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Hydrological Sciences Journal

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

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HYDROLOGICAL SCIENCES JOURNAL – JOURNAL DES SCIENCES HYDROLOGIQUES, 2016
http://dx.doi.org/10.1080/02626667.2016.1230674

OPINION PAPER

Adaptation of water resources systems to changing society and environment: a statement by the International Association of Hydrological Sciences

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ABSTRACT

We explore how to address the challenges of adaptation of water resources systems under changing conditions by supporting flexible, resilient and low-regret solutions, coupled with on-going monitoring and evaluation. This will require improved understanding of the linkages between biophysical and social aspects in order to better anticipate the possible future co-evolution of water systems and society. We also present a call to enhance the dialogue and foster the actions of governments, the international scientific community, research funding agencies and additional stakeholders in order to develop effective solutions to support water resources systems adaptation. Finally, we call the scientific community to a renewed and unified effort to deliver an innovative message to stakeholders. Water science is essential to resolve the water crisis, but the effectiveness of solutions depends, inter alia, on the capability of scientists to deliver a new, coherent and technical vision for the future development of water systems.

ARTICLE HISTORY
Received 6 November 2015
Accepted 9 August 2016

EDITOR
D. Koutsoyiannis

ASSOCIATE EDITOR
not assigned

KEYWORDS
water resources systems; socio-hydrology; bottom-up approach; resilient design; catchment

1 Introduction

Environmental change is increasingly exerting pressures on hydrological processes and thus on water resources, attracting the growing attention of hydrologists and water resources scientists (Macleod *et al.* 2007, Wagener *et al.* 2010, Koutsoyiannis 2013, 2014, Montanari *et al.* 2013, Ben-Zvi 2014). Change is the result of several driving forces, including the physical and ecological evolution of the hydrosphere as well as explicit human efforts to harness the water cycle. It can also result from implicit anthropogenically-induced impacts on hydrological processes due to, for example, increased standards of living and demographic expansion.

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In fact, the world population increased from about 1.6 billion in 1900 to the current value of more than 7 billion and is projected to grow up to 9 billion by 2050 (see Koutsoyiannis 2011; see also http://www.census.gov/population/international/data/idb/worldpopgraph.php). The exploitation of Earth's resources has enabled the establishment of modern societies, although environmental sustainability issues have arisen (Meadows *et al.* 1972, Loucks and Gladwell 1999, Scheffer *et al.* 2001, Pauly *et al.* 2002, Diamond 2005, Rockström *et al.* 2009, Rodell *et al.* 2009, Godfray *et al.* 2010).

Indeed, a large proportion of the world's population is now experiencing water stress (Vörösmarty *et al.* 2000, 2010, WWAP 2015; see also Figures 5–7 in Koutsoyiannis 2011). Recent years have seen severe water shortages in Australia (i.e. the Millennium Drought, see Van Dijk *et al.* 2013), and California is currently experiencing the worst drought on record (http://ca.gov/drought/). Furthermore, several countries suffer from water problems caused by inadequate water supply infrastructure (Cairncross *et al.* 1990, Hall *et al.* 2014). The search for alternative energy supplies to support growing populations and more resource-intensive lifestyles also affects water resources systems (WRS). For instance, in the Netherlands, during the hot summer of 2003, thermal power plants had to be switched off because the river water could no longer receive hot cooling water (McDermott and Nielsen 2012). While hydropower and thermal power infrastructure have obvious impacts (as acknowledged by the many studies on the water–energy nexus, Glassman *et al.* 2011, Hussey and Pittock 2012, François *et al.* 2014, Conway *et al.* 2015), the unintended consequences for aquifers arising from the exploitation of shale gas reserves are beginning to be recognized (Barnett *et al.* 2012). In Australia, for example, one of the main issues impacting water resources management at present is the rapid development of coal seam gas (CGS) extraction plants. Such CGS development impacts both water quantity and quality in aquifers, and potentially water quality in streams as well if the extracted water is not adequately treated before being released into the river network (Hamawand *et al.* 2013).

The additional demands placed on water resources throughout the 20th century were met through the expansion of water supply infrastructure with concomitant impacts on water quality and freshwater ecosystems (Gleick 1998). Such infrastructures are now affected by degradation and ageing effects, which need to be assessed for their hydrological, ecological, social and economic consequences, requiring an integrated approach (Croke *et al.* 2014). Indeed, as human societies, we face difficult choices about our future infrastructure recognising the need to prevent continued impairment of the ecological goods and services that are essential to economic viability and human wellbeing (Castelletti *et al.* 2012). Furthermore, the effects of feedback mechanisms (which can either dampen or enhance impacts) need to be considered.

The history of WRS is part of the history of humanity (Wittfogel 1957, Biswas 1970, Schama 1995, Hassan 2011, Costanza *et al.* 2012). Since ancient times humans have built WRS, such as reservoirs, embankments, canals and water treatment plants, to efficiently use water, buffer variability and minimize the impact of water-related natural hazards, such as floods, droughts and diseases. Water resources systems were conceived to provide societies with water for a range of purposes, including irrigation, industry, drinking and sanitation. The improvement and efficiency of WRS have been a matter of research for centuries, through which we have developed an understanding of the evolution of WRS and how such systems should be managed. However, human beings have not always been able to identify the long-term impacts of changing environmental dynamics on WRS. The design of WRS has always required a careful analysis of water demands and environmental impacts to produce innovative and durable solutions (Rogers 2007). While many of the current challenges in WRS are not entirely new, environmental change is now progressing at an unprecedented pace, and the research community is therefore called to make new efforts to devise innovative interventions.

Water resources are closely related to factors that may change through space and time. These factors include demographics, lifestyle, water demand, climate, technological, societal and economic development, as well as the political economy. In the last 50 years there have been massive improvements in life expectancy, declines in mortality from disease and malnutrition, and economic advances across large parts of the world. These have caused measurable improvements in the lifestyles of millions of people and resulted in a marked increase of the gross domestic product in the developed world. The ongoing growth of the world's population places increased demands on water of sufficient quantity and quality for domestic, agricultural and industrial uses. Furthermore, developed and developing regions are increasingly linked through the virtual water trade associated with food and other commodities (Dalin *et al.* 2012, Carr *et al.* 2012a). Virtual water trade can mitigate the effect of temporary and chronic local water scarcity when water-scarce countries import water-intensive products (Konar and Caylor 2013), whilst it can also undermine the sustainable use of local freshwater resources and societal resilience to drought when water-scarce countries choose to export water-intensive products in response to global markets (Hepworth *et al.* 2010).

