect oestrogen concentrations in soils, resulting in levels that exceed natural background and require improvements in management practices.

Urban areas are characterized by complex terrain and interactions of natural and built flow pathways and channels, providing a challenge to many river and floodplain models. Recent advances include work by Kesserwani and Liang (2015), who implemented and examined the required complexity of different state-of-the-art numerical schemes for 2D flood simulation in complex terrain, including urbanized areas. Mejía *et al.* (2014, 2015) implemented a stochastic model of streamflow for urbanized basins to examine changes in flow regime due to conventional stormwater management, as well as urban growth, and Rossel *et al.* (2014) examined the scaling of basin-level dispersion mechanisms in an urban context. These last three studies emphasize emergent urban hydrological features that can be used to analyse and compare the behaviour of urban basins across regions. A key aim driving this research is to better understand and characterize the impact trajectories and impact hotspots associated with the spatio-temporal evolution of urban stormwater systems, both within and between cities. This could serve to provide a scientific basis for advancing engineering design and stormwater management in cities. It entails knowing and characterizing the way cities, their water infrastructure, landscape, soils, population and land use, have evolved in space and time.

5 Water governance, decision-making and uncertainty: global lessons

Achieving sustainability in water consumption and supply, while enabling continued development, is a global challenge. Hydro-meteorological hazards also have far-reaching implications for water security, with political, social, economic and environmental consequences. Both factors emphasize the need to use state-of-the-art knowledge in decision-making processes for water governance.

5.1 Changes in water governance

Assessment of changes in water supply and resources, economy and water policy is necessary for sustainable water management, good living standards and environmental stewardship. The Working Group on Sustainable Water Supply in an Urban Change is comparing changes in the economy and water policy since the 1980s for a number of countries, which differ in size, environmental conditions, population trends and water demands. They found the largest growth in water use in India: along with China it leads global water consumption. In contrast, a decrease caused by the changes after the collapse of the Soviet Union has been observed in Russia (Bibikova 2011). Iran, which has 10 times less territory and half the population of Russia, consumes more water than the latter and has doubled water withdrawal since 1980. However, the renewable water resources of Iran are 34 times smaller (Bibikova *et al.* 2014) and, in spite of the growing population, domestic water supply has decreased by 9%, leading to water stress.

Water is used most effectively (i.e. highest ratio of GDP to consumed water) in developed countries with a limited agricultural water supply. However this indicator has recently increased considerably for China (Koronkevich *et al.* 2013). The quality of water resources and their management is defined by countries' water law and policy. Although Russia, China and Iran have different approaches, water remains the state's property in all these countries (Caponera 1992, Naff 2009). Water policy in the EU is moving towards establishing a comprehensive water law to control creation, allocation and distribution of water rights (Goldfarb 1988). The most complicated situation was found in India, where the existing structure of community access to water was replaced by granting ownership rights to the riparian landowner. There is ambiguity and inconsistency between the rights of the people and the rights of the state to use water resources, which makes governance difficult (Goldfarb 1988).

5.2 Uncertainty in risk and resources

Water governance measures for flood risk reduction are typically designed to ensure both better flood management and an increase in infrastructure resilience. However, the assessment of hydro-meteorological risk must take into account uncertainty (Rodríguez-Rincón *et al.* 2015). Numerical tools and models that represent reality in an incomplete manner incorporate errors that can interact and aggregate to compromise prediction reliability. Moreover, extreme hydro-meteorological events are dynamic over a range of time scales, due to climate variability and socio-economic changes, among others, which further increases the uncertainty in the projections. Therefore, the Working Group on Hydro-meteorological Extremes: Decision-making in an Uncertain Environment is examining how this incomplete science can be used for better decision-making in the face of inevitable uncertainties in both our knowledge and the future climate. They aim to develop new, robust approaches to quantify uncertainty in data and scenarios. The magnitude of registered damages and losses in recent events around the world reveal the urgency of doing so even under a context of limited predictability.

Sensitivity analysis and uncertainty estimation are becoming an increasingly important and expected part of both modelling and management strategies (e.g. Hall 2013, Baroni and Tarantola 2014, Pianosi *et al.* 2015). Panta Rhei has an explicit aim to improve uncertainty estimation, in Science Question 4, *How can we use improved knowledge of coupled hydrological–social systems to improve model predictions, including estimation of predictive uncertainty and assessment of predictability?* In this context, more importance is being placed on recognizing different types of uncertainty (Refsgaard *et al.* 2013). We can distinguish between uncertainties arising from random chance ("aleatory" uncertainty), and those arising from a lack of knowledge about the phenomenon being considered, the epistemic uncertainty. Concepts such as ambiguity, reliability, vagueness, fuzziness, greyness, inconsistency and surprise that are not easily represented as probabilities may be considered aspects of epistemic uncertainty. The Working Group on Epistemic Uncertainties is developing methods to characterize and quantify these uncertainties, with a focus on assessing what we think we know by improved analysis of the observation process (McMillan and Westerberg 2015) and its impacts on hydrological metrics (Westerberg and McMillan 2015), or through more considered methods of comparison between model and data (e.g. Beven and Smith 2015, Nearing and Gupta 2015). Others (e.g. Dottori *et al.* 2013, Serinaldi 2015) have considered the appropriateness of the information that is provided by hydrologists to decision makers. Initial steps have been made to characterize the uncertainty in coupled socio-hydrological systems (Viglione *et al.* 2014). The uncertainty in the anthropogenic forcing of such coupled systems is significant; how significant when compared to the potential for epistemic uncertainty in forecasts of future hydrological boundary conditions (e.g. in precipitation: Chen *et al.* 2013, Ruffault *et al.* 2014) remains an open question.

5.3 Many sources of water knowledge

Most socio-hydrological systems exhibit natural variability or anthropogenically induced changes (Koutsoyiannis 2013, Hirsch and Archfield 2015, Marani and Zanetti 2015). This provides multiple challenges in decision making and has led to the development of alternate decision making processes (Fuller 2011, Korteling *et al.* 2013, Singh *et al.* 2014). For example, the Thirsty Future Working Group is examining the challenge for urban infrastructure management of multiple water system failures during flood events under conditions of climate and environmental change and population growth (Brown 2010, Field 2014). Monitoring and modelling of operational water systems during normal and extreme conditions, their cost, energy and resource use, and long-term sustainability is necessary to prioritize water management issues, and map viable operational and adaptation measures. Rather than relying solely on engineering solutions, a participatory approach to research through collaboration with policy regulators and multiple stakeholders will ensure that the framework focuses on both solutions and impacts. This research addresses the Panta Rhei Science Question 6, *How can we support societies to adapt to changing conditions by considering the uncertainties and feedbacks between natural and human-induced hydrological changes*?

Water knowledge is produced widely within society, across certified disciplinary experts and non-certified expert stakeholders and citizens (Lane *et al.* 2011, Krueger *et al.* 2012). The Transdisciplinarity Working Group aims to scrutinize these knowledge practices and enable them to work together productively for a more complete understanding of human–water relations and the design of appropriate interventions (Krueger *et al.* 2015; Fig. 4). This means going beyond state-of-the-art water research between and across traditional disciplines, which has failed to integrate disciplinary paradigms (Bracken and Oughton 2006), and where understanding has thus remained partial and interventions conflicting. The social sciences in particular should not be seen in a service role

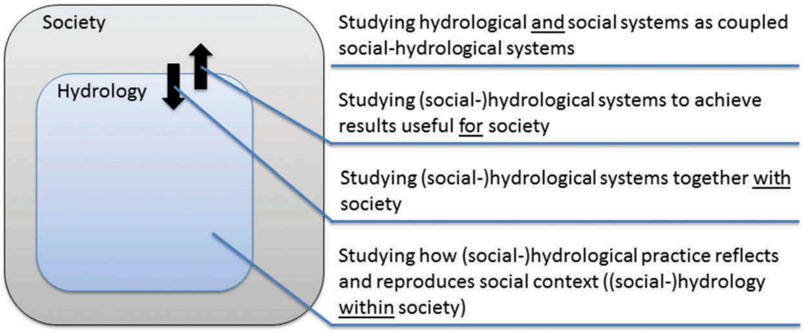

Figure 4. Four different interpretations of the study of hydrology and society.

subordinate to the natural sciences, as is frequently the case (Strang 2009). Research practices embed and are embedded in particular social contexts (Budds 2009, Bouleau 2014, Lane 2014, Linton 2014). We need more empirical evidence to understand how culture, politics and economics shape water research and *vice versa*, and bring alternative knowledge and implications into water politics where they were not previously considered (Cook *et al.* 2013, Fernandez *et al.* 2014). Transdisciplinary research where certified and non-certified experts challenge each other agonistically counters potential lock-in to particular water policies and technologies that may be inequitable, unsustainable or unacceptable (Maynard 2015).