Although the literature is replete with predictions of fundamental shifts in the water cycle as a result of climate change (Bruins 2000, Vörösmarty *et al.* 2010, Van Dijk 2013, Field *et al.* 2014, Döll *et al.* 2015), for many WRS the human impacts on the water cycle in terms of societal change and land-use change may be of the same order of magnitude, if not greater, than those predicted as stemming directly from climate change (Grafton *et al.* 2012, Dyer *et al.* 2014, Haddeland *et al.* 2014). For instance, both deforestation and afforestation, which exhibit variable patterns at the global scale (FAO 2011) and mainly result from human-induced land-use changes, are known to control changes in runoff, flood regimes (Ranzi *et al.* 2002, Hall *et al.* 2014) and sediment loads. Therefore, robust attribution to climatic, socio-economic, land use and water demand changes needs to be carried out, and confidence levels should be assigned to each contribution (Jiménez Cisneros *et al.* 2014), although it is likely that human pressure on WRS will be the main threat for WRS in the future.

The above challenges for WRS dictate that adaptation to the current changing world is an essential research and technological priority. Adaptation to change is a key focus of the Panta Rhei Scientific Decade 2013–2022 of the International Association of Hydrological Sciences (IAHS) (Montanari *et al.* 2013, McMillan *et al.* 2016). Efficient adaptation strategies require a forward-looking vision on future water demands and water availability, as well as building technologies and institutions that can adapt to unforeseen circumstances. A deeper understanding of the two-way interactions between water and humans, as envisaged by the new research agenda under the umbrella of socio-hydrology (Sivapalan *et al.* 2012, 2014, Sivapalan and Blöschl 2015), holds key insights into these possible futures. To this end, the International Commission on Water Resources Systems (ICWRS) of IAHS convened a topical conference entitled "Evolving Water Resources Systems—Understanding, Predicting and Managing Water–Society Interactions". The conference was held in Bologna, Italy, 4–6 June 2014 under the organization of the University of Bologna, Italy, and resulted in the publication of a book of proceedings (Castellarin *et al.* 2014). The conference was characterized by vibrant discussions of ways to better understand and represent the co-evolution and mutual interactions of water and society. A round table was organized during the conference to summarize the main issues raised during this discussion, and the outcomes were subsequently refined through a web-based consultation and eventually led to the formulation of the IAHS statement aimed at identifying research and operational priorities for adapting WRS to a changing world. In this respect, the Bologna IAHS 2014 conference represents a rare experience of wide-ranging community discussion and synthesis of a topical research-technical question.

The purpose of this paper is to summarize the rationale and the scientific motivations that led to the preparation of the statement and to present the statement itself, therefore providing a forward looking perspective for the adaptation of WRS to the changing world. In Section 2 we explore the challenges for the adaptation and design of WRS under changing conditions. We then proceed to outline the relevant characteristics of a resilient and flexible WRS design (Section 3), the main drivers in coupled human–water systems (Section 4) and the key role of the water resources scientific community towards these objectives (Section 5). A set of conclusions is finally drawn.

2 Challenges for the adaptation and design of water resources systems under change

Historically, WRS have been continuously adapted to meet increasing water demands and to solve problems related to insufficient water availability, water pollution and natural hazards. For example, the industrial revolution that produced an unprecedented concentration of people in cities resulted in frequent cholera epidemics in the 19th century, and new strategies for WRS were developed, such as fast conveyance of wastewater and rainwater to the outside of the city through the sewer network (Barles 1999, Johnson 2007). Nowadays, adaptation of WRS is still a very relevant problem, as societies continue to develop and face threats of environmental change. Adaptation today, however, is more challenging than in the past as water problems are increasingly complex because of increasing demands and pressures, and more rapid changes in society, climate and hydrological systems (Vörösmarty *et al.* 2000, 2010, Jin *et al.* 2009, Van Der Zaag *et al.* 2009, Grafton *et al.* 2012, Polo *et al.* 2014, Bai *et al.* 2016). The main response to water shortages in the past, namely, increasing the water storage in lakes and artificial reservoirs or aquifers, is of concern today for its limited durability, its social and environmental impacts and the lack of additional opportunities for storage in many countries (McCully 1996).

When planning adaptation strategies, the awareness of unpredictable future challenges often leads to excessively precautionary design, which can make the proposed solutions economically infeasible or environmentally unsustainable. Indeed, the classical top-down approach, based on using large-scale prediction of future scenarios for the environment and society to estimate design variables for WRS adaptation, usually provides solutions that cannot be employed for specific case studies (Blöschl *et al.* 2013b). Being precautionary in this sense has meant producing designs that tend to be more rigid, less flexible and thus less adaptive, which may lead to path dependency and lock-in, i.e. precisely the opposite of resilience. The quest for a durable, but ultimately insufficient, solution may prevent the identification of feasible or innovative ways forward (see Fig. 1, inner loop). This situation is exacerbated by the global economic crisis, which has produced a lack of resources for the public sector. Clearly, there is an urgent need for researchers to suggest flexible and resilient design options (see Fig. 1, outer loop), where the goal is to identify a suitable adaptation in view of economic constraints and environmental sustainability. A resilient design should start at the local scale of each WRS and should

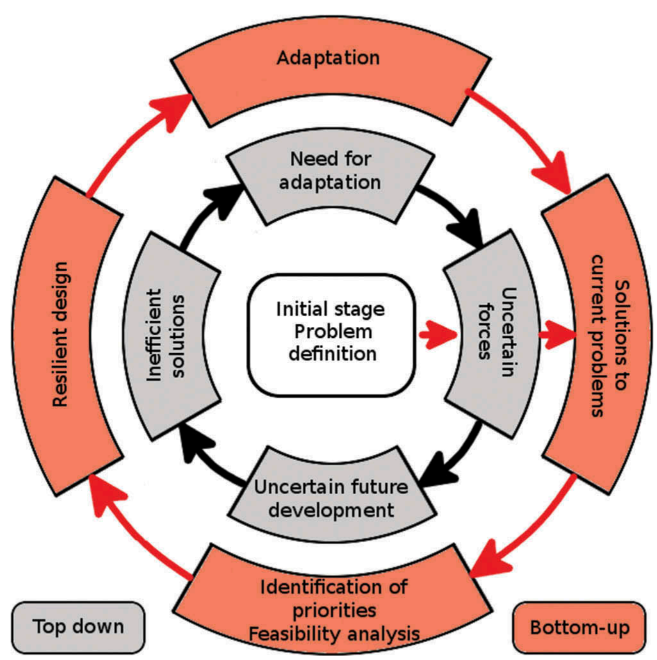

Figure 1. Water resources systems adaptation: a comparison between the classical top-down approach (inner loop) and a more flexible and resilient bottom-up approach (outer loop). Both (black and red) arrows represent causal influence and temporal sequence.

explore the factors and conditions that will ensure resilience against plausible future challenges, therefore adopting the so-called bottom-up approach (Wilby and Dessai 2010).

3 Premises and concepts for a resilient design

Resilient WRS have the capacity to adapt to changing conditions and to maintain or regain their functionality after a stress or disturbance. Water resources availability and water demands are indeed affected by a multitude of uncertainties interacting with each other, and reflecting the limited predictability of future environmental and social configurations (Polo *et al.* 2014). Flexibility is a fundamental requirement to ensure resilience (De Neufville and Scholtes 2011): a flexible design creates systems easily adapted to different "futures". Saito *et al.* (2012) claim that the implementation of flexible or adaptive development and management strategies and the delineation of incremental decisions are essential for dealing with the substantial uncertainties associated with the future (e.g. climate change, population dynamics, economic costs). A resilient design would allow us to adapt WRS, based on incremental learning during their management, through an improved understanding of the underlying processes, as already demonstrated by Steinschneider and Brown (2012) and Zhang and Babovic (2012).

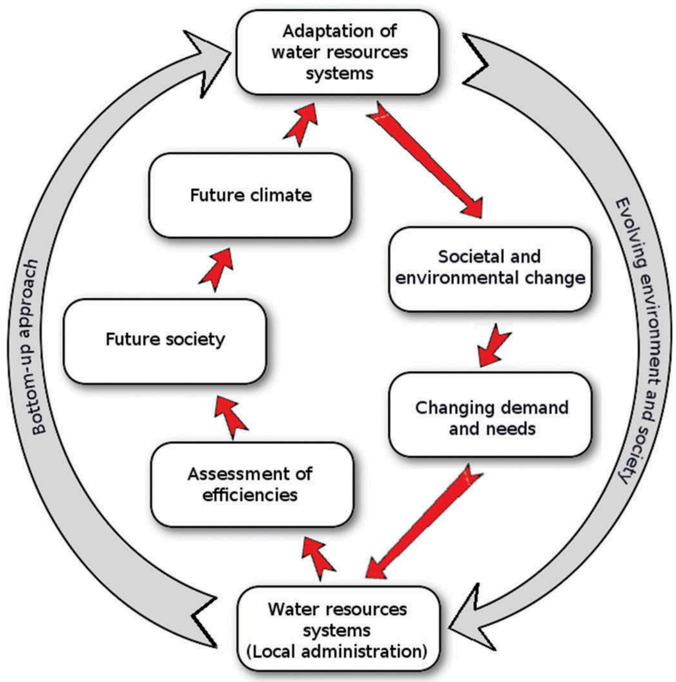

Figure 2. Workflow of the bottom-up approach for water resources systems (WRS) adaptation. This continuous workflow is based on (1) assessment of WRS status, (2) prioritization of WRS targets and (3) the decision-making process.

3.1 The bottom-up approach for water resources systems adaptation

The bottom-up approach, also known as the "assess-risk-of-policy" approach, as it explores alternative solutions to adapting the WRS first, takes as a starting point the vulnerability (i.e. the inability to withstand the effects of a hostile environment) and resilience of an existing WRS in the present situation (Brown and Wilby 2012, see Fig. 1 outer loop). The projected future conditions are then considered in a subsequent stage, when the resilience of alternative solutions to cope with future driving forces is evaluated. It is important to note that the bottom-up approach does not imply that predictions of the effects of future scenarios are unnecessary or uninformative. Predictions of the future status of WRS are still essential to support the design process (Brown *et al.* 2012, Li *et al.* 2014), although they are given a very different role than in the scenario-based (or top-down) approach. While in the scenario-based approach predictions set the basis for the identification of solutions, in the bottom-up approach predictions are used to evaluate the alternative solutions that were identified at the beginning of the process, based on the pragmatic analysis of the status of the WRS and the associated hydrological context (Van Pelt and Swart 2011). The effectiveness of the bottom-up approach is frequently questioned by stakeholders because it may accept the chance of failures against future projections. This is because adaptation strategies are often falsely perceived as free of residual risk when they are so-called "efficient solutions" resulting from a top-down approach. Such an interpretation is clearly misleading, as any adaptation process is prone to failures. The critical analysis of future hydrological projections is an added value of the bottom-up strategy. Adaptation strategies enable learning in a transparent and participatory way that is essential for management in the face of uncertainty.

The workflow of the bottom-up approach is presented in Fig. 2. The first step is a comprehensive assessment of the status of the considered WRS and the identification of the adaptation actions, which include addressing current inefficiencies, the resilience to environmental changes, the economic effectiveness and the need to limit the environmental impact of the adaptation process (see e.g. Klijn *et al.* 2015). Consequently, WRS targets need to be prioritized. This step is particularly challenging in view of the complexity of the adaptation process and its uncertainties. While current inefficiencies may be evaluated with limited uncertainty, future environmental and societal changes may be difficult to predict. Environmental impact assessment is equally difficult to deal with, mainly because of (a) the uncertainty in the physical processes governing the hydrological cycle and thus water resources availability, and (b) our lack of understanding of water requirements of key ecological processes or environmental assets (Poff and Zimmerman 2010). Besides this, open research questions remain, such as how to quantitatively describe the reactions of society to environmental changes and which indicators we should use to build dynamic models.

Decision making is the next step in the bottom-up approach. It is a continuous process (Fig. 2), where the efficiency of management strategies is evaluated on a regular basis to adapt and improve the strategies in the light of new knowledge or as systems change (Smith and Porter 2010, Kreibich *et al.* 2014). We also need to identify possible and potential risks, and increase the awareness and understanding of the benefits of accepting certain levels of risk when striving for minimal hydrological (engineered) solutions.