6 Global hydrological challenges in the Anthropocene

6.1 Global water scarcity

6.1.1 Global water crisis

The scientific community is already debating the global water crisis (Sivakumar 2011, Srinivasan *et al.* 2012, IAHS 2015), and uses the term "water emergency" explicitly when referring to food-water security for specific areas of the world. With rapid socio-economic development, water scarcity has become a bottleneck for sustainable development in more countries and regions of the world (Oki and Kanae 2006, Vörösmarty *et al.* 2010). Water scarcity occurs on many different scales ranging from global to river basin and municipality. Its severity is highly dynamic, depending on continuous shifts of consumption patterns, socio-economic development, increasing water pollution and climate change.

There are still many shortcomings of previous water scarcity indicators. First, they are usually limited to water quantity (mainly surface and groundwater, or the "blue" water, but rarely soil water, or "green" water), neglecting the effects of water quality on water scarcity. Second, they are mainly focused on human water use, but ignore the environmental flow requirements. Third, still many studies focus on annual averages and hence hide the very important temporal and spatial variations of water resources and uses (Savenije 2000).

Members of the Working Group on Water Scarcity Assessment: Methodology and Application developed a simple regional approach for assessing water scarcity considering both water quantity and quality, making use of easily obtainable data (Zeng *et al.* 2013). This approach adopted the commonly used criticality ratio method (Vörösmarty *et al.* 2000) to assess quantity-induced water scarcity, and used grey water footprint, an indicator that quantifies the effects of water pollution to water resources in a volumetric way, to assess quality-induced water scarcity. The method assumed that 80% of the blue water resources should be maintained for environmental flows. Such an assumption may not be realistic and may be an overestimation of environmental flow requirements (EFR). Given this, a quantity-quality-EFR (QQE) approach is being developed to explicitly consider environmental flow requirements in the water scarcity assessment (Liu *et al.* 2016). Such an approach, combined with the nutrient flow assessment for pollutants (Liu *et al.* 2010), could effectively assess water scarcity by explicitly considering quantity, quality and environmental flows.

An example of water scarcity caused by water quality is the Mexico-Mezquital coupled hydrological systems being studied by the Working Group on Integrating History, Social Conflicts and Hydrology: From Semi-pristine to Highly Modified Hydrological Systems. Many centuries of human settlements have depleted the Mexico aquifer and industrial activity continues to drive population growth. Untreated drainage from Mexico Valley has been conducted artificially to the Mezquital Valley, changing Mezquital characteristics from a clean-arid to a polluted-productive agricultural valley (Jiménez and Chavez 2004). Mexico City is already in water crisis and Mezquital Valley may soon follow, as growing industry and agriculture deplete clean water from the aquifer, and Mexico City seeks to solve part of its water needs by recycling 10 m^3/s from Mezquital Valley (Conagua 2012).

6.1.2 Climate change impact on water scarcity

A robust assessment of water scarcity considering both climatic and socio-economic changes is vital for policy makers at the river basin level. By understanding how these two sources of change interact, we address Science Question 2, *How do changes in hydrological systems interact with, and feedback to, natural and social systems driven by hydrological processes?* Gain and Wada (2014) analysed future water scarcity of the Brahmaputra basin, comparing water demand and availability on monthly, seasonal and yearly scales. They showed that it is important to estimate water demand in terms of both water withdrawals and consumptive water use, and to assess groundwater recharge affected by climate change together with future demands for groundwater abstraction.

Schewe *et al.* (2014) used a large ensemble of global hydrological models (GHMs) forced by five global climate models and the latest greenhouse-gas concentration scenarios (Representative Concentration Pathways) to synthesize current knowledge about climate change impacts on water resources and water scarcity. The results show that climate change will exacerbate regional and global water scarcity. The ensemble average projects that a global warming of 2°C above present temperatures will confront an additional 15% of the global population with a severe decrease in water resources and will increase the number of people living under absolute water scarcity (<500 m^3 per capita per year) by another 40% compared with the effect of population growth alone.