Finally, solutions for adaptation should be developed in collaboration with stakeholders. Strategies developed within a broad group of stakeholders capturing a range of interests are expected to be more ethically sound and equitable than those developed by a small group of elite professionals (Gleick 1998). The inclusion of a wide variety of interests and opinions not only ensures that the strategies address stakeholder needs and priorities, but the integration of local knowledge with that of technical experts can help derive strategies that are feasible in practice (Carr *et al.* 2012b, Carr 2015). The whole process of the bottom-up approach requires a continuous awareness of different perspectives from the local to the global scale and back. While the driving concepts for adaptation need to be conceived at the global scale, the assessment of the societal needs and the local inefficiencies must be carried out at the local scale, and this is the responsibility of local institutions and administrators. Incremental decisions that are considered today as no-regret (or rather low-regret) require continuous control by stakeholders and researchers, as new knowledge can improve these solutions and lead, in the long run, to increased benefits (Petrucci *et al.* 2014). In the planning of interventions, this focus on further understanding of cause–effect relationships combines well with an acceptance of uncertainty and knowledge limitations in approaches for assumption-based planning (Dewar *et al.* 1993, Efstratiadis *et al.* 2015, Koutsoyiannis and Montanari 2015, Thirel *et al.* 2015, Di Baldassarre *et al.* 2015b) and adaptive policy making (Walker *et al.* 2001). In effect, it helps to combine planning, monitoring of plan implementation, and a continuous interaction between planning and research agendas (Hermans *et al.* 2013).

3.2 The importance of data

In order to detect, understand, and better predict the impact of change on co-evolving coupled human–water systems, and monitor WRS adaptation, it is necessary to have access to relevant and reliable monitoring data (Wilby and Dessai 2010, Zander *et al.* 2013, Hutton *et al.* 2014, Sarr *et al.* 2015). An enhanced hydrological monitoring activity should be promoted, which may also take into account new types of data offering novel opportunities to detect changes (e.g. Voss *et al.* 2013, Ceola *et al.* 2014a, 2015a, Richey *et al.* 2015). We should also promote the continuous and integrated acquisition of related socio-economic data for improved risk management under conditions of change (Kreibich *et al.* 2014).

Furthermore, we need systems and practices to enable the sharing of data, information and knowledge (Zander *et al.* 2013). This includes explicit consideration and communication of uncertainties in these data, so that robust conclusions about actual change can be drawn (Brown 2010, McMillan *et al.* 2012, Juston *et al.* 2014, Westerberg *et al.* 2014). Horsburgh *et al.* (2011), for example, set out the architecture and functional requirements for an environmental observatory information system that supports collection, organization, storage, analysis and publication of hydrologic observations. Similar technologies integrating a wide range of environmental data (including observational time series, simulations, geo-referenced data and projections) for water resources management efforts have been successfully implemented for transboundary river systems, such as for example the Okavango River (Kralisch *et al.* 2013, Helmschrot *et al.* 2014), and the Kara River (Badjana *et al.* 2015). These information systems are used by various user groups and have proved to be a useful tool for the assessment of changes. In addition, the rescue and recycling of usually analogue historical data, in particular in data-scarce regions, becomes an inevitable source for change assessments (Kaspar *et al.* 2015).

Sharing information on the governance aspects of water resources is another fundamental requirement in understanding how institutions react to water problems and the adaptation of WRS. Experience shows that governance processes and institutions are important in explaining the success and failure of implementing water plans and policies, such as the EU Water Framework Directive, the China 2011 No. 1 Central Policy Document, and the South African Water Law (Kemerink *et al.* 2013, Moreira *et al.* 2014).

3.3 The role of predictability for the identification of future scenarios and the evaluation of alternative solutions

Whether upfront in the traditional scenario-based approach, or in a secondary step of the bottom-up approach to WRS adaptation advocated above, predictions play a key role in evaluating alternative solutions for WRS adaptation under future hydro-climatic and socio-economic conditions (Bai *et al.* 2016, Verburg *et al.* 2016). However, predictions are inherently uncertain. In order to increase predictability, and thus reduce uncertainty (Pielke *et al.* 2004), reliable deterministic representations of the systems involved should be introduced, along with stochastic representations of inherent randomness. Nevertheless, one should always be aware of residual uncertainty, which is still very relevant in hydrological predictions and may lead to generating unrealistic scenarios. For instance, let us focus on hydrological models at the catchment scale. When these are calibrated against observations, under ideal conditions and the steady-state assumption for their control volume and variables, the hydrological models are usually characterized by average efficiencies around 0.6–0.8 (Hrachowitz *et al.* 2013, Blöschl *et al.* 2013a). Conversely, the efficiency that one may expect when these models are applied to predict future variables is certainly lower, because of unsteady conditions, resulting in inefficient calibration, for out-of-sample applications (Barnett *et al.* 1998, 2006, Feddema *et al.* 2005). Therefore, one should not assume that deterministic solutions in hydrology are always efficient. Determinism should be supported by a solid basis, while a probabilistic approach should be applied to model uncertainty (Montanari and Koutsoyiannis 2012, Ceola *et al.* 2014b).

When dealing with WRS, introducing reliable model representations means one has to suitably decipher the dynamics of the systems themselves, which implies the understanding of the processes governing water availability and water demands in coupled human–water systems. Most of the WRS-related modelling efforts to date, however, have neglected relevant feedbacks that the dynamics of society may introduce to hydrological systems. Therefore, the predictions that can be obtained with this approach could not account for incremental changes that over the long term have led to spectacular failures (e.g. the Aral Sea between Kazakhstan and Uzbekistan, the Murray-Darling River Basin in Australia (Ison and Wallis 2013, Kandasamy *et al.* 2014), and the Republican River Basin in the USA). In order to underpin investment decisions or large-scale policy changes, there is thus a need to (a) predict (or project) changes to the water systems over longer time scales and larger spatial scales (whole countries, states or regions), and (b) to account for the dynamic co-evolution of the systems of interest as a result of internal (or endogenous) feedbacks between coupled human and natural systems in response to external (or exogenous) drivers such as climate and socio-economic factors, as recently outlined by Sivapalan *et al.* (2012, 2014) and reviewed by Troy *et al.* (2015a, 2015b).

3.4 The dialogue with stakeholders and policy makers

When moving to the practical implementation of solutions for the adaptation of WRS, the dialogue with administrators and policy makers represents a key challenge, because of gaps in knowledge, communication and administrative responsibilities. Through establishing an understanding of the functioning of coupled hydrological and social systems at higher administrative levels, we may profit from the collective intellect, knowledge and information, and trigger creativity and innovation in policy making.

One way to attract the attention of administrators and policy makers is to bring together scholars from several sister disciplines. Scientists interested in water systems, including hydrologists, ecologists and biogeochemists, in close cooperation with scientists from social and economic science disciplines, should aim towards revolutionary efforts in this regard. Moreover, there is growing recognition that research and management need to make better use of, and integrate, non-scientific, managerial and societal local knowledge with scientific knowledge (Fazey *et al.* 2006, Raymond *et al.* 2010, Thompson *et al.* 2013, Krueger *et al.* 2016). In fact, it is well recognized that environmental modelling requires the involvement of stakeholders (Voinov and Bousquet 2010) to make sure the models meet the informational needs of decision makers, incorporate vital stakeholder values and data, and are subsequently trusted by all stakeholders. These models should thereby include the expertise from researchers and non-researchers transparently and adhere to democratic ideals (Van Delden *et al.* 2011, Krueger *et al.* 2012, Voinov *et al.* 2014). Multi-disciplinary projects such as Water Infrastructure Solutions from Ecosystem Services Underpinning Climate Resilient Policies and Programmes ("WISE-UP to Climate", IUCN 2015) are building on these principles to try and affect real change in WRS in the developing world, with demonstration projects in Ghana and Kenya.

4 Drivers and trade-offs in socio-hydrology

4.1 Changes in socio-hydrological systems

Coupled human–water systems operate at all temporal and spatial scales, extending from catchments and river basins to global systems, and from individual human actions to community and national decisions, through to their manifestation in terms of trade on a global scale (Sivapalan and Blöschl 2015). The systems are interconnected across these scales, in a space–time scale hierarchy, requiring attention to scale transformations and abstractions during up-scaling and down-scaling when modelling these coupled systems.

Future changes include climate, land-use and societal change, with societal changes possibly dominating in terms of pressure on WRS (Grafton *et al.* 2012, Dyer *et al.* 2014, Haddeland *et al.* 2014, Bai *et al.* 2016, Brondizio *et al.* 2016). In fact, human impacted areas are widespread all over the world (Fig. 3), and may be further transformed by societal changes. An interesting example is human migration, a phenomenon that has been widely studied and debated in the last decade (Black 2001, Castles 2002, Renaud *et al.* 2007, Jäger *et al.* 2009). As shown by Selby and Hoffmann (2014), for example, human migration is closely related to physical water scarcity: droughts, water shortages and desertification (that

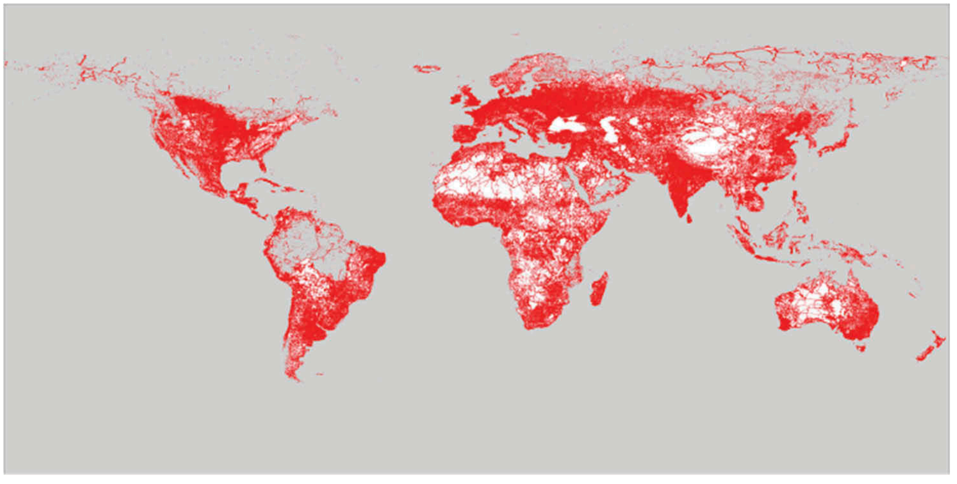

Figure 3. Human impacted areas on the biosphere, identified through mapping of roads, railways and settlement density (by T. Hengl (http://globio.info) [CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons).

is, human-induced, temporary or permanent imbalances in water availability) are among the chief drivers of migration, along with societal crises, floods or other natural hazards. Conversely, these migration patterns have a huge impact on water demands and land-use changes, which cannot be easily anticipated given the often rapid and unpredictable nature of such societal crises. Indeed, who would have predicted the massive displacement of people due to conflicts such as the present one in Syria, and the subsequent stresses these migrations put on water resources?

Whereas the impacts of society on water are well documented by hydrological studies focusing on e.g. the impacts of dams and water quality decline associated with human activities, urbanization, climate change and pollution (Poff and Zimmerman 2010, Beck *et al.* 2012), the impacts of water on society (i.e. in terms of human practices, politics, economics, migration and human geographies, among others) have historically been the subject of disciplines other than hydrology (see e.g. Barnes and Alatout 2012, Winiwarter *et al.* 2013, Linton and Budds 2014).

For instance, political and societal change triggered by a focusing event, such as significantly improved preparedness and adaptation following an extreme flood, has been explained by focusing event theory (Kreibich *et al.* 2011). Changes of values assigned to specific environmental needs, are expected to be particularly difficult to foresee (Elshafei *et al.* 2014). For instance, much higher value is now given to river water quality compared to the past (Van Emmerik *et al.* 2014, Sivapalan and Blöschl 2015). Therefore, if we want to predict human practices and societal development, e.g. in terms of population size, economic development, consumption patterns and values, and their impact on the evolution of WRS (Domeneghetti *et al.* 2015), we should look at the aforementioned disciplines for interdisciplinary collaborations.