6.2 Hydrological extremes: a global issue in the Anthropocene

6.2.1 Attribution of droughts and floods

Droughts and floods are caused by interactions between weather anomalies, the terrestrial ecosystem and the human environment. Drought is differentiated from water scarcity: drought is a (temporary) lack of water compared to normal conditions, whereas water scarcity is a (long-term) lack of water compared to desired conditions. Drought and flood risks emerge from the exposure of humans and assets during extreme hydrological events (e.g. Merz *et al.* 2010). Therefore, changes in drought and flood risks or costs can result from multiple factors, including increases in exposed assets, climate change and human interventions in river systems and catchments (Vorogushyn and Merz 2013, Di Baldassare *et al.* 2013a). Thus, detection and attribution of past changes in drought and flood risk is challenging, particularly due to the complex interaction of physical and socio-economic processes and their large spatial and temporal heterogeneity. The question of whether drought and flood risk increase over time, and if so, why, is very relevant for policy response in terms of risk management and adaptation strategies (Bouwer 2011).

Hydrological drought research typically focuses on understanding the natural processes underlying water availability (Van Loon 2015). In recent years progress has been made on the development and testing of drought indices (Bloomfield and Marchant 2013, Stagge *et al.* 2015), the influence of evapotranspiration (Teuling *et al.* 2013), snow (Staudinger *et al.* 2014) and geology (Stoelzle *et al.* 2014) on drought severity, drought modelling and forecasting in Africa (Sheffield *et al.* 2014, Trambauer *et al.* 2015), and effects of climate change on drought (Prudhomme *et al.* 2014, Wanders *et al.* 2015). The Working Group on Drought in the Anthropocene is aiming to broaden that view and start to understand how humans influence drought, and *vice versa* (Van Loon *et al.* 2016.; Fig. 5). Up to now the working group has focused on modelling and quantification of human activities on drought occurrence and severity (e.g. Van Dijk *et al.* 2013, Van Loon and Van Lanen 2013, Wanders and Wada 2015). To fully incorporate human processes, a framework is needed that includes human drivers, modifiers, impacts, feedbacks and the changing baseline of drought in the Anthropocene. Examples of human responses to drought, which induce feedbacks in the system, include reductions in water use, changes in agricultural practices, increases in groundwater extraction, and building storage or water transfer infrastructure. Research done within this framework needs to combine qualitative and quantitative data and methods to answer research questions related to drought in the Anthropocene in a more holistic way by explicitly including interactions between humans and the hydrological cycle. The drought community can learn from flood research, which is much further developed in integrating human and natural processes, in terms of understanding, quantification and prediction.

At the opposite hydrological extreme, flood damage in Europe and worldwide has increased considerably in recent decades, particularly due to an on-going accumulation of people and economic activities in risk-prone areas (Barredo 2009, Merz *et al.* 2012). The Working Group on Changes in Flood Risk aims to understand, quantify and model the links between physical and socio-economic drivers and changes in flood risk, and explore adaptation pathways. Their first activities identified and analysed potential drivers for changes in vulnerability, specifically susceptibility. Significant temporal changes in private precautionary measures, mainly triggered by flood experience, were quantified in German case studies (Kreibich *et al.* 2011, Kienzler *et al.* 2015). Current work aims to identify the main factors determining event-level flood damages, based on a European-wide collection of case studies.

6.2.2 Physical drivers of flood changes

In 2013, severe floods occurred in Mexico when two tropical storms converged, culminating in serious damage and widespread persistent flooding (Pedrozo-Acuña *et al.* 2014). This unprecedented event followed extreme flood events over the last decade caused by record-breaking precipitation across central Europe in 2002 and 2013 (Becker and Grünewald 2003, Merz *et al.* 2014, Schröter *et al.* 2015), the UK (Slingo *et al.* 2014), Pakistan (Webster *et al.* 2011) and Australia (van den Honert and McAneney 2011).

The aim of the Working Group on Understanding Flood Changes is to understand the physical processes relating floods to their drivers to understand how and why floods have changed and may change in the future. A result of this work will be to understand the sensitivity of floods to different changes in their drivers, and the uncertainty in predictions. The group has reviewed the state of the art of understanding flood regime changes in Europe (Hall *et al.* 2014). They identified the need for a synthesis of (1) data-based detection methods, focusing on long duration records and flood-rich and flood-poor periods, and (2) modelling methods for flood change attribution, for future flood change scenarios that cover the full uncertainty range, and low-dimensional models that account for feedbacks between the natural and human systems.

6.2.3 Cultural impacts of floods

Cultural heritage is often at risk in flood events. Cultural heritage includes tangible structures: buildings, monuments, documents and artefacts, but also aspects of environment and landscape that are considered cultural landmarks. Protection of this heritage must consider hazard assessment, vulnerability and exposure estimation, and mitigation actions that can take place before, during or after the event. The Working Group on Floods in Historical Cities is developing an integrated system for the management of flood risk for cultural heritage sites, and is establishing a corresponding information

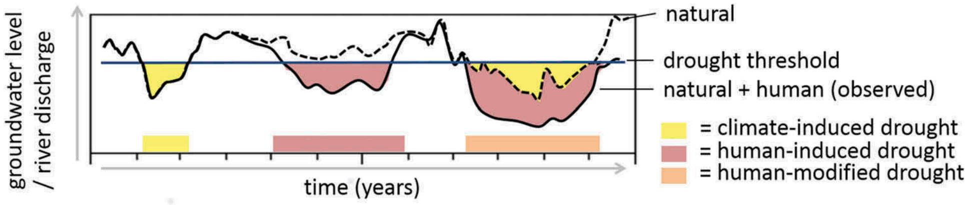

Figure 5. Drought types: climate-induced drought, human-induced drought, modified drought. Reproduced from Van Loon *et al.* (2016) with permission.

platform that helps to identify environmentally friendly solutions. The group aims to support engineering design and to provide tools to decision makers. This necessarily involves a wide range of disciplines from geology, geotechnical engineering, structural engineering, surveying engineering, computer science and hydrology. As with so many of the Panta Rhei initiatives, success will only be achieved through including the expertise and opinions of a wide range of scientists and stakeholders.

7 Discussion and conclusion

As the science community contributes to water governance decisions, we must recognize that water knowledge is inherently uncertain, and comes in many forms and from many people. This paper itself contains multiple viewpoints on how to study the changing socio-hydrological system, and there is potential for conflict as different working groups approach common aims. For example, the theme of water and energy is approached in terms of drivers of the physical system, and also in terms of common footprints of water and energy. The theme of people as decision makers is approached in terms of socio-hydrology, as a poorly understood dynamic system; in terms of water governance, as an outcome of political and economic climates; and in terms of transdisciplinarity, as a sphere of understanding created by multiple stakeholders. We hope that this paper specifically, and Panta Rhei as a whole, will lead to new and productive dialogues on these questions.

Concern about a global water crisis has focused attention on many developing and emerging countries, which are suffering scarcity in water quantity and quality. These challenges reinforce the need to escape from a traditional bias in science funding towards studying water resources in developed countries. A future challenge for the hydrological community is to bring together knowledge from scientists around the globe, such as in the recent advances in hydrological research in Africa (Hughes *et al.* 2015), and to understand if and how water knowledge can be exchanged between countries. In this light, during the 26th IUGG (International Union of Geodesy and Geophysics) General Assembly in Prague, a new Task Force for Representing Developing Countries was created within IAHS, which will collaborate closely with Panta Rhei.

Panta Rhei will work with the IAHS Education Working Group to design a mentoring network for young scientists, particularly in developing countries, to maintain and strengthen links with established hydrologists. Given the risks posed by environmental change to all sectors of water use and management (Döll 2015), the future demand for skilled hydrological professionals can only increase. These professionals will need new and evolving skill sets to match the unknown hydrological issues of the future. Some aspects of hydrological research, such as transboundary issues, are likely to gain much greater importance in the future (Douven *et al.* 2012). The breadth of potential subject areas means that educators must reach beyond their personal experience and knowledge of hydrology, and place more reliance on the wider hydrological community to educate hydrology students (Wagener *et al.* 2012). Alongside traditional transfer of subject-based expertise, students must learn interdisciplinary skills, such as problem-solving techniques and methods for stakeholder engagement. Thus, the lecturer moves from an “expert” to a “facilitator” role (Pathirana *et al.* 2012), and student-centred, active learning becomes more prominent (Thompson *et al.* 2012, Lyon *et al.* 2013). As part of this, new technologies and tools, such as film (Let’s Talk About Water 2015) and access to real-time data (McDonald *et al.* 2015), will enable hydrology educators to enrich the learning experience.

In conclusion, there are many challenges associated with understanding and predicting change in hydrology and society, and empowering communities to mitigate and adapt to those changes. Such challenges can only be met by the concerted and joint efforts of hydrologists and affected societies around the world.

Acknowledgements

We thank IAHS for their vision and support for the Panta Rhei hydrological decade. We also thank all scientists who participate in a Panta Rhei working group, and therefore contribute to the success of the initiative. We are grateful to Demetris Koutsoyiannis, Thorsten Wagener and an anonymous reviewer for their constructive and thorough comments that helped us to improve this paper.

Disclosure statement

No potential conflict of interest was reported by the authors.

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