For water resources planning it is critical to understand the role of spontaneous, and sometimes counter-intuitive, societal developments. Urban planners have rarely been able to anticipate spontaneous urbanization (often in marginal areas), leading to impacts such as the rapid depletion of groundwater through extensive use of local groundwater abstractions and often dramatic land subsidence in megacities, with steeply increasing risks of flooding and economic damage (Kreibich and Thieken 2008). The co-evolution of society with the water system has often been overlooked or dealt with in a too simplistic or optimistic manner. Trying to understand these spontaneous processes is crucial for better management of land and water resources in the future and development of more robust methods for intervention planning.

The focus therefore needs to be on connections and feedbacks by identifying the most important components of the system, and how they are related to other components of that system (Fig. 4). Is it possible that an adaptation action can lead to negative side effects, especially on the long time horizon? A better understanding of cause–effect relationships (i.e. human–water feedbacks) can be tremendously useful for more prudent water management in the long term, even if we cannot anticipate the actual trajectory of the system evolution with confidence.

4.2 Socio-hydrological modelling approach

Socio-hydrology aims to build on the past through cause–effect reconstructions of coupled changes in hydrology and society, thereby documenting multiple feedback loops throughout

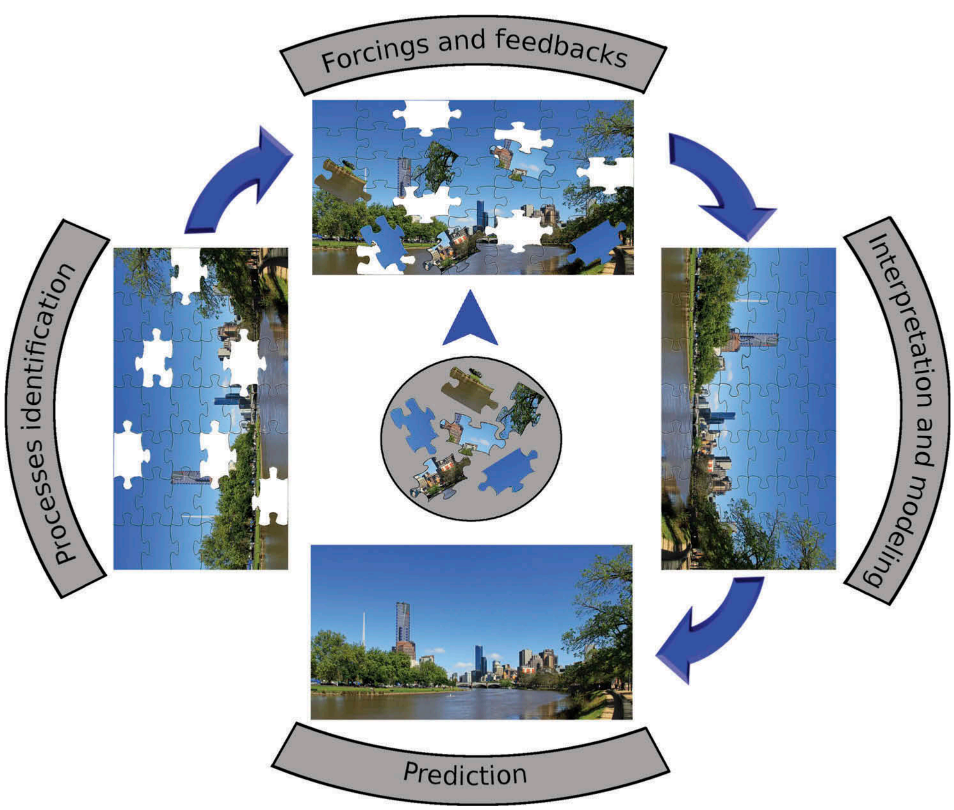

Figure 4. Identification and interpretation of processes, prediction and modelling in socio-hydrology.

history in multiple geographical domains (see Fig. 4). In particular, while the classic Integrated Water Resource Management (IWRM) approach mainly focused on the one-way relationship between hydrology and social systems, the field of socio-hydrology aims to focus on their co-evolution, that is, the two-way dynamic relationship between humans and hydrology. Within the context of WRS, the challenge is to decipher how the future society will affect water availability, water quality and water distribution. How to choose effective indicators to the process interactions between humans and hydrology and how to reliably detect and model such feedbacks are still open research questions. Refining reliable model representations of the above co-evolution would provide insights and reduce uncertainty associated with future scenarios, and in this way support improved operational designs (Gómez-Beas *et al.* 2012). Understanding and modelling the two-way coupling and the co-evolution of human–water systems requires an interdisciplinary approach (Macleod *et al.* 2007, Braden *et al.* 2009, Hamilton *et al.* 2015), which is also the key motivation of socio-hydrology. Perhaps the greatest challenge in this endeavour is reconciling the different research philosophies, methods and data used by different disciplines (Krueger *et al.* 2016).

In socio-hydrological studies there are few sources of hard observational data and the associated uncertainties are therefore expected to be large, hence models tend to be conceptual. The time period covered by socio-hydrological studies is very long, and can potentially be the entire recorded history of humanity. Socio-hydrological models are not, therefore, expected to deliver predictions in the deterministic sense. Rather, they are expected to deliver indications on the possible joint evolution of society and water, namely, insights on how society might react to increasing threats on water resources and, in turn, how water resources will react to increasing societal pressures.

The socio-hydrological approach, to be realistic, should take rapid societal developments into account. Little attention has previously been given to dynamic, sometimes dramatic developments (i.e. black swans; see Blöschl *et al.* 2013b), although scientific interest in the role of surprises in complex human–water systems is emerging (Merz *et al.* 2015, Di Baldassarre *et al.* 2015b). Immediate adaptation of water resources management plans is sometimes necessary in responding to conflict-associated developments. For example, the need for disaster relief in conflict-affected areas is important, since people, particularly in water-scarce areas, often face dramatic deterioration of established water supply and water treatment, or even lack of access to potable water or water for food production. Establishing adaptive and resilient water management systems that address such developments must therefore be among the highest priorities for communities, governments and donors in a post-conflict or post-disaster situation in the short term, and thus for science as well.

One way to learn about such water–society interactions is to bring together the knowledge from the vast amount of case studies that exist in this field that have analysed past situations to identify which decisions were taken to address a certain water management issue and why (e.g. Zeitoun *et al.* 2014). Of course, each case study is set in a certain cultural and political environment that shapes the decisions taken to intervene in the situation. The main research challenge here is to generalize societal practices from an individual case study so as to be able to contribute to a more universal understanding of socio-hydrological issues. There is, therefore, a need for international projects that bring together place-based studies, and synthesize findings and commonalities.

A systems approach is needed at the heart of this new paradigm (Macleod 2010). The systems approach emphasizes the dynamic coupling of the system components as opposed to the static coupling of pre-arranged scenarios. Indeed, integrating water and land management in catchments under environmental change requires systems-based approaches that: can be predicted, monitored and evaluated; are based on common flexible frameworks, such as ecosystem services; enable scientific credibility to be combined with practical usefulness; and improve the linkages between data–models–evidence–policy through place-based studies (Macleod and Haygarth 2010).

Several studies have already proposed models to describe human–water systems interactions (Di Baldassarre *et al.* 2013, 2015a, van Emmerick *et al.* 2014, Viglione *et al.* 2014, Elshafei *et al.* 2015).

Modelling results heavily depend, of course, on the associated assumptions. Assessing their reliability – and the related uncertainty – remains an open research question in socio-hydrology. Data on society–hydrology interactions are needed to validate the modelling hypotheses, if socio-hydrological models are to be used for engineering design. The final aim is to understand the way in which the coupled human–water system may develop under different future scenarios, rather than simply model the future societal environment.

4.3 Criticism and peculiarity of socio-hydrology

Socio-hydrology has recently been the subject of intensive debate (see Di Baldassarre *et al.* 2015a, Gober and Wheater 2015, Loucks 2015, Troy *et al.* 2015a, 2015b, Montanari 2015, Sivapalan 2015). In particular, the capability of socio-hydrological models to capture human behaviour has been questioned, pointing out the inherently random and unpredictable nature of human decisions. Notwithstanding the fact that generally we cannot predict human behaviour, it is still important to learn from the experience of the past, generalize the findings in terms of causal links between humans and water, and develop theory that enables us to make statements about the possible future dynamics so as to avoid some of the spectacular mistakes we made in the past (e.g. Aral Sea). In this sense, predictions in socio-hydrology are fundamentally different from those that are usually made in hydrology (Srinivasan *et al.* 2016). In hydrology the intention is usually to predict time series of water fluxes (with uncertainty), under a range of socio-economic and climatic boundary conditions. In contrast, “predictions” in socio-hydrology do not aim at predicting time series. They aim at predicting phenomena emerging from the feedbacks between people and water in a quantitative and generalizable way. For example, socio-hydrological models may suggest that, under changing circumstances, a lock-in situation may entail, i.e. sub-optimal management strategies that persist due to the characteristics of the prevailing governance structure that arose because of the path dependence of the coupled system. Clearly, this kind of prediction is a far cry from those we are used to in hydrology, but they are needed for high-level, long-term decision making.

5 The leading role of the water resources scientific community

The concepts discussed so far emerge from a pragmatic and holistic assessment of the urgent need to adapt WRS by building on their long history and the experience that humans gained of their management. The water resources community, with its track record of working at the interface of disciplines and facing policy, plays a leading role here. Besides the scientific role of identifying solutions, the WRS community within the developing field of socio-hydrology has the role and the duty to communicate the above message to decision makers, institutions and funding agencies, to emphasize the value of, and the need for, new monitoring techniques, new data (Brown 2010), new interdisciplinary research efforts and open access to scientific information (Ceola *et al*. 2015b). The WRS science community needs to elaborate a unified and cohesive vision and a clear message to deliver to administrators, stakeholders and the public. Water resources research usually focuses on the limited scale of a single catchment, therefore inducing the perception that the associated challenges and solutions are only marginally important. It is therefore necessary to emphasize the global value of water resources research: water security and mitigation of water-related hazards are global problems that ultimately manifest themselves locally, hence can only be solved locally, but with a globally coherent vision (UN Water 2013, Cudennec *et al*. 2015). While local administrators are responsible for providing the necessary information and establishment of policies and management plans that are required to underpin feasible solutions, hydrologists and water scientists in general are responsible for providing the necessary scientific basis for these solutions and for giving visibility to their mission, by enhancing the dialogue with not only scientists in related disciplines but also the media, governments and the funding agencies.

Scientific publishing in hydrology and WRS is critical in this regard (Koutsoyiannis *et al.* 2016). The scientific community and scientific associations should take a leading role in promoting the visibility of water research, which is currently not getting enough consideration. A major effort is needed to promote open access, inexpensive and high quality publications that extend the global outreach of scientific research in this area, together with the dialogue with all key stakeholders, to ensure a sustainable relationship between humans and water during and beyond the third millennium we are in.

6 Conclusions

Adaptation of WRS in a changing world requires a paradigm shift based on the identification, design and use of resilient and low-regret solutions to current problems and the unsustainable situations they lead to. Such solutions should make the best use of available natural and intellectual resources. Designing and managing water and land resources in catchments under environmental change requires systems-based approaches that can be monitored and evaluated. They need to be practically useful, flexible, scientifically credible and give future generations the ability to respond to needs that we cannot even foresee today. The increasing need for monitoring WRS cannot be overstated. There may be the perception in some circles that WRS have been reasonably well monitored in the past, but since we are living in a period of rapid change, the need for monitoring of the processes of change and the effects that humans have on WRS requires further intensification of observations to support our understanding of the complexity of the coupled human–water systems. While solutions to current problems can be identified by using actual data and information, their resilience with respect to future changes involves prediction, which hinges on a deeper understanding of the linkages and feedbacks between hydrology and society. Although cultural, economic and political developments are difficult to predict, investigating their dynamics and feedbacks may allow us to gain a broader vision of likely future developments. To this end, we need to benefit from the available knowledge of the linkages between data–models–evidence–policy and case studies, to better anticipate the possible future co-evolution of WRS and society. Adaptation of WRS must be pursued with a pragmatic but evolving and dynamic approach, framed within the context of hydrological, social and engineering sciences. Finally, there is the need to enhance the dialogue among the water resources research community, social scientists, economists, administrators, stakeholders and the public, to bring visibility to the related challenges and ways forward.

The above concepts are the basis of a statement of the International Association of Hydrological Sciences, which is presented in the Appendix. The statement aims at bringing to the attention of scientists and policy makers around the world that the adaptation of WRS is an urgent task, for which societal dialogue, advanced engineering design and a pragmatic assessment, understanding and modelling of societal and environmental changes are needed. It is time for the water resources community to play a leading role in planning the future of WRS, to provide reliable support to their design and to environmental conservation actions for the benefit of future generations of humanity.

Acknowledgements

The authors gratefully acknowledge the International Association of Hydrological Sciences (IAHS) community, particularly the Panta Rhei – “Everything Flows” research initiative within which the present work was developed. The constructive reviews by an anonymous referee and Z.W. Kundzewicz are greatly appreciated.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

IW acknowledges the support of the People Programme (Marie Curie Actions) of the European Union's 7th Framework Programme FP7/2007-2013/(grant agreement no. 329762). TK is funded, through IRI THESys, by the German Excellence Initiative. SC, AM, AC, and ET acknowledge financial support from the EU funded project SWITCH-ON (603587).

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APPENDIX

The Prague statement by the International Association of Hydrological Sciences (IAHS) on the adaptation of water resources systems

A need for action to develop water resources management systems

Recognizing the human right on access to safe water and protection from water hazards of every individual as enshrined in international law,

Noting with satisfaction the current and past efforts made by governments, agencies and community groups to provide access to safe water, to protect the environment and to mitigate water hazards,

Acknowledging that there is a global water crisis with critical needs for immediate action,
We, the delegates to the conference of the International Association of Hydrological Sciences in Prague, June 20–26, 2015 are deeply concerned by the water problems humanity is experiencing with increasing frequency and severity and express the following concerns and recommendations.

The hydrosphere is experiencing a global water crisis caused by uneven freshwater availability in space and time, overexploitation, environmental degradation and the more frequent occurrence of floods and droughts. In fact, 842 000 people die annually from inadequate water supply and the annual economical damage induced by floods is nearly 14 billion US dollars (average 1980–2014). This crisis is fuelled by often fragmented water management and by economic problems, especially in water-scarce regions. Low efficiency of water resources management systems, in terms of high water losses and energy consumption, is no longer sustainable and may cause irreversible damage to our societies if not promptly mitigated. At the same time water demand is ever increasing in many parts of the world, due to population growth, economic development and changing lifestyles, exacerbating the risk of unsafe water supply.

Devastating floods around the world belong to the largest disasters in terms of economic loss and financial damage. These floods are expected to increase further as a result of land use change (such as the intensification of agricultural management and surface sealing due to urbanization), modifications of the river system (such as river training and harnessing) and more intense precipitation extremes related to climate change. More importantly, the number of people and the economic value of assets in flood prone areas have increased throughout the world, as a result of urbanization and encroachment of floodplains, exposing an increasing number of people to floods. These factors all contribute to increased flood risk to both humans and their economic goods.

Water resources management systems are the artefacts put in place to make freshwater available to people and to protect them from water threats. Their correct functioning is essential for people's wellbeing. Immediate action is therefore needed to evolve water resources management systems in order to address the present challenges of the global water crisis.

A call for immediate actions of governments

We call upon all local, regional and national governments and urge them to develop effective solutions to the water crisis by developing water resources management systems:

In order to address problems of freshwater availability and supply, the full spectrum of technical, organizational, economic, political, legal and social approaches should be considered, and implemented as needed.

In order to address flood risks, a holistic approach of integrated flood risk management should be adopted that considers all phases of the disaster cycle – mitigation, preparedness, response and recovery.

In all instances, a sustainable approach should be adopted ensuring that long-term issues are addressed. A comprehensive monitoring of the status of water resources is therefore needed to be able to adapt to changes in a flexible and ecologically sustainable way.

Instruments of managing water resources management systems should be tailored to the local hydrological, legal and societal situations to adapt to the dramatic global changes in the environment and society.

Cooperation of all stakeholders is needed based on a participatory approach, involving users, planners and policy-makers at all levels, in particular at the river basin scale.

Water resources management systems are a cultural heritage of humanity, yet the infrastructure to manage them efficiently and effectively is ageing and the requirements are changing. A balanced approach of preservation and adaptation is needed to meet the needs of a changing world.

The evolution of water resources management systems requires a sound scientific basis. Advice from the scientific community should therefore play an essential role in planning their future configuration and management.

A call for immediate actions of the international scientific community

We also call upon members of the international scientific community and urge them to develop practical and implementable methods and techniques to support adaptation of water resources management systems to the current and future challenges.

Adaptation of water resources management systems should build on observed evidence and rigorous system understanding. An improved understanding of hydrological processes is therefore needed, in particular at the local scale, and put into the context of broader river basin and groundwater issues.

An interdisciplinary and transdisciplinary approach is required to understand the multiple triggers of the water emergencies, and elaborate visions and solutions that are viable technically, environmentally and socially.

Assessment of the water future and management options is often carried out through scenario analyses. While useful for a set of questions, they do not usually account for dynamic feedbacks. Novel methods of socio-hydrology are needed that represent the long term feedbacks between hydrology and society in an explicit way.

The value of monitoring of water resources cannot be overestimated, particularly during times of change. Novel, efficient and accurate monitoring systems are needed in support of research and management practice.

Approaches to adaptive management are needed that identify priority targets and lead to feasible solutions. Given the multiple uncertainties, robust vulnerability-based approaches should be particularly developed that are people-centred and aim at reducing their vulnerability and enhancing their resilience, and give favourable outcomes under a broad spectrum of possible futures.

A call for immediate actions of research funding agencies

Finally, we call upon the research funding agencies at both national and international levels and urge them to provide funding that is commensurate with the challenges of the global water crisis.

- Enhanced funding is needed to improve the understanding of hydrological processes at all scales. Fundamental research is equally important as applied research, and is equally likely to become societally relevant, albeit over longer time scales.
- Funding is needed to address the big questions of the water future through both small and large research groups. Interdisciplinary research within projects and across projects is essential to make progress in

understanding and developing environmentally sustainable water resources management systems.

- Given the paramount role of adaptive management, long term funding is essential, in particular for Hydrological Observatories that unravel the long term feedbacks between water-related processes.
- Networking between scientists around the world is already receiving substantial funding. Mobility and international collaboration should continue to be funded at a high level.
- The support of young water scientists through structured doctoral programmes and other initiatives should be strengthened. The young generation will be the managers of the water resources management systems of the future, so investing in their education will pay back multiple times.

Adopted by acclamation, in the city of Prague, Czech Republic, on this 26th of June 2